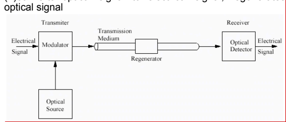
Wavelength Division Multiplexing (WDM)
1.Need for Tb/s networks
(1)Explosive growth of Internet traffic, High bandwidth applications such as multimedia, videoconferencing, medical imaging and supercomputer visualization
2.Existing networks
(1)Use optical fiber as a replacement for copper
(2)Electronic bottleneck (a few Gb/s)
3.Wavelength division multiplexing
(1)Divides bandwidth on a fiber into several non-overlapping channels (wavelengths)
(2)Simultaneous message transmission on different wavelengths on the same fiber

Basic Optical Transmission System
1.Optical Transmitter
(1)Light source (LED or Laser) is modulated according to the electric signal to produce on/off light pulses
2.Optical Receiver
(1)Photodetector (eg. Photodiode) receives optical signal and produces electric signal
3.Electrical Regenerator
(1)To boost signal strength
(2)converts optical signal to electrical signal, regenerates optical signal

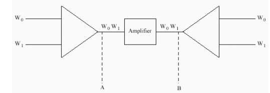


WDM transmission system
1.Divide available spectrum (bandwidth) centered at 1.55 micron into hundreds of wavelength channels with spacing of about 100GHz or 0.8nm
2.Simultaneous transmission of signals each on a different wavelength on a fiber link (Refer Figure 6)
3.Every wavelength operates at the peak electronic rate of a few Gbps independent of other wavelengths
4.Optical (wavelength) multiplexers and demultiplexers are used to combine and separate several hundreds of wavelengths
5.Erbium-doped fiber amplifiers (EDFAs)
(1)Amplify all the wavelengths at the same time regardless of their modulation methods, bit rates, and power levels
(2)Placed at a distance of 120 km as against 40 km in case of electric regenerators

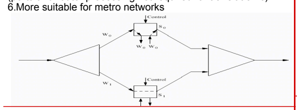
WDM vs. multifiber non-WDM
Assume a traffic requirement of W wavelengths on a link
1.WDM system cost:
One multiplexer, One fiber, One demultiplexer, EDFA amplifiers at every 120 km
2.Multifiber non-WDM system cost
W fibers, Electric regenerators at every 40 km for every fiber (or wavelength)

WDM Network Elements
1.LT- Line terminal- multiplexing and demultiplexing all the wavelengths (say W) (1)Requires W transponders or W wavelength ports (transmitters and receivers).
2.WADM: wavelength add drop multiplexer- selectively add/drop wavelengths, allow optical bypassing of signal between a pair of line terminals
3.WXC: wavelength cross-connects- selectively add, drop wavelengths and and also switch a wavelength from any fiber to any other fiber
4.WADMs and WXCs require fewer ports (determined by wavelengths dropped or added)

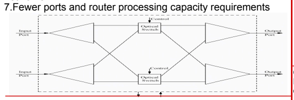
WDM Point-to-Point Networks
0.Use WDM point-to-point links 1.Use line terminals at every node 2.At every node transponders or transmitters/receivers at wavelength ports are required to drop/add all wavelengths 3.Opto-electric-opto (o-e-o) conversion at every node for every wavelength. Requires large buffer and high electronic processing capacity 4.Easy implementation 5.Early WDM networks come under this category 6.Cost effective if the transit traffic is not large



Wavelength Add/Drop Multiplexers (WADMs)
1.Allow optical bypassing of transit traffic
2.Selectively drop and add wavelengths between fixed input-output fiber pair
3.Built from multiplexers, demultiplexers and 2×2 switches
4.The switch can be in a "bar" or "cross" state
5.Fewer ports and router processing capacity requirements (ports and router processing not required for transit traffic)
6.More suitable for metro networks



Wavelength Crossconnects (WXCs)
1.Allow optical bypassing of transit traffic
2.Selectively drop and add wavelengths and also optically switch signals from any input to any output fiber
3.Built from multiplexers (one for each input fiber), demultiplexers (one for each output fiber) and optical switches (one for each wavelength)
4.Also referred to as wavelength selective crossconnect (WSXC) as incoming signal is switched to the outgoing fiber on the same wavelength
5.More flexible switching compared to WADMs
6.More suitable for arbitrary mesh topology in long-haul networks
7.Fewer ports and router processing capacity requirements

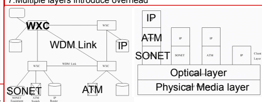


Wavelength-routed Networks
--Built from WADMs and WXCs
1.Circuit Switched network, connection-oriented service
2.Wavelength Reuse, Scalability
(1)A lambda on two different links can be simultaneously used by two different client traffic
3.Suitable for WANs, MANs
(1)WAN: wide area network; (2)MAN: metropolitan area network

Distributed Control Protocols
1.No central controller to keep the up-to-date network state information
2.Control messages are exchanged to select/reserve wavelength on a route
3.Routes can be pre-determined (OR) computed by the source node (source routing) by using network state information obtained using a link-state protocol similar to OSPF (OR) hop by- hop routing by looking up routing tables built from link-state or distance vector protocols
4.Control messages, actions by various nodes (source/destination and intermediate nodes), and design parameters together define a protocol. Link state, resource usage discovery, wavelength reservation, and switch configuration are done by routing and signaling protocols

Wavelength-routed WDM Networks
1.A lightpath is uniquely identified by a physical route and a wavelength
(1)Wavelength continuity constraint: Use the same wavelength on all links traversed by a path
(2)No need for o-e-o conversion and buffering at intermediate nodes
(3)Refer figure: Lighpath p0 ispresented by the physical route 0→1→2 and wavelength w0 (no o-e-o at node 1)
2.Single-(light) hop and multi-(light) hop communication
3.Multi-hop communication requires electronic processing between two consecutive lightpaths . Uses logical or virtual or lightpath topology.
4.Routing and Wavelength Assignment (RWA) refers to selecting a physical route and wavelength for a lightpath

WDM backbone network
1.Can transport a variety of traffic such as IP, SONET, and ATM simultaneously (Refer Figure)
2.Provides transparent lightpath service to client layers such as SONET (synchronous optical network), ATM (asynchronous transfer mode), IPMPLS (multiprotocol label switching), and Ethernet
2.Transparency: regardless of bit rate, modulation, and protocols
3.Protocol layer options for WDM networks
4.Presently service providers prefer to transport IP traffic over WDM through SONET/ATM
5.SONET advantages: high speed transmission, well-defined interface, and survivability
6.ATM advantages: flexible bandwidth allocation, quality of service (QoS)
7.Multiple layers introduce overhead



Static Traffic Demand
1.A set of lightpath requests (in terms of s-d pairs or physical paths) is given. The objective is to maximize the number of lightpaths routed (OR) to route all the requests minimizing the resources (wavelengths or fibers) required
2.Useful for Capacity planning: long-term, medium-term
3.Static Lightpath Establishment problem
4.May employ computationally complex algorithms

Dynamic Traffic Demand
1.Lightpath requests arrive one by one in a random manner, stay for a finite time before leaving the network
2.An important objective is to minimize the connection blocking probability
3.Performance may be poorer than that of static traffic demand, because the future requests are not known
4.Dynamic Lightpath Establishment
5.Computationally simpler algorithms are preferred

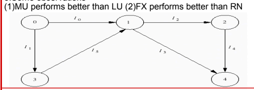
Example : Static and Dynamic Traffic Demand
Dynamic routing – demands are routed in the given order. First free wavelength is chosen when more than one wavelength are free. No lightpath can be established for <0,2> as the route is not wavelength-continuous
Static routing – all the demands can be routed if we establish lightpaths in the order <1,3>, <0,2>, <0,1>, and <2,3> (longest-path first policy is used)

Wavelength Assignment vs.Graph Coloring
1.The problem of wavelength assignment for a set of paths is related to the problem of node coloring in a graph
(1)Graph coloring is to assign a color to each node such that adjacent nodes are assigned different colors and the total number of colors is minimized
2.Construct a path graph where a node represents a path. Create an edge between two nodes (if and only) if the corresponding paths traverse at least one common link
3.Coloring the graph with minimum number of colors is equivalent to assigning wavelengths to the paths with minimum number of wavelengths.

