Optical Networking

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Outline

- Introduction
- First Generation Optical Networks
  - Fiber Distributed Data Interface (FDDI)
  - Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH)
- Second Generation Optical Networks
  - Wavelength Division Multiplexing (WDM)
  - Optical Networking Components
  - Wavelength Routing Networks

Introduction

Introduction(1)

- Advantages of Optical Transmission
  - Large bandwidth permits high data transmission, which also supports the aggregation of voice, video, and data
  - Technological improvements are occurring rapidly, often permitting increased capacity over existing optical fiber
  - Immunity to electromagnetic interference reduces bit error rate and eliminates the need for shielding within or outside a building
  - Glass fiber has low attenuation, which permits extended cable transmission distance
  - Light as a transmission medium provides the ability for the use of optical fiber in dangerous environments
  - Optical fiber is difficult to tap, thus providing a higher degree of security than possible with copper wire
  - Light weight and small diameter of fiber permit high capacity through existing conduits

Introduction(2)

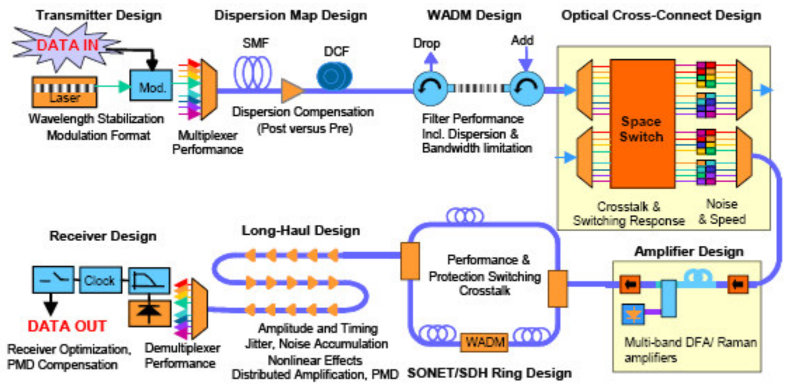
- Disadvantages of Optical Transmission
  - Cable splicing:
    - Welding or fusing: you must clean each fiber end, then align and carefully fuse the ends using an electric arc.
      - Time consuming
      - Least amount of signal loss between joined elements.
    - Gluing
      - Bonding material that matches the refractive index of the core of the fiber.
      - Time consuming
      - Higher loss of signal power than fusing.
    - mechanical connectors
      - Considerably facilitate the joining of fibers,
      - More signal loss than do the other two methods
      - Can reduce the span of the fiber to a smaller distance.

Introduction(3)

- Fiber cost:
  - On a (bit/s)/km basis, the fiber cost will always be less than that for copper cable.
  - Some organizations may require only a fraction of the capacity of the optical fiber.
    - It is often difficult to justify fiber to the desktop and similar applications where the cost of copper cable may be half or less than the cost of fiber.

Introduction(4)

- The big picture



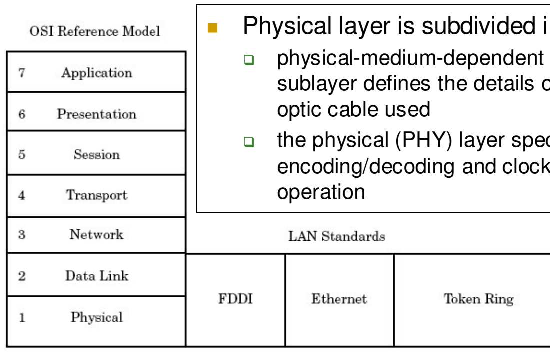
First Generation Optical Networks

Fiber Distributed Data Interface (FDDI)

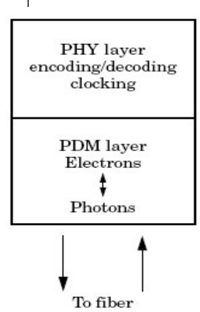
- Dates back to the early 1980s
- FDDI uses token-passing scheme
- Uses two fiber pairs, each operating at 100 Mbits/s.
- Data rates approaching 90% of its 100 MB/s operating rate
- FDDI was, and in some locations still is, commonly used at the Internet Service Provider (ISP) peering points that provide interconnections between ISPs.
- Relatively expensive

FDDI Position in the OSI Reference Model

- FDDI is defined as the two bottom layers of the seven-layer OSI reference model
- It provides a transport facility for higher-level protocols such as TCP/IP



- Physical layer is subdivided into:
  - physical-medium-dependent (PMD) sublayer defines the details of the fiber-optic cable used
  - the physical (PHY) layer specifies encoding/decoding and clocking operation



FDDI 4B/5B Coding

- The selection of the 4B/5B coding was based on the need to reduce the signaling level from 200 MHz to a 125-MHz rate (cost reduction)
- Each bit is encoded using non-returnto-zero-inversion (NRZI) transmission
- Because 4 bits are encoded into 5 bits, this means there are 16, 4-bit patterns.
- Those patterns were selected to ensure that a transition is present at least twice for each 5-bit code.
  - DC balance: important for thresholding at receiver
  - For some input data sequences the worst case DC unbalance is 10%
- Because 5-bit codes are used, the remaining symbols provide special meanings or represent invalid symbols.
- Special symbols
  - I symbol is used to exchange handshaking between neighboring stations,
  - J and K symbols are used to form the Start Delimiter for a packet,
    - which functions as an alert to a receiver that a packet is arriving.

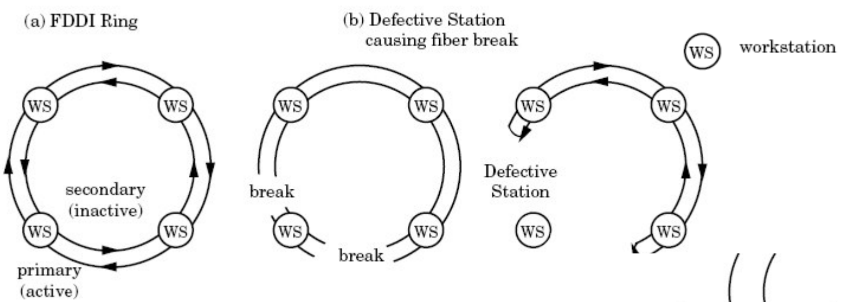
FDDI Fiber Specifications

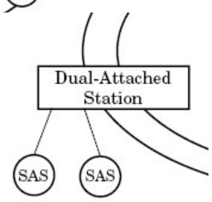
- **OPTICAL FIBER SUPPORT**
  - FDDI can support **62.5/125**-, 50/125-, and 100/140-µm multimode fiber sizes. Maximum distance 2 Km.
  - FDDI also supports the use of single-mode fiber,
    - Long-distance transmission (up to 40 Km)
    - FDDI single-mode fiber is commonly specified as 8/125, 9/125, and 10/125.
- **OPTICAL TRANSMITTER**
  - 850, 1300, and 1550 nm
  - 850 and 1300 nm for multimode fiber
  - 1300 and 1500 nm for single-mode fiber
  - For single-mode fiber laser diodes must be used
- **ATTENUATION**
  - For multimode fiber
    - PMD standard specifies a power budget of 11.0 dB
    - Maximum cable attenuation is 1.5 dB/km at 1300 nm.
  - single-mode fiber
    - power budget extends from 10 to 32 dB

Core/Cladding

this means that up to 11 dB of the optical signal can be lost.

FDDI Ring Structure





- FDDI backbone consists of two separate fiber-optic rings,
  - *primary ring:* active
  - *secondary ring:* “on hold,”
- Station Types
  - Class A:dual-attachment stations, Class B: single-attachment station.

SONET/SDH(1)

- Current transmission and multiplexing standard for high speed signals
  - North America: Synchronous Optical Network (SONET)
  - Europe, Japan and rest of the world: Synchronous Digital Hierarchy (SDH)
- Prior to SONET and SDH: Plesiochronous Digital Hierarchy (PDH)
  - 4KHz sampled at 8KHz quantized at 8 bits per sample → 64kb/s

Transmission rates for PDH

Level	North America [Mb/s]		Europe [Mb/s]		Japan [Mb/s]
0	DS0	0.064		0.064	0.064
1	DS1/T1	1.544	E1	2.048	1.544
2	DS2/T2	6.312	E2	8.448	6.312
3	DS3/T3	44.736	E3	34.368	32.064
4		139.264	E4	139.264	97.728

SONET/SDH(2)

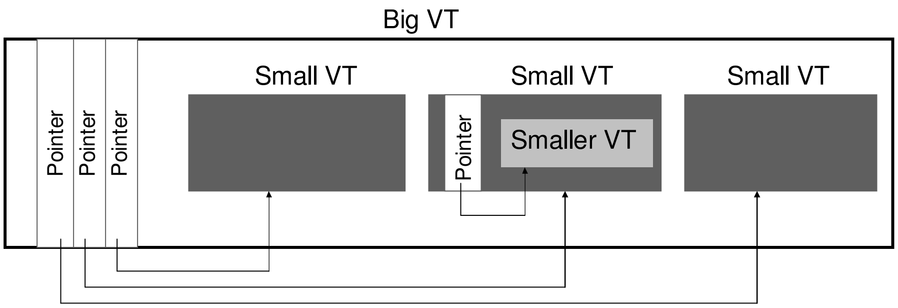
- PDH versus SONET/SDH
  - Multiplexing
    - PDH: Difficult to pick low bit rate stream from high bit rate stream
    - In PDH, clocks of lower bit streams are not perfectly synchronous
      - Higher rates are not integral multiples of 64Kb/s
        - Bit stuffing needed
        - Mulltiplexers and Demultiplexers complicated
    - In SONET/SDH a master clock is used→MUX and DEMUX much easier
  - Management
    - Unlike PDH, SONET/SDH standards are rich of management and traffic performance monitoring information
  - Interoperability
    - SONET/SDH define standard optical interfaces
    - PDH: different vendors define different line coding, optical interfaces,...
  - Networking
    - SONET/SDH: Service restoration time is less than 60 ms
    - PDH: restoration time is several seconds to minutes