Routing and Wavelength Assignment (RWA)
1.Wavelength assignment is a unique feature
2.A poor RWA algorithm leads to performance degradation
3.Performance metric
(1)No. of wavelengths or fibers required (static demand)
(2)Connection blocking probability (dynamic demand)
4.RWA for static traffic demand: Computationally complex, iterative algorithms can be used
5.RWA for dynamic traffic demand: Computationally simple algorithms are required

Layered Graph Representation
1.A WDM network with W wavelengths per fiber can be represented as a layered graph with W layers, each corresponding to a wavelength
2.在 layer i, a node corresponds to a routing node and an edge corresponds to a wavelength i on the fiber link between the end nodes of the edge
3.Path search can be done on each of the layer to choose a "good" physical path and wavelength to satisfy a connection request

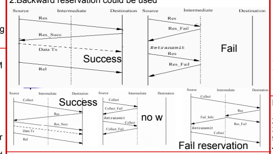
Wavelength Assignment Methods -Example
1.Most Used (MU), Least Used (LU), Fixed Order (FX), Randomorder (RN)
2.Refer Figure which shows a network with 6 links. Suppose that wavelengths w0, w1, w2, and w3 are used on 2, 5, 1, and 4 links, respectively. Assume that route R with free wavelengths w0, w2, and w3 is chosen to satisfy a request. Given this,
(1)MU searches in the order w1,w3,w0, and w2 and selects w3
(2)LU searches in the order w2,w0,w3, and w1 and selects w2
(3)FX searches in the order w0,w1,w2, and w3 and selects w0
(4)RN searches in the order w1,w2,w3, and w0 (say) and selects w2
3.Some observations
(1)MU performs better than LU (2)FX performs better than RN



Routing Algorithms
1.Fixed Routing (FR)
(1)For every node pair one pre-computed path is given
2.Fixed Alternate Routing (FAR)
(1)For every node pair, a set of precomputed paths given
(2)The paths are searched in fixed order; the first free path is chosen
3.Least Congested Path Routing (LCR)
(1)For every node pair, a set of precomputed paths given
(2)Choose the path which has the maximum number of free common wavelengths
4.Exhaust Routing (ER)
(1)Given a network state. Represent it as a layered graph. Choose a shortest path (minimum cost path) selection algorithm (eg. Dijkstra's) on wavelength layers
(2)Dijkstra's algorithm-Self study –Refer notes on "minimum cost path selection"; non-examinable
Complexity
N: number of nodes, W: number of wavelengths, H: hop length of the longest path between any node-pair, K: maximum number of alternative routes between any node-pair. The worst case time complexity are given below.
FR: O(HW) FAR: O(KHW), LCR: O(KHW), ER: O(N2W)

Centralized vs. Distributed Control
Route and wavelength selection by centralized or distributed control
1.Centralized control
(1)A central manager (controller) is used to keep track of the network and lightpath state information.
(2)RWA is efficient as it has up-to-date network status information
(3)Not scalable, more suitable for small networks
(4)Single-point (central manager) failure
2.Distributed control
(1)No central controller is assumed
(2)Every node has knowledge about the state of the links incident on it; can collect the network state from others (may not be accurate)
3.Control messages are exchanged to select and reserve a route and wavelength
4.Scalable; Good choice for large networks

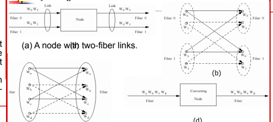
Forward Reservation (refer Figure)
1.Reserve wavelength(s) during forward traversal
2.Cancel the excess reservations during backward traversal
Backward Reservation (refer Figure)
1.Collect free wavelength(s) during forward traversal
2.Choose a wavelength at the destination node
3.reserve it during backward traversal
Congestion-based Routing
1.Choose the path with maximum number of (common) wavelengths available
2.Backward reservation could be used



VPN over WDM
1.A virtual private network (VPN) is a communication network between two or more network nodes built for private use over a public network
2.VPN simulates a WAN over the public network to offer secured services between branch offices of private organizations.

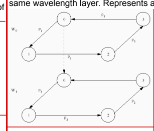
Wavelength-convertible Networks
1.Wavelength converter is a device that can convert a wavelength to another wavelength optically
2.Two types of wavelength converters
(1)O-E-O wavelength converters (e.g. commercial transponders):Expensive, high energy consumption
(2)Optical wavelength converters (mostly prototypes at lab):More expensive
3.Degree of wavelength conversion (D): one wavelength to any of D wavelengths (i.e. D-1 other wavelengths excluding itself)
4.Wavelength inter-change cross-connect (WIXC), wavelength converting(WC), wavelength interchange (WI) nodes
5.WC networks perform better than Wavelength Selective (WS) networks because WC relaxes wavelength continuity constraint
6.Benefits: Converters relax wavelength continuity constraint

Multi-Fiber Network
1.Space division multiplexing, a bundle of F fibers on a single link, each fiber carries W wavelengths
2.Wavelength continuity constraint is overcome to a certain extent
3.Equivalent to a single-fiber network with each fiber carrying FW wavelengths and each node having wavelength conversion capability of degree F



(c) Mapping of wavelengths from input fibers to output fibers. (c) Wavelength re-labeling. (d) Equivalent converting node with conversion degree = 2.

Routing in Convertible-Networks
1.Layered Graph representation of a convertible network
2.Vertical Edge (converting edge) : between the same node on two different wavelength layers. Represents wavelength conversion within a node
3.Horizontal edge (wavelength edge) : between two nodes on the same wavelength layer. Represents a wavelength on a fiber



Blocking performance in Convertible Networks
Consider a path with H hops with W wavelengths per link. Let p be the probability that a wavelength is used (or occupied) on a link. This event is assumed to be independent of the use of other wavelengths on the same link (wavelength independence) and is independent of the use of the same and other wavelengths on other links (no link correlation). Calculate blocking probability on the path Pnc when no wavelength conversion is employed and the path Pfc when every node has full wavelength conversion capability.

$$P_{nc} = [1-(1-p)^H]^W$$
$$P_{fc} = 1-(1-p^W)^H$$

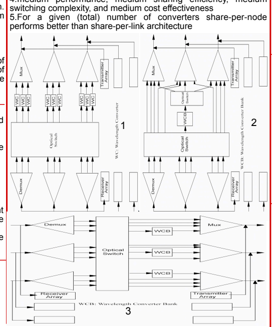
(1-p)^H: probability that a given wavelength is free on all the links on the path
1-(1-p)^H: probability that a given wavelength is not free on the path
[1-(1-p)^H]^W: probability that none of W wavelengths is free on the path
P^W: probability that all wavelengths on a link are occupied
1-p^W: probability that some wavelength is free on a given link
(1-p^W)^H: probability that at least one wavelength is free on each of H links on the path

Wavelength-convertible Switch Architectures: Dedicated WC
switch / Share-per-node WC switch / Share-per-link WC switch
1.D: No. of input, output links, W: No. of wavelengths
2.Differ in performance, sharing efficiency, and switching complexity

Dedicated WC switch Architecture 1
1.Associated with every outgoing link and a wavelength, there is a wavelength converter
2.A DW-by-DW optical switch is used
3.DW converters are used
4.No request will be blocked due to the lack of wavelength converters
5.High performance, low (no) sharing efficiency, low switching complexity, and low cost effectiveness