SONET/SDH(3)

- SONET/SDH
  - Lower speed PDH is mapped into *synchronous payload envelope* (SPE), or *synchronous container* in SDH
  - Path overhead bytes are added to the SPE
    - Path overhead unchanged during transmission
    - Allows PDH monitoring end-to-end
  - SPE+path overhead = *virtual tributary* VT (*container* in SDH)
  - VT may be placed at different points within a frame (125 μs)
  - Many small VTs can be multiplexed into a larger VT (see next slide)
  - The overhead of each VT includes a pointer to smaller VTs multiplexed into the payload of the larger VT
  - This hierarchical structure simplifies extraction of low speed stream from high speed stream

SONET/SDH(4)

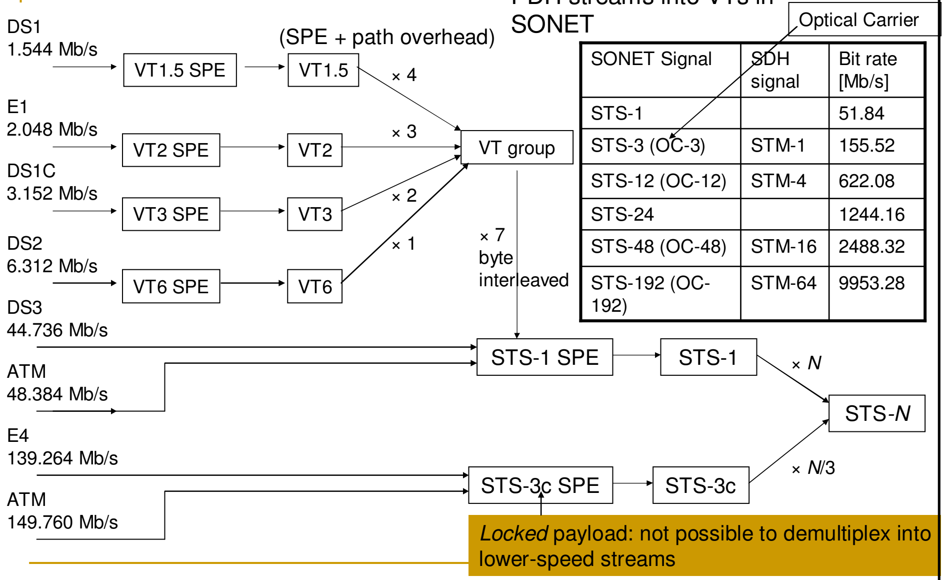
Hierarchical multiplexing structure employed in SONET and SDH



- In SONET: VTs with four sizes
  - VT1.5, VT2, VT3, VT6 that carry 1.5, 2, 3, 6 Mb/s PDH streams
  - VT group = 4 VT1.5s or 3 VT2s or 2 VT3s or a single VT6
  - Basic SONET SPE (STS-1) = 7 VT groups = 51.84 Mb/s
  - STS-*N* = *N* × STS-1 (byte interleaved) *STS = Synchronous Transport Signal*
  - STM-*1 = synchronous Transport Module* = 155 MB/s

SONET/SDH(5)

The mapping of lower-speed PDH streams into VTs in SONET

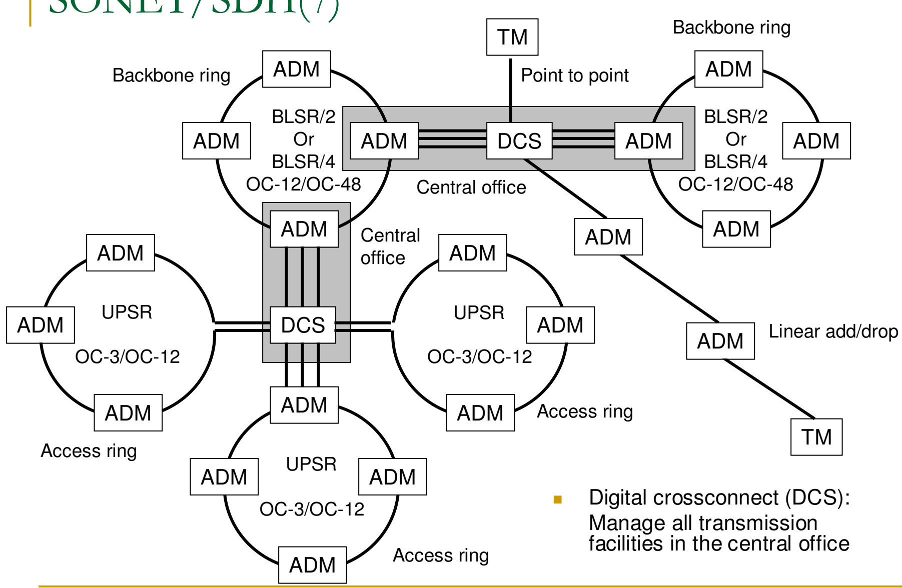


SONET Signal	SDH signal	Bit rate [Mb/s]
STS-1		51.84
STS-3 (OC-3)	STM-1	155.52
STS-12 (OC-12)	STM-4	622.08
STS-24		1244.16
STS-48 (OC-48)	STM-16	2488.32
STS-192 (OC-192)	STM-64	9953.28