Share-per-Node WC switch Architecture 2
1.At a node, a wavelength converter bank (WCB) with k (say) converters is used.
2.DW-by-(DW+k) and k-by-Dk optical switches are used
3.A request may be blocked due to the lack of wavelength converters
4.low performance, high sharing efficiency, high switching complexity, and high cost effectiveness

Share-per-Link WC switch Architecture 3
1.At a node, a wavelength converter bank (WCB) with k' (say) converters is used for every outgoing link
2.A DW-by-(DW+Dk) optical switch is used
3.A request may be blocked due to the lack of wavelength converters
4.medium performance, medium sharing efficiency, medium switching complexity, and medium cost effectiveness
5.For a given (total) number of converters share-per-node performs better than share-per-link architecture



Converter placement
1.Given K number of converters and N≥K number of nodes, how do we choose K nodes such that placing the converters at these nodes yields the optimum performance
2.A node with light transit traffic or little mixing of traffic may not be a good candidate for converter placement
3.The distance between two converting nodes is a significant factor

Converter Placement on a Path
1.Assumptions:
(1)The connection blocking probability is taken as the optimization criterion (2)Full wavelength conversion (3)Link load correlation is negligible (4)Wavelength independence model is assumed (5)Every link has the same number of wavelengths (6)The link load is uniform, i.e. the wavelength occupancy probability is the same on all the links
2. It can be shown that placing K converters uniformly on a path will result in optimal blocking probability, i.e. if the segments formed by placing the converters have equal success probability, then the performance in terms of end-to-end success probability of the path is maximum

Heuristic Logical Topology Design Algorithm (HLDA)
1.Objective: To minimize congestion
2.Idea: To maximize single-hop traffic flow
3.Consider node-pairs one by one in non-increasing order of their traffic demand
4.Establish a lightpath if permissible and update traffic by subtracting the next highest traffic .If not permissible, set traffic to zero.
5.LPRS: select a shortest path based on propagation delay or hop count
6.LPWS: Choose a free wavelength with the lowest index

Minimum delay Logical Topology Design Algorithm (MLDA)
1.Ensures a shortest propagation delay path for every pair of nodes
2.Create a lightpath for every edge in the physical topology
3.Follow a procedure similar to HLDA to establish other lightpaths

Predetermined VT and Lightpath Routes
1.Given a VT in terms of s-d pairs and physical routes,
2.The objective is to minimize the number of wavelengths required or to maximize the number of lightpaths routed when the #wavelengths is limited
3.A Design Heuristic
(1)Sort lightpaths in non-increasing order of their physical hop length
(2)Consider wavelengths one by one
(3)Assign the current wavelength to all the edge-disjoint routes, before proceeding to the next wavelength

Network survivability techniques
Proactive methods (protection approach)
1.Resources are pre-assigned to the backup lightpaths
2.Guaranteed and fast service restoration
3.Excessive resource usage

Reactive methods (dynamic restoration approach)
1.Back up paths are searched (selected) dynamically after the failure occurrence
2.Service restoration is slow and not guaranteed
3.Better resource utilization

Path-based failure recovery
Path-based methods
1.Employs end-to-end detouring (rerouting), back up lightpath is established between the end nodes of the failed lightpath
2.Primary and backup lightpaths may use different wavelengths
3.Better resource utilization (compared to link-based recovery)
4.If any of the links on primary path p1 failed, traffic will be rerouted through backup path p1
5.Failure is detected by the end nodes of the failed link. (failure detection)
6.The end nodes of the failed paths traversing the failed link need to be notified of the failure (failure notification);signaling protocol required
7.Source node uses a signaling protocol to activate / configure the backup path and reroute the traffic (backup activation)

Link-based recovery
Link-based methods
1.Employs local detouring, backup lightpath is established between the end nodes of the failed link
2.Primary and backup lightpaths must use the same wavelength
3.Poor resource utilization
5.Consider a primary path p1 traversing 0-1-5, If link 0-1 fails, backup b11: 0-3-4-1-5 will be used by the failed traffic. If link 1-5 fails, backup b12: 0-1-2-5 will be used by the failed traffic.
6.Note that the working segment is retained and backup is routed around the failed link.
7.Failure detection and backup path activation
7.There is no need for failure notification as the end nodes of the failed link are responsible for rerouting

Backup Resource sharing
1.Dedicated backup method
(1)Backup path is exclusively reserved (no sharing)
(2)Switches are readily configured for backup, no need for backup activation, fast service restoration
(3)Paths p1 and p2 use backup paths b1 and b2, respectively; b1 and b2 do not share any wavelength channel (wavelength on fiber)
(5)Excessive resource usage

2.Backup multiplexing (shared backup)
(1)Different backup lightpaths can share a wavelength channel if the corresponding primary lightpaths do not fail simultaneously
(2)Single link failure model: If two primary lightpaths are link-disjoint then their backups can share a channel
(3)Paths p1 and p2 are link-disjoint; their backup paths b1 and b2 share a wavelength channel (wavelength on link 5→1)
(4)Better resource utilization

Primary-backup multiplexing
1.Allows a channel to be shared by a primary lightpath and one or more backup lightpaths
2.Less than 100% service guarantee
3.Better resource utilization and smaller blocking probability when compared to backup multiplexing technique
4.If a channel on a backup lightpath of a connection is used by some primary lightpath, the connection becomes non-recoverable
5.In a dynamic traffic demand scenario, a non-recoverable connection may regain recoverability
6.Primary p1 and backup b3 share a wavelength on link 5→2
7.Primary p3 and backup b1 share a wavelength on link 1→2
8.If p3 (p1) fails, p1 (p3) becomes recoverable

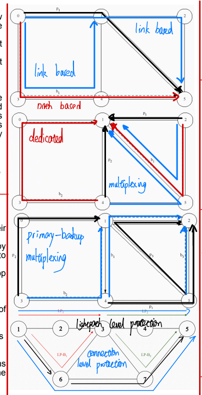
Failure-dependent vs. failure-independent
Backup and primary-backup multiplexing methods may employ failure-dependent or failure-independent path-based restoration
Failure-dependent methods
1.Associated with every link i traversed by a primary lightpath, there is a backup lightpath i
2.When link i fails backup lightpath-i is used
3.Better resource utilization as the backup path can use the working channels used by the failed primary lightpath
Failure-independent methods
1.Only one backup lightpath is used for a primary lightpath
2.Backup lightpath is link-disjoint with the primary lightpath
3.When a primary lightpath fails, irrespective of which of its links failed, the same backup lightpath is used
4.Stringent requirement of link-disjoint-ness
5.Computationally simple algorithms are possible

Segment-based Method
1.A segment is a sub-path traversing a sequence of contiguous links of a path
2.Provide a backup-segment for each primary segment
3.Tradeoff between link-based and path-based
4.In terms of blocking performance, resource utilization, recovery time

Lightpath vs. Connection Level protection
Lightpath level recovery (optical layer survivability)
1.Assume path-based recovery
2.Associated with each lightpath there is a link-disjoint backup lightpath
3.LP-B1 and LP-B2 between the end nodes of LP1 and LP2 can be used as backup
4.If a link fails, the lightpath traversing the link failes and the associated backup lightpath is used

Connection level recovery (client layer survivability)
1.Assume path-based recovery
2.Every lightpath is an unprotected lightpath
3.Client layer: primary connection and backup connection are link disjoint
4.Primary connection (p) traverses a set of unprotected lightpaths
5.Backup connection (b) traverses a set of unprotected lightpaths

Pros and Cons: Optical vs. Client Layer Protection
Optical Layer Recovery (Lightpath Level)
1.Fast recovery as failures need to be notified to the end nodes of the failed lightpaths at optical layer
2.Client layer recovery needs notification to the end nodes of the failed connections at client layer; signaling to upper layers incurs delay
3.When a link fails, fewer lightpaths fail as compared to failed connections; large amount of signaling in case of client layer recovery
Client Layer Recovery (Connection Level)
1.Smaller bandwidth granularity compared to wavelength-level large granularity in lightpaths
2.As a result, connection-level protection provides better resource sharing



Burst Rescheduling
1.Migrating an existing burst to a new wavelength: could be useful to schedule a new burst which otherwise would have been dropped; It results in lower burst loss
2.Can be used with LAUC: Only the last (latest burst) on a wavelength is considered for migration
3.Can be used with LAVF: Any existing burst can be considered for migration
4.Rescheduling needs extra signaling as the next node needs to be notified of the change of wavelength

Burst Loss Probability
1.Assume that there are F (burst) flows arriving at a link in an OBS network. If each flow's arrival follows Poisson distribution and the burst lengths of bursts follow exponential distribution, the burst loss probability on this link can be estimated by Erlang B formula.
2.Rationale: an OBS link can be modeled as an M/M/K/K server where K=W, where W is the number of wavelengths per link.
3. The burst loss probability on a link in OBS networks, r, can be estimated by where ρ is computed as follows
The arrival rate of the ith flow: \lambda_i
The mean burst length of the ith flow: 1/\mu_i
The load of the ith flow: \rho_i = \lambda_i / \mu_i
The total load over this link: \rho = \sum \rho_i

$$r = \frac{\frac{\rho^W}{W!}}{\sum_W \frac{\rho^n}{n!}}$$

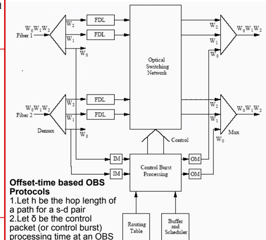
Optical packet switching
1.Traditional non-WDM IP routers perform routing, forwarding and switching operations in electronic domain
2.IP packet: header+payload 3.Packet switching uses statistical multiplexing
4.Routing table maintenance and lookup: (1)Slower operation (2)Can be speeded up by using efficient table-lookup algorithms and data structures
5.Switching: directing packet to the output port:
Needs to be speeded up especially for WDM networks
6.IP packets can be switched in the optical domain to speed up the switching operation; reduced buffer requirement
7.Header and payload data are sent together in a packet
8.The header is extracted from the packet, processed electronically. The outgoing port is then decided by table lookup
9.Payload is switched optically to the output port
10.The header is inserted into the payload before transmission
11.Fiber delay lines (FDLs) with different lengths are used for buffering (delaying) the packet optically until the header is processed
12.Packet synchronization, cost of switching fabric become the bottleneck

Optical Access Networks
1.Optical Fiber based Fiber to the home (FTTH) solutions
2.N: subscribers, L km average distance between CO and user: (a) 2N transceivers and N×L total fiber length (b) active curb switch- 2N+2 transceivers and L total fiber length (c) N+1 transceivers and L total fiber length
3.PON is an attractive solution: (1) Uses inexpensive passive optical splitter/coupler (2)small number of optical elements, total minimum fiber length

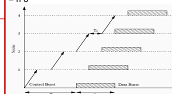
IP-over-WDM: Switching Technologies
1.Optical circuit switching
(1)Communication through lightpaths
(2)Two-way reservation: Long delay, wavelengths cannot be used during the reservation process
(3)Traffic cannot enter or leave at the intermediate nodes, low bandwidthwavelength utilization
2.Optical burst switching: Switching entity is a burst(爆炸), technology is premature
3.Optical packet switching: Switching entity is a packet, technology is premature

WDM Optical Burst Switching Networks
What is a burst? A: Collection of data packets having the same ingress and egress address and some common attributes such as quality of service (QoS)
Optical Burst switching (OBS) networks
1.Bursts are assembled at the ingress edge router
2.Burst assembly could be based on a time-threshold or size threshold
3.Control and data parts of a burst are transmitted separately with a time gap; control packet goes ahead of data burst
4.Data burst is switched optically, control packet (also called control burst or control message) is processed electronically

OBS Node Architecture
Built from demux, mux, IM, OM, FDL, optical switching network (OSN), and control packet processing unit (CPPU)
1.IM –input module: Optical receiver unit for the control wavelength
2.OM –output module :Optical transmitter unit for the control wavelength
3.FDL (fiber delay line) (Optional) optical buffer, delays bits in optical domain for short time
4.OSN–Multi-stage interconnection network (e.g. Benes topology) Employs wavelength converters; for a burst, input and output wavelengths can be different
5.CPPU (1)Extract burst information from the control packet (2)Buffers control packet, processes based on its arrival time, schedules bursts, sends control signals to OSN



Offset-time based OBS Protocols
1.Let h be the hop length of a path for a s-d pair
2.Let δ be the control packet (or control burst) processing time at an OBS node
3.Send the control burst first and then the data burst with an initial offset time, T ≥ hδ
4.Control packet carries information such as burst arrival time and burst duration
5.OBS node processes control packet and reserves a wavelength for the burst duration on the outgoing link using a scheduling algorithm
6.JET (just enough time) protocol uses minimum initial offset time T = h δ



(To: offset time, Tc: control pkt. processing time, lb: burst length or duration)

QoS in OBS networks
1.Multiple classes of services with different QoS requirements (e.g. burst loss, delay)
2.With the queuing delay restricted to the edge nodes, burst transfer delay is defined by the propagation delay. Therefore, there are not many issues in dealing with delay
3.More consideration is given for burst loss
4.pJET (prioritized JET) provides service differentiation to ensure isolation between classes
(1)Low priority class uses minimum initial offset time (base offset time)
(2)High priority class uses extra offset time in addition to the base offset time
(a)Reserves wavelengths well in advance when compared to the low-priority class
(b)An extra offset time of "three times the mean duration of low-priority class bursts" ensures 95% class isolation for a certain traffic model.

Burst Scheduling Algorithms
1.Suppose that a control packet arrives at time t with the info: offset time to, burst duration d.
2.A burst scheduling algorithm chooses a wavelength channel on the outgoing link which is free from time t+ to to time t+ to + d
3.Unscheduled time of a wavelength is the time after which no burst is scheduled
4.Desirable properties: (1)Wavelengths must be used efficiently, tight packing of bursts is preferred. (2)Algorithm must not be computationally very complex

Scheduling Algorithms
1.FFUC (first fit unscheduled channel):(1)Keeps track of the unscheduled time of every wavelength channel(2)Chooses the first channel which is free (w1 in the figure)(3)Time Complexity: O(W), W – no. of wavelengths
2.LAUC (Latest available unscheduled channel): (1)Keeps track of the unscheduled time of every wavelength channel (2)Chooses the latest available channel (w4 in the figure)(3)Time Complexity: O(W), W – no. of wavelengths
3.LAVF (Latest available void filling): (1)Keeps track of the voids on every wavelength channel (2)Chooses the channel which fills the void tightly than other channels (w3 in the figure) (3)Time Complexity: O(WM), W – no. of wavelengths, M – number of voids or bursts on a wavelength assuming that the voids are searched linearly

PON: Point-to-multipoint (PtMP) network
1.Possible Topologies: (a) Tree, (b) Bus, and (c) Ring
2.Transmission between OLT and ONUs
(1)OLT: optical line terminal at CO connecting to MAN/WAN
(2)ONU: optical network unit at the end-user side
(3)Downstream broadcast, upstream time division multiplexing
3.Advantages of PON
(1)Allow long distances between CO and users, up to 20 km
(2)Minimal fiber deployment (3)Downstream broadcast allow for video broadcast (4)No need for active components (5)Allow upgrade to higher bit rates