SONET/SDH(6)

- SONET/SDH network configurations (see next slide)
  - Point-to-point
    - Node at ends
      - Terminal Multiplexers (TM)
      - Line Terminating Equipment (LTE)
  - Linear
    - Inserting add/drop multiplexers (ADM) between TM in point-to point-links.
    - Allows insertion or extraction of smaller traffic at mid-points
  - Rings
    - ADM with added function of protection: High level of availability
    - Unidirectional path-switched rings (UPSRs)
    - Bidirectional line-switched rings (BLSRs)
      - Two fibers BLSR/2, four fibers BLSR/4

SONET/SDH(7)

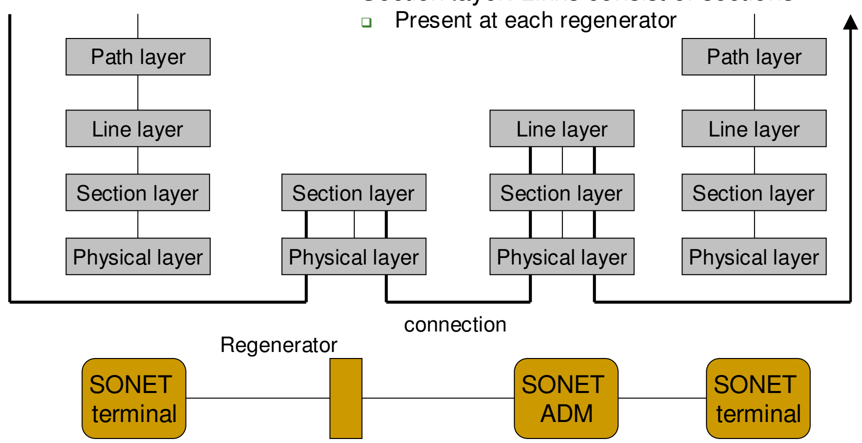


- Digital crossconnect (DCS): Manage all transmission facilities in the central office

SONET/SDH(8)

SONET/SDH layers

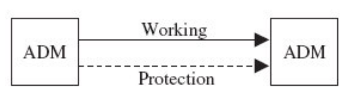
- Path layer: End-to-end connections
- Line layer:
  - Multiplexes a numer of path-layer connection into a single link
  - Responsible for protection switching
- Section layer: Links consist of sections
  - Present at each regenerator



SONET/SDH(9)

SELF-HEALING SONET/SDH RINGS

- Causes for a ring to go down:
  - Failure of a fiber link:
    - Fiber is accidentally cutoff
    - The transmission or receiver equipment on the fiber link fail.
    - SONET/SDH device fails (rare)
- Services automatically restored: using the *automatic protection switching (APS)* protocol.
  - The time to restore the services has to be less than 60 msec.
- Link protection:
  - *Dedicated 1 + 1,*
    - The two devices are connected with two different fibers.
    - The SONET/SDH signal is split and simultaneously transmitted over both fibers.
    - The destination selects the best of the two signals based on their quality.
    - The working and protection fibers have to be *diversely routed*



SONET/SDH(10)

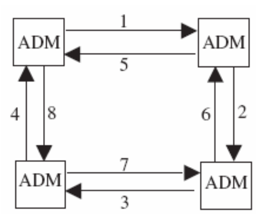
SELF-HEALING SONET/SDH RINGS

- Link protection:
  - 1:1 scheme,
    - Two diversely routed fibers: a *working fiber* and a *protection fiber*.
    - The signal is transmitted over the working fiber.
    - If this fiber fails, then the source and destination both switch to the protection fiber.
  - The 1:*N* scheme
    - Generalization of the 1:1 scheme,
    - *N* working fibers are protected by a single protection fiber.
    - Only one working fiber can be protected at any time.
    - Once a working fiber has been repaired, the signal is switched back, either automatically or manually, from the protection fiber to the working fiber.