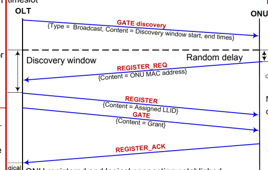
Ethernet PON (EPON)
1.Carries traffic encapsulated in Ethernet frames, IEEE 802.3ah standard
2.Most popular layer 2 networking technology
3.Low cost Ethernet line cards with a range of bit rates ranging from 10 Mbps to 10 Gbps and beyond are available
4.Support for quality of service by traffic prioritization (802.1p), virtual LAN tagging (802.1q)

Downstream Operation
1.Broadcast: OLT transmits Ethernet frames, pass through a 1:N splitter (N=8 to 32), received by each ONU
2.Ethernet frame format: header, payload, and FCS (frame check sequence, CRC)
3.Each ONU is assigned a logical link identifier (LLID) when it registers with the network: (1)LLID: 2 bytes within first 8 byte of preamble in Ethernet frame
4.Ethernet frames broadcast by the OLT are extracted/accepted by an ONU based on LLID

Upstream Operation
1.More than one ONU cannot transmit upstream to OLT simultaneously if we want to avoid collisions
2.Need for some arbitration mechanism to avoid collisions
3.The traditional CSMA/CD type collision resolving MAC is not desirable
(1)Transmission from an ONU to OLT is directional, so collisions cannot be detected at the ONUs
(2)OLT can detect collision, but the propagation time is long (up to 20 km)
4.The distance from OLT to different ONUs need not be the same
5.All ONUs are synchronized to a common time reference
6.Each ONU is allocated a timeslot to transmit
(1)Frames are buffered at an ONU until the time slot begins
(2)The time slot concept is not like the slot in fixed TDM; it is a time slice or period assigned to an ONU
(3)The length of a timeslot assigned to an ONU can be dynamically changed adapting to the present queue length

Multi-Point Control Protocol (MPCP)
1.MPCP aims to define a signaling protocol between OLT and ONUs
2.MPCP facilitates dynamic timeslot allocation
3.MPCP is standardized in IEEE 802.3ah
4.MPCP has 3 functions: (1)Discovery processing (2)Report Handling (3)Gate Handling

Discovery processing
1.Process of a newly-connected or offline ONU registering in the network
2.OLT periodically broadcasts a discovery window specifying start and end time
3.ONU: (1)Waits for a random time within the given window (2)Transmits Register-Req message with its MAC address
4.OLT: Registers ONU and assigns a LLID, transmits REGISTER message
5.OLT: Transmits a GATE message specifying the time slot to transmit
6.ONU: Transmits a REGISTER-ACK message during the assigned timeslot

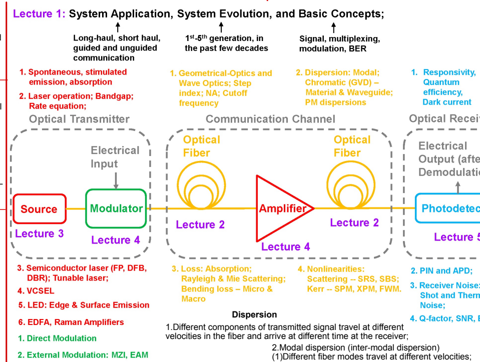


ONU registered and logical connection established

Report Handling
1.REPORT messages are sent by ONUs to OLT indicating the bandwidth requirements
2.REPORT messages are sent periodically
3.REPORT message contains the length of the time slot desired based on the current queue length at the ONU
4.OLT processes REPORT messages from the ONUs and allocate time slots for the next round

GATE handling
1.GATE messages are sent by the OLT to ONUs specifying the timeslots assigned
2.GATE message specifies ONU LLID, transmission start time and transmission duration (length)
3.ONU starts transmitting its frames to OLT when the local clock reaches the assigned transmission start time

Clock Synchronization
1.Clock synchronization is needed between the OLT and each ONU
2.The distance between the OLT and different ONUs (RTTs) need not be the same (RTT: round trip time)
3.Not physically synchronized, logical synchronization based on time stamping
4.Each ONU has a local clock
5.When an OLT sends a message: (1)Timestamp=local clock (say, t0) (2)Sends timestamp along with the message
6.When an ONU receives a message: Local clock = timestamp (t0) carried in the message
7.When an ONU sends a message
(1)Timestamp=local clock=t1=time when message was received + waiting time at ONU; t1=t0+twait
(2)Sends timestamp along with the message
8.When an OLT receives a message
(1)Note the local OLT clock (t2) and timestamp on the message (t1)
(2)RTT = 2tp = t2-t1 (how?): (a)t2=t0+tp+twait+tp, t1=t0+twait
(b)tp= propagation between OLT and ONU



Dispersion
1.Different components of transmitted signal travel at different velocities in the fiber and arrive at different time at the receiver;
2.Modal dispersion (inter-modal dispersion)
(1)Different fiber modes travel at different velocities;
(2)Only at multi-mode fibers;
3.Chromatic dispersion (intra-modal dispersion)
(1)Also called group-velocity dispersion (GVD);
(2)GVD has two contributions:
(i)Material dispersion: due to l-dependence of fiber material;
(ii)Waveguide dispersion: due to waveguide design;
4.Polarization-mode dispersion
(1)Different polarization components of a pulse travel at different velocities.

Advantages of Optical Fiber:
(1)Low loss (0.16 dB/km) (2)Wide bandwidth (3)Wavelength multiplexing (4)Small size and light weight (5)Immune to interference (6)Flexible delivery of light (7)Enhanced safety (8)Signal security (9)Abundant of raw material (10)Manufacturability

Loss and Power
Power ratio in dB $10\log(\frac{P_2}{P_1})$
Power level (in dBm) $10\log[\frac{P(mW)}{1mW}]$

Attenuation in Optical Fibers

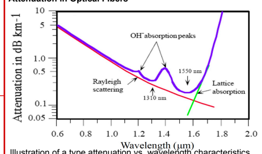


Illustration of a type attenuation vs. wavelength characteristics of a silica based optical fiber. There are 2 communication channels at 1310nm and 1550nm

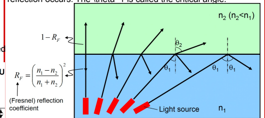
Fiber Loss
1.Material Absorption
(1)Intrinsic absorption by SiO2: electronic resonance in ultraviolet at \lambda < 0.4 mm; vibrational resonance in infrared at \lambda > 7.0 mm;
(2)Extrinsic absorption by impurities (transition metal elements);
(3)Extrinsic absorption by OH- ion (main source for extrinsic absorption): vibrational resonance of OH- ion at \lambda~2.7 mm and its harmonics and combination tones at 1.39 mm, 1.24 mm, 0.95 mm.
2.Rayleigh Scattering
(1)Microscopic fluctuation of silica molecule density →random fluctuation of the refractive index on a scale smaller than optical wavelength \lambda.
(2)Loss proportional to $1/\lambda^4$
3.Mie Scattering (Waveguide Imperfection)
(1)Imperfection of waveguide (e.g., irregularities in the core-cladding interface, diameter fluctuation);
(2)Index inhomogeneity on a scale larger than optical wavelength \lambda.

Attenuation Coefficient
1.Change in the average optical power P of a bit stream propagating inside the fiber follows Beer's law: $dP/dz = -\alpha P$ where \alpha(unit: m^-1 or km^-1) is the attenuation coefficient. If Pin is the power launched at the input end of a fiber with length L, the output power Pout can be written as $P_{out} = P_{in}e^{-\alpha L}$
It is customary to express α in units of dB/km.

$$\alpha[dB/km] = -\frac{10}{L}\log_{10}\left(\frac{P_{out}}{P_{in}}\right) = -\frac{10}{L}\log_{10}(e^{-\alpha L}) = 10\alpha\log_{10}e \cong 4.343\alpha$$

Typical fiber loss at 1.55 μm is 0.2 dB/km, which means 95.5% of photons survive after 1-km transmission. This value is close to the fundamental limit of 0.16 dB/km.