SONET/SDH(11)

SELF-HEALING SONET/SDH RINGS

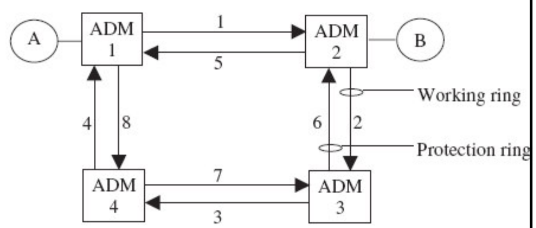
- Self-healing SONET/SDH ring architectures are distinguished by
  - *Number of fibers*: A SONET/SDH ring can consist of either two or four fibers. the working and protection rings are *route diverse*.
  - *Direction of transmission*: A SONET/SDH ring can be *unidirectional* or *bidirectional*.
  - *Line or path switching*: Protection on a SONET/SDH ring can be at the level of a *line* or a *path*.
    - *Line* is a link between two SONET/SDH devices and might include regenerators.
    - A *path* is an end-to-end connection between the point where the SPE originates and the point where it terminates.
    - *Line switching* restores all of the traffic that pass through a failed link
    - *Path switching* restores some of the connections that are affected by a link failure.



SONET/SDH(12)

SELF-HEALING SONET/SDH RINGS

- **Two-fiber Unidirectional Path Switched Ring (2F-UPSR)**
  - Example: The working ring consists of fibers 1, 2, 3, and 4; the protection ring consists of fibers 5, 6, 7, and 8.
  - Unidirectional: A transmits to B over fiber 1 (working), and B transmits to A over fibers 2, 3, and 4 (working).
  - Protection: path level using 1 + 1

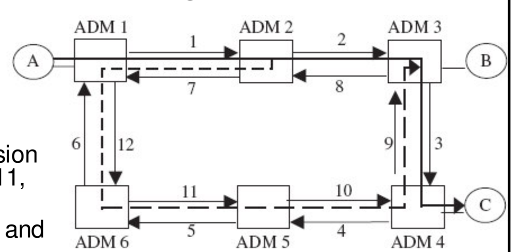


  - Simple ring architecture: Used as a metro edge ring to interconnect PBXs and access networks to a metro core ring.
  - Typical transmission speeds are OC-3/STM-1 and OC-12/STM-4.
  - Disadvantage:The maximum amount of traffic it can carry is equal to the traffic it can carry over a single fiber.

SONET/SDH(13)

SELF-HEALING SONET/SDH RINGS

- **Two-fiber Bidirectional Line Switched Ring (2F-BLSR)**
  - Used in metro core rings.
  - Example:
    - Clockwise transmission (Ring 1): Fibers 1, 2, 3, 4, 5 and 6.
    - Counter-clockwise transmission (Ring 1): Fibers 7, 8, 9, 10, 11, and 12.
    - Rings 1 and 2 carry working and protection traffic.



    - Assume: each fiber is OC-12/STM-4. Then, two OC-3/STM-1s are allocated to working traffic and the other two to protection traffic.
    - Since only two OC-3/STM-1s can be used for working traffic, the maximum capacity that the 2F-BLSR can carry over both Rings 1 and 2 is OC-12/STM-4.
    - The capacity allocated to protection traffic on either Rings 1 and 2 can be used to carry low priority traffic.

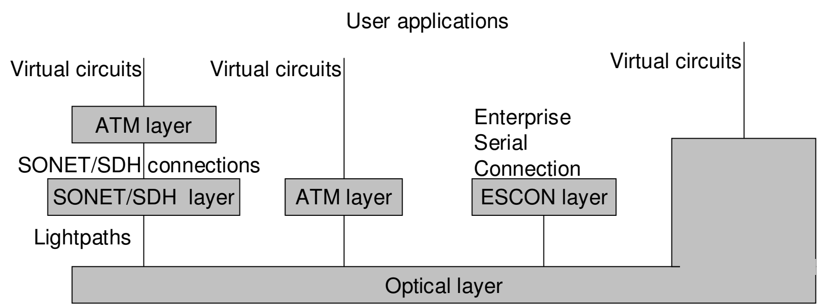
SONET/SDH(14)

SELF-HEALING SONET/SDH RINGS

- **2F-BLSR**
  - Bidirectional:
    - Ring 1 or Ring 2, depending on the route of the shortest path to the destination.
    - A transmits to B over the working part of fibers 1 and 2 of Ring 1,
    - B transmits to A over the working part of fibers 8 and 7 of Ring 2.
  - Fiber 2 fails:
    - line switching: Traffic over fiber 2 automatically switched to the protection part of Ring 2.
    - All of the traffic will be rerouted to ADM 3 over the protection part of Ring 2 using fibers 7, 12, 11, 10, and 9.
    - From there, the traffic continue on following the original path of the connection.
    - Consider a connection from A to C (solid line).
    - When fiber 2 fails, the traffic from A will be rerouted (dotted line).
    - At ADM 3, it will be routed back to ADM 4 over fiber 3.