Snell's Law and Total Internal Reflection
Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
If the incident angle is larger than a certain value \theta_1 where sin(\theta_1)=n2/n1, there is no refraction light and total internal reflection occurs. The \theta_1 is called the critical angle.



Numerical Aperture of Step-Index Fiber
$n_1\sin\phi_c = n_2$, $\theta_c = 90 - \phi_c$, $n_0\sin\theta_a = n_1\sin\theta_c$
Numerical aperture (NA), which represents the light-gathering capability of an optical fiber, can be expressed as

$$NA = n_0\sin\theta_{max} = n_1\sin(90-\phi_c) = n_1\cos(\phi_c) = n_1\sqrt{1-\sin(\phi_c)^2}$$
$$= n_1\sqrt{1-\left(\frac{n_2}{n_1}\right)^2} = \sqrt{n_1^2 - n_2^2} \cong n_1\sqrt{2\Delta}$$

where $\Delta = (n_1 - n_2)/n_1$

Capacity Estimate of Step-Index Fiber (Geometrical-Optics)
For a step-index fiber of length L, the shortest path (L) occurs for $\theta_i = 0$, whereas the longest path $(L/\sin(\phi))$ occurs for $\theta_i = \sin^{-1}(n_1\sin(90-\phi_c)/n_0)$. Thus, the time difference between the two paths can be expressed using geometrical-optics as

$$\Delta T = \frac{n_1}{c}\left(\frac{L}{\sin\phi_c} - L\right) = \frac{n_1 L}{c}\left(\frac{1}{(n_2/n_1)} - 1\right) = \frac{L}{c}\frac{n_1(n_1-n_2)}{n_2} \cong \frac{L}{c}\frac{n_1^2}{n_2}\Delta$$

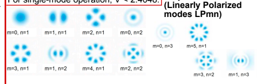
Approximately, the time difference should be less than the bit duration, 1/B. An order-of-magnitude estimate of bit rate:
$\Delta T < 1/B$ Hence, we have: $BL < \frac{n_2}{n_1^2}\frac{c}{\Delta}$
Rough estimation of fundamental limitation of step index fibers, which is originated from intermodal dispersion
Smaller index step → higher bitrate-distance product

Cutoff Condition
1.A mode is uniquely identified by its propagation constant \beta.
2.Mode index (or effective index): $n_1 > \bar{n} = \beta/k_0 > n_2$
3.A mode ceases to be guided when nbar<=n2 (cutoff condition).
4.The normalized frequency V is defined as

$$V = k_0 a \cdot NA = k_0 a\sqrt{n_1^2 - n_2^2} \approx (2\pi/\lambda)an_1\sqrt{2\Delta}$$

5.We define a normalized propagation constant b as $b = \frac{\beta/k_0 - n_2}{n_1 - n_2}$ $M \approx V^2/2$
6. Number of modes in a multi-mode fiber can be estimated by
7. Cut off frequency Vcut-off = 2.4048;
For single-mode operation, V < 2.4048;

Step-Index Fiber Modes (Linearly Polarized modes LPmn)



Modal Dispersion
As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width after transmission would be determined by the transmission time of the slowest and fastest modes.

Group-Velocity Dispersion
1.As the signal propagates along the fiber (length=L), each spectral component travels independently and undergoes a time delay of T = L / vg, where vg is the group velocity defined as

$$v_g = (d\beta/d\omega)^{-1}$$

If the spectral width of the source is \Delta w, the extent of pulse broadening is governed by

$$\Delta T = \frac{dT}{d\omega}\Delta\omega = \frac{d}{d\omega}\left(\frac{L}{v_g}\right)\Delta\omega = L\frac{d^2\beta}{d\omega^2}\Delta\omega = L\beta_2\Delta\omega$$

where $\beta_2 = \frac{d^2\beta}{d\omega^2}$

When expressed by the range of wavelengths, the pulse broadening can be written as

$$\Delta T = \frac{d}{d\lambda}\left(\frac{L}{v_g}\right)\Delta\lambda = DL\Delta\lambda$$

$$\omega = \frac{2\pi c}{\lambda} \qquad \Delta\omega = -\frac{2\pi c}{\lambda^2}\Delta\lambda$$

where $D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2$

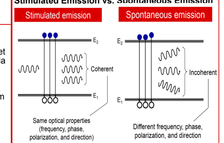
Dispersion Limitations
1.The effect of dispersion on bit rate B can be estimated by using the following criteria:
It provides an order-of-magnitude estimate of the BL product by single mode fiber.

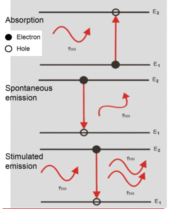
$$B\Delta T < 1 \qquad BL|D|\Delta\lambda < 1$$

Fiber Nonlinearities
1.Stimulated Light Scattering
(1)Stimulated Brillouin Scattering (SBS): (a)Acoustic phonon (vsound, GHz); (b)Backward direction; (c)Frequency shift by about 11 GHz (Stokes shift); (d)Gain spectrum extremely narrow (<100 MHz);
(2)Stimulated Raman Scattering (SRS): (a)Optical phonon (c, THz); (b)Both directions;; (c)Frequency shift by about 13 THz (Stokes shift); (d)Gain spectrum extends over 20-30 THz;
2.Nonlinear Refractive Index: (a)Self-Phase Modulation (SPM) (b)Cross-Phase Modulation (XPM) (c)Four-Wave Mixing (FWM)

Mechanisms of Light Emission
1.For atomic systems in thermal equilibrium with their surrounding, the emission of light is the result of: (1) Absorption (2)And subsequently, spontaneous emission of energy
There is another process whereby the atom in an upper energy level can be triggered or stimulated in phase with the incoming photon. This process is: (1)Stimulated emission (2)It is an important process for laser action
3 processes involved: 1.Absorption 2.Spontaneous emission. 3. Stimulated emission

Stimulated Emission vs. Spontaneous Emission



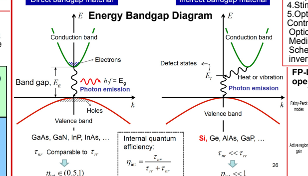


Bandgap Engineering
For $In_{1-x}Ga_xAs_yP_{1-y}$ compositions on InP substrate, the bandgap (eV) can be expressed using the empirical relation:
$E_g = 1.35 - 0.72y + 0.12y^2$
where $0 \leq y \leq 1$
The fractions x and y follows x/y=0.45 to ensure lattice match.
By suitable choice of x and y, the $In_{1-x}Ga_xAs_yP_{1-y}$ laser can be designed to operate in the wide wavelength range from 1.0 – 1.65 μm.
Peak emission wavelength $\lambda(\mu m) = \frac{1.24}{E_g(eV)}$

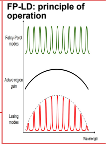
Edge-Emitting vs. Surface-Emitting
Surface-emitting device
Advantage: (1)On-chip testing (2)Low coupling loss to fiber (3)Easy to make arrays
Disadvantage: (1)Low output power (2)Short-l output
Edge-emitting device
Advantage: (1)High output power (2)Easy to make long-l devices
Disadvantage: (1) Low yield (2)Difficult to test the devices (3)High coupling loss to fiber

LASER: principle of operation
1.Presence of metastable states (3 or 4 level system)
2.Energy pumping
3.Population Inversion
4.Stimulated emission
5.Optical feedback
Contribute to Optical Resonator, Gain Medium, and Pumping Scheme (population inversion)