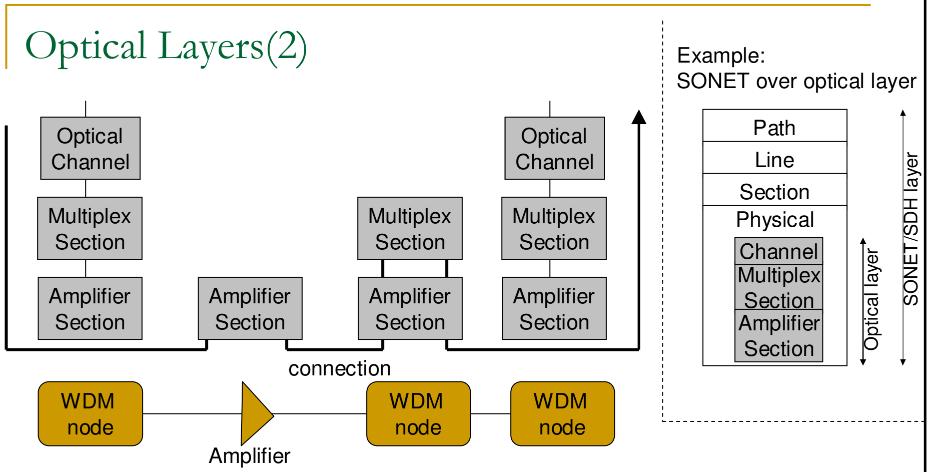
Second Generation Optical Networks

Optical Layers(1)



- Physical Layer
  - First generation networks:
    - Point-to-point, full bandwidth over single wavelength to layers above
  - Second generation networks:
    - Variable amounts of bandwidth
    - Optical layer: Provide ***lightpaths*** to varaity of first-generation optical layers

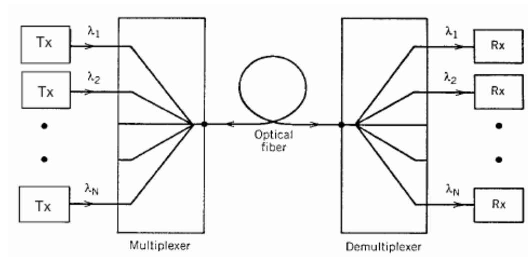
Optical Layers(2)



- Optical layer OC (lightpath layer): end-to-end connections
  - Each lightpath traverses a number of links, each link carries multiple wavelengths (WDM).
- Optical multiplex section OMS: point-to-point
  - Consists of several segments

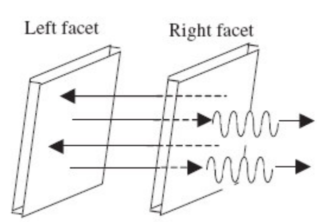
WDM OPTICAL NETWORKS

- Considerable increase in traffic became a driving force for WDM and its evolution into dense WDM (DWDM).
- WDM refers to the technology of combining multiple wavelengths onto the same optical fiber.
- Each wavelength is a different channel.
- At the transmitting end, there are *W* independent transmitters. Each transmitter *Tx* is a light source, such as a laser, and is independently modulated with a data stream. The output of each transmitter is an optical signal on a unique wavelength λ_i , $i = 1, 2, \ldots, W$.
- WDM: ~200 GHz spacing
- DWDM: ~50 GHz spacing



Components: Lasers(1)

- A *laser* is a device that produces a very strong and concentrated beam.
- It consists of an energy source which is applied to a *lasing* material, a substance that emits light in all directions and it can be of gas, solid, or semiconducting material.
- The light produced by the lasing material is enhanced using a device such as the *Fabry-Perot resonator cavity*.
- This cavity consists of two partially reflecting parallel flat mirrors, known as *facets*.
- These mirrors are used to create an optical feedback which causes the cavity to oscillate with a positive gain that compensates for any optical losses.
- Light hits the right facet and part of it leaves the cavity through the right facet and part of it is reflected.
- Part of the reflected light is reflected back by the left facet towards the right facet, and again part of it exits through the right-facet and so on.

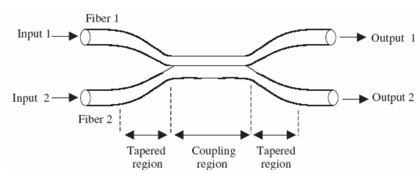


Components: Lasers(2)

- Consider a wavelength for which the cavity length (i.e., the distance between the two mirrors) is an integral multiple of half the wavelength.
  - For such a wavelength, all of the light waves transmitted through the right facet are in phase. Such a wavelength is called a *resonant wavelength* of the cavity.
  - Since there are many resonant wavelengths, the resulting output consists of many wavelengths.
- It is desirable that only a single wavelength comes out from the laser.
  - Using a filtering mechanism that selects the desired wavelength.
  - Another cavity can be used after the primary cavity where gain occurs.
  - Using reflective facets in the second cavity, the laser can oscillate only at those wavelength resonant for both cavities.
- Tunable lasers
  - More convenient than making different lasers for specific wavelengths.
  - Several different types of tunable lasers exist, varying from slow tunability to fast tunability.

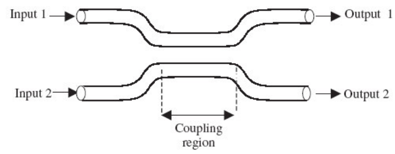
Components: 2 × 2 Couplers(1)

- The 2 × 2 coupler is a basic device in optical networks,
  - *Fused-fiber* coupler.
    - Fabricated by twisting together, melting, and pulling two single-mode fibers so that they get fused together over a uniform section of length.
    - Known also as *directional coupler*.
    - The coupled optical power is varied by varying the length of the coupling region, the size of the reduced radius of the core in the coupling region, and the difference in the radii of the two fibers in the coupling region.
    - There is always some power loss when the light goes through the coupler.



Components: 2 × 2 Couplers(2)

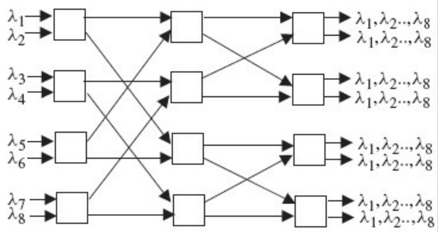
- *Waveguide coupler*
  - A *waveguide* is a medium that confines and guides a propagating electromagnetic wave. A waveguide coupler has two identical parallel guides in the coupling region.
  - As in the fused-fiber coupler, part of the light going down one guide is coupled onto the other guide.
  - The degree of interaction between the two guides can be varied through the width of the guide, the gap between the two guides, and the refractive index between the two guides.



- *3-dB coupler*:
  - Power is divided evenly between output ports
- *Splitter*: One input, two outputs
- *Combiner:* Two inputs, one output

Components: 2 × 2 Couplers(3)

- Star coupler: Combines power from *N* inputs and splitts evenly to *N* outputs
  - Fused-fiber method, limited to small *N*
- Combining 3-dB couplers in Banyan network
  - Number 3-dB of couplers = $(N/2) \log_2 N$
  - Each input is associated with a different wavelength.
  - The star coupler combines all of the wavelengths together and then evenly distributes them on all of the output ports.
  - It can also be used as 1-to-*N* splitter (demultiplexer) or an *N*-to-1 combiner (multiplexer).



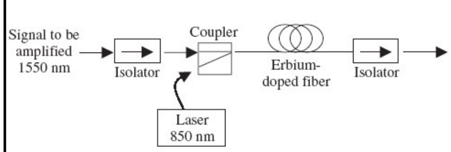
Components: Optical Amplifiers(1)

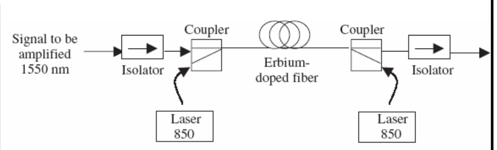
- Optical amplification is used to restore the strength of the signal.
- In a WDM link we can use:
  - power amplifiers,
  - in-line amplifiers,
  - preamplifiers.
- Prior to optical amplifiers, the optical signal was regenerated by first converting it into an electrical signal, then apply *1R* or *2R* or *3R* regeneration, and then converting the regenerated signal back into the optical domain.
  - 1R, the electrical signal is simply re-amplified, in
  - 2R, the signal is re-amplified and re-shaped, and in
  - 3R, the signal is reamplified, re-shaped, and re-timed.

Components: Optical Amplifiers(2)

- 1R can be done optically without knowledge of the bit rate and the framing format
  - Currently, re-shaping and re-timing cannot be done in the optical domain.
- Optical 1R can be applied simultaneously to the combined signal of all of the wavelengths in a WDM link.
- Types of optical amplifiers,
  - ***Erbium-doped fiber amplifier*** *(EDFA)*, (see next slide).
  - Semiconductor optical amplifier (SOA)
  - Raman amplifier.

Components: Erbium-doped fiber amplifier



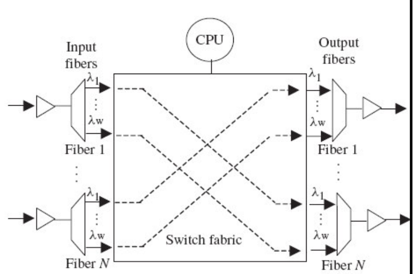


Two-stage EDFA

- A laser that operates at 980 nm or 1480 nm is emitted into the fiber and is combined through a coupler with the signal in the 1550 nm window that needs to be amplified.
- An isolator is used to prevent reflections into the amplifier.
- Two-stage EDFA shown is much more common.
  - In the first stage, a *co-directional* laser pumps into the coupler in the same direction as the signal to be amplified, and
  - in the second stage, a *counter-directional* laser pumps into the coupler in the opposite direction of the signal to be amplified.
  - Counter-directional pumping gives higher gain,
  - Co-directional pumping gives better noise performance.