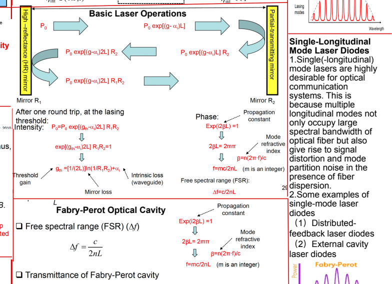
Energy Bandgap Diagram



FP-LD: principle of operation

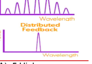


Basic Laser Operations



Single-Longitudinal Mode Laser Diodes
1.Single-(longitudinal) mode lasers are highly desirable for optical communication systems. This is because multiple longitudinal modes not only occupy large spectral bandwidth of optical fiber but also give rise to signal distortion and mode partition noise in the presence of fiber dispersion.
2.Some examples of single-mode laser diodes
(1) Distributed-feedback laser diodes
(2) External cavity laser diodes

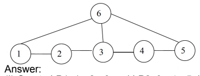
Fabry-Perot Optical Cavity
❑ Free spectral range (FSR) (Δf)
$\Delta f = \frac{c}{2nL}$
❑ Transmittance of Fabry-Perot cavity
$$I_{out} = I_{in}\frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(4\pi nL/\lambda)}$$
where n is the refractive index inside the cavity, L is the cavity length, and R is the reflectance of the cavity facets.



Distributed-Feedback Laser Diodes (DFB-LDs)
1.Polarized light; 2.Single-mode excitation; 3.Narrow linewidth (typically sub MHz ~ tens of MHz); 4.Threshold current (typically 10~20 mA); 5.High output power; 6.Moderate reliability; 7.High modulation bandwidth (~20 GHz); 8.Expensive (low yield)

DFB and DBR LASER
Distributed-Feedback (DFB) Laser
Distributed Bragg Reflector (DBR) Laser
Bragg condition:
Grating period
m : the order of Bragg diffraction (integer)
$\bar{n}$: effective refractive index
$$\Lambda_B = \left(\frac{m\lambda}{2\bar{n}}\right)$$

Consider a Consider a WDM network with six nodes and 2 wavelengths per fiber as shown in the figure below. It is required to route a client connection from node 1 to node 5 which can traverse one or more lightpaths. It is constrained that a lightpath can traverse at most two physical hops. Explain the lightpaths that could be created and how the connection could be routed with (i) lightpath-level protection and (ii) connection-level protection.

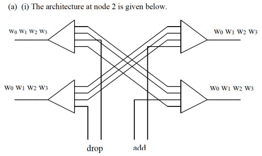


Answer:
(i) Create LP1: 1->2->3 and LP2: 3->4->5. Lighpath LP3:1->6->3 can be used to protect LP1. Lighpath LP4:3->6->5 can be used to protect LP2. All the lightpaths can use wavelength w0. Connection is routed on LP1 and LP2.
(ii) Create LP1: 1->2->3, LP2: 3->4->5, and LP3: 1->6->5 all on wavelength w0. Route the primary connection on LP1 and LP2 and the backup connection on LP3. Another possible way is to route the primary connection on LP3 and the backup connection on LP1 and LP2.

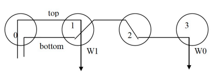
Q2 In a WDM network with 8 wavelengths per fiber, fixed-alternate routing method is employed. For node-pair <1,6>, the following alternative routes R1 and R2 are searched in the given order.
R1: 1-> 2->3->4->5->6   R2: 1->7->8->6
A given wavelength is used on a link with probability 0.4. The above event is assumed to be independent of the use of other wavelengths on the link and is also independent of the use of the same and other wavelengths on other links. It is assumed that node 4 has full-degree wavelength conversion capability and no other node in the network has wavelength conversion capability. Now, for a connection request <1,6>, determine
a) the probability that route R1 is assigned to the request?
b) the probability that route R2 is assigned to the request?
c) the probability that the connection request is accepted?
Answer:
The success probability of the request in sub-segment of length l, denoted by
$f(l) = 1-(1-\rho'^l)^W$ where $\rho' = 1-\rho$.
In this problem,
- There is only 1 converter located at node 4,
- The probability that a given wavelength is occupied on a link is $\rho=0.4$, $\rho'=0.6$,
- Number of wavelengths on each link, W=8
a) R1: 1->2->3->4->5->6
For R1, there are 2 segments of length 3 and 2, therefore $l_0=3$ and $l_1=2$,
$f(3) = 1-(1-0.6^3)^8 = 0.8573$
$f(2) = 1-(1-0.6^2)^8 = 0.9719$
The success probability of the end-to-end call on R1 is calculated as,
$f(3)*f(2)= 0.8573*0.9719=0.8332$
Since fixed-alternate routing method is employed, R1 will be given the highest priority, it will be assigned to the request if it is free.
The probability that route R1 is assigned to the request, P(R1) = 0.8332.
b) R2 = 1->7->8->6
For R2, there is only 1 segment of length 3, l=3
f(3) = 0.8573
The success probability of the end-to-end call on R2 is 0.8573
Since fixed-alternate routing method is employed, R2 will be used only when R1 is not available, so the probability that route R2 is assigned to the request,
P(R2)= 0.8573*(1-P(R1))
= 0.8573*0.1668
= 0.1430
c) Since P(R2) is calculated when R1 can not be used, so, the probability of the connection request is accepted is simply adding P(R1) and P(R2).
The probability that the connection request is accepted is therefore
P(R1)+P(R2)= 0.8332 + 0.1430
= 0.9762

Q3 It is required to design fixed-WXCs for use in a network in which every node has two input fibers (top and bottom) and two output fibers (top and bottom), and every fiber carries four wavelengths w0, w1, w2, and w3. A WXC at node i drops wi from the top input fiber and wi+1 from the bottom input fiber. Further, it adds wi to the bottom output fiber and wi+1 to the top output fiber. Here, modular arithmetic is used, for example, 3+1 is 0. Other wavelengths are "crossed", i.e. a wavelength from the bottom input fiber is switched to the top output fiber and vice versa. (i) Show the architecture of a fixed-WXC at node 2. (ii) Show how the lightpaths originating at node 0 are routed in a 4-node unidirectional network. Assume that the nodes are labeled 0 through 3 in the clockwise direction.

(a) (i) The architecture at node 2 is given below.



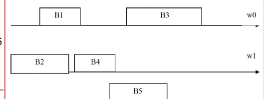
(ii) The two lightpaths originating at node 0 are shown below.



Q4 Consider a unidirectional WDM physical ring network with six nodes connected as 0→1→2→3→4→5→0. Each node has a WADM connected to an IP router. In addition, node 0 has three transmitters and three receivers and all other nodes have fewer transmitters and receivers. A logical (virtual) topology is designed over the physical network. The logical topology comprises three logical rings, R1, R2, and R3. Ring R1 comprises lightpaths traversing one physical link. Ring R2 comprises lightpaths traversing two physical links. Ring R3 comprises lightpaths traversing three physical links. (i) Determine the node pairs where lightpaths are set up for each of the three rings. (ii) What is the minimum number of wavelengths per fiber required to set up the virtual topology? (iii) Determine the number of transmitters and receivers required at each of the nodes.
Answer:
(i) Ring R1: <0,1>, <1,2>,<2,3>,<3,4>,<4,5>,<5,0>
Ring R2: <0,2>, <2,4>,<4,0>
Ring R3: <0,3>, <3,0>

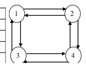
(ii) We can assign the same wavelength to all lightpaths in the same logical ring. Different logical rings must use different wavelengths as they use common links. Hence, THREE wavelengths are required per fiber.
(iii) From part (i) we can observe that 3,1,2,2,2, and 1 lightpaths originate (terminate) from (at) nodes 0,1,2,3,4, and 5, respectively. Therefore 3,1,2,2,2, and 1 transmitters and receivers are needed at nodes 0,1,2,3,4, and 5, respectively.