Components: Optical Cross-connects(1)

- An *optical cross-connect (OXC)* is an $N \times N$ optical switch,.
  - it can switch the optical signal on incoming wavelength λ_i of input fiber k to the outgoing wavelength λ_i of output fiber m.
  - If it is equipped with converters, it can also switch the optical signal of the incoming wavelength λ_i of input fiber k to another outgoing wavelength λ_j of the output fiber m.
  - OXC can also be used as an *optical add/drop multiplexer (OADM)*.
  - In the example shown, wavelengths λ_1 and λ_W of input fiber 1 are directed to output fiber N. Likewise, wavelengths λ_1 and λ_W of input fiber N are directed to output fiber 1.
- An OXC should have:
  - Low switching time (burst switching appl.)
  - Low *insertion loss:* power lost because of the presence of the switch in the optical network.
  - Low *crosstalk:* the ratio of the power at an output from an input to the power from all other inputs.
  - Low polarization-dependent loss.

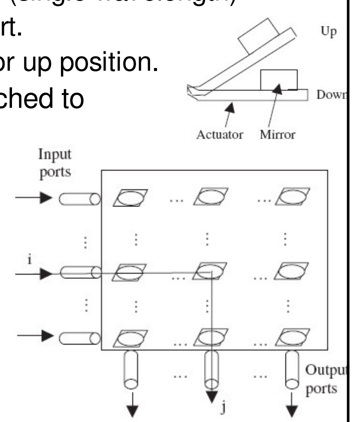


Components: Optical Cross-connects(2)

- Technologies for building a switch fabric of an OXC,
  - Multi-stage interconnection networks of 2 × 2 switches (directional couplers)
    - *electro-optic switch*, *thermo-optic switch*, and the *Mach-Zehnder interferometer*.
  - Digital *micro electronic mechanical systems (MEMS),*
  - *Semiconductor optical amplifier*s *(SOA)*.
- *Micro electronic mechanical systems (MEMS):*
  - dimension from a few hundred microns to millimeters.
  - fabricated on silicon substrates using standard semiconductor
    processing techniques.
  - robust, long-lived, and inexpensive to produce.

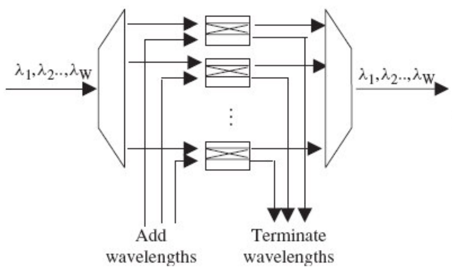
Components: Optical Cross-connects(3)

- The 2D MEMS is a square array of $N \times N$ micro-mirrors (actuator and a mirror) arranged in a crossbar.
  - Each row of micro-mirrors = an input port, (single wavelength)
  - Each column of micro-mirrors = output port.
  - A micro-mirror can be either in the down or up position.
- For a wavelength on input port *i* to be switched to output port *j* ,
  - all micro-mirrors along the *ith* row, from column 1 to port $j - 1$ have to be in the down position,
  - the micro-mirror in the (*i, j*) position has to be up,
  - the micro-mirrors on the *jth* column from rows $i + 1$ to *N* have to be in the down position.

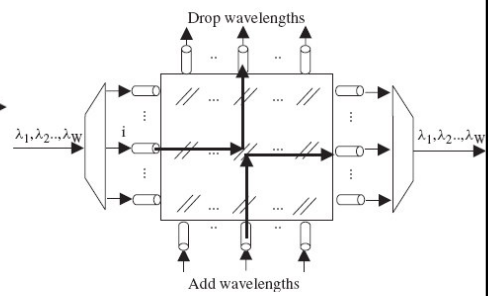


Components: Optical Add-Drop Multiplexer

- OADM can drop a number of incoming wavelengths and insert new optical signals on these wavelengths. The remaining wavelengths of the WDM link are allowed to pass through.
- The wavelengths that it adds/drops can be either statically or dynamically configured.
- OADM can be easily implemented using the 2D MEMS architecture.



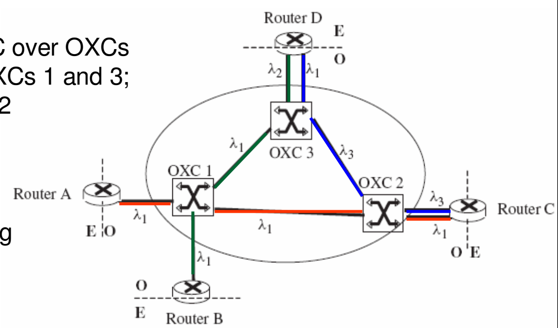
OADM Logical diagram



2D MEMS OADM

Wavelength Routing Optical Networks

- Lightpaths
  - Circuit-switched network.
  - This connection is a circuit-switching connection and is established by using a wavelength on each hop along the connection's path.
- Exmaple
  - Lightpaths from router A to C over OXCs 1 and 2; from B to D over OXCs 1 and 3; and from C to D over OXCs 2 and 3.
  - OXC 3 contains wavelength converter
  - Assumed single fiber carrying *W* wavelengths,
  - Unidirectional transmission.



References

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- Others
  - Gilbert Held, " Deploying Optical Networking Components," McGraw-Hill.
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