Q5 Suppose that a burst-switching network with 2 wavelengths per fiber uses burst rescheduling along with the Latest Available Unscheduled Channel (LAUC) scheduling algorithm to improve burst loss performance. Use five bursts to illustrate the benefit of burst rescheduling such that only the first four bursts can be scheduled with LAUC and burst rescheduling helps to schedule the fifth burst. Sketch the timeline for the 2 wavelengths in your illustration.



Q6 A variant of HLDA algorithm works as follows. Instead of subtracting the next highest value whenever a lightpath is established between a node-pair, it subtracts a fixed value which is equal to the lowest non-zero entry in the initial traffic demand matrix. Consider a WDM network and the normalized traffic demand between node-pairs as shown in the Figure, and Table below, respectively. Assume that there are two wavelengths w0 and w1 per fiber and each node is equipped with two transmitters and two receivers. Show a virtual topology using this variant of HLDA. For each iteration of the algorithm, list the node-pair considered and the physical route and wavelength chosen to establish the lightpath. Give the reason if a lightpath cannot be established. For a node-pair, choose the shortest physical route which is free. If more than one (shortest) route with the same number of hops are free, choose the one which traverses in the clockwise direction. Use a fixed-order wavelength assignment method and choose the free wavelength with the lowest index.

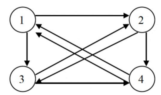
Nodes	1	2	3	4
1	0	0.70	0.95	0.55
2	0.65	0	0.75	0.90
3	0.22	0.85	0	0.60
4	0.80	0.50	0.45	0



The trace of the algorithm is given below.

Iteration	node-pair	route	wavelength
1	1,3	1->3	w0
2	2,4	2->4	w0
3	3,2	3->1->2	w0
4	4,1	4->3->1	w1
5	2,3	2->1->3	w1
6	1,3	No wavelength is free	
7	1,2	1->2	w1
8	2,4	no transmitter at 2	
9	2,1	no transmitter at 2	
10	3,2	no receiver at 2	
11	3,4	3->4	w0
12	4,1	4->2->1	w0

The virtual topology is shown in the following figure



Q7 Determine the cost of deploying a point-to-point network, a curb-switched network, and a passive optical network (PON) for ten homes in a residential apartment. For the point-to-point network, the distance from the CO to the apartment is 5 km. For the other networks, the distance from the CO to the curb switch/ splitter is 5 km. The curb switch/splitter is located at a distance of 50 meters from the apartment. The cost of fiber installation is $200 per meter. The cost of a curb switch includes a fixed component of $15,000 and a variable component of $500 per port. The cost of a splitter includes a fixed component of $700 and a variable component of $100 per port. The cost of a transceiver is $750.
Answer:
Point-to-point Network
Total Cost = Cost of 10 fibers + Cost of 20 transceivers
Total Cost = $10 x 200 x5000 + $ 20 x 750
Total Cost = $10, 015, 000
Curb-switched network
Total Cost = Cost of 1 fiber of length 5 km + Cost of 10 fibers of length 50 meters + Cost of curb Switch of 10 ports + Cost of
22 transceivers
Total Cost = $1, 136, 500
Passive optical network
Total Cost = Cost of 1 fiber of length 5 km + Cost of 10 fibers of
length 50 meters + Cost of passive splitter of 10 ports + Cost of 11 transceivers
Total Cost = $1, 109, 950

Q8 Consider a linear network with IP routers located at nodes A, B, C, and D in that order. There is a traffic demand of 2 Gbps from node A to node C, 4.5 Gbps from node A to node D, 2.2 Gbps from node B to node C, and 2.5 Gbps from node B to node D. It is decided to employ WDM network elements at these nodes to meet the traffic demand. Assume that a wavelength operates at the rate of 2.5 Gbps. Determine the number of wavelengths, and ports and buffers required at each of the nodes, when: (i) point-to-point WDM links with LTs are employed, and (ii) WADMs are employed.

(i) Point-to-Point WDM links
Since the link from node B to node C carries 5 paths, 5 wavelengths are required. We note that buffers and ports are required for the traffic added, dropped and pass-through at every node for point-to-point WDM networks. The requirements are tabulated below. The buffer size is proportional to the indicated value in column-3 of the table.

Node	Ports	Buffer (Gb)
A	3	6.5
B	5	11.2
C	5	11.2
D	3	7.0

(ii) WADM-based networks
Since there are 5 lightpaths we need only 5 wavelengths. We note that buffers and ports are required only for the traffic added, dropped when WADMs are used. The requirements are tabulated below. The buffer size is proportional to the indicated value in column-3 of the table.

Node	Ports	Buffer (Gb)
A	3	6.5
B	2	4.7
C	2	4.2
D	3	7.0

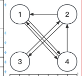
Q1Consider a variant of the HLDA algorithm which works as follows. Instead of subtracting the next highest value whenever a lightpath is established between a node-pair, it subtracts a fixed value of 0.1. Consider a WDM network and the normalized traffic demand between node-pairs as shown in the figure and Table 1, respectively. Assume that there are two wavelengths w0 and w1 and each node is equipped with two transmitters and two receivers. (a)Design a virtual topology using the above algorithm. For each iteration of the algorithm, list the node-pair considered and the physical route and wavelength chosen to establish the lightpath. Give the reason if a lightpath cannot be established. For a node-pair, choose the shortest physical route which is free. If more than one route with the same number of hops are free, choose the one which has the same number of free wavelengths; if all the free pairs have the same number of free wavelengths, then choose the one which traverses in the clockwise direction. Use a fixed-order wavelength assignment method which chooses the free wavelength with the lowest index among the free wavelengths. Give your answer in the format as in Table 2 below. (b) Suppose that traffic flows are routed on the virtual topology using the shortest path routing. For each node pair, give the path for traffic routing. Give your answer in the format as in Table 3 below. Compute load on each lightpath and tabulate it in Table 4. (c) Calculate the average weighted number of (virtual) hops and congestion.

Nodes	1	2	3	4
1	0	0.78	0.8	1.00
2	0.75	0	0.8	0.70
3	0.32	0.72	0	0.60
4	0.65	0.64	0.55	0

The trace of the algorithm is given below:

Iteration	Node Pair	Physical Path	Wavelength	Remarks
1	1,4	1→2→4	w_0	clockwise
2	1,4	1→3→4	w_0	more free wavelength
3	1,4	N/A	N/A	Node 1 no Tx
4	2,3	2→4→3	w_1	clockwise
5	1,3	N/A	N/A	Node 1 no Tx
6	1,2	N/A	N/A	Node 1 no Tx
7	2,1	2→1	w_0	
8	3,2	3→1→2	w_1	clockwise
9	2,3	N/A	N/A	No free wavelength
10	2,4	N/A	N/A	No free wavelength
11	4,1	4→3→1	w_1	clockwise
12	2,1	N/A	N/A	Node 1 no Rx
13	4,2	4→2	w_0	
14	3,2	N/A	N/A	No free wavelength
15	3,4	N/A	N/A	Node 4 no Rx
16	4,3	N/A	N/A	No free wavelength
17	4,1	N/A	N/A	No free wavelength
18	3,1	N/A	N/A	No free wavelength

Traffic flow <s,d>	Route on virtual topology	No. of (virtual) hops
<1,2>	1-4-2	2
<2,1>	2-1	1
<1,3>	1-4-2-3	3
<3,1>	3-2-1	2
<1,4>	1-4	1
<4,1>	4-1	1
<2,3>	2-3	1
<3,2>	3-2	1
<2,4>	2-1-4	2
<4,2>	4-2	1
<3,4>	3-2-1-4	3
<4,3>	4-2-3	2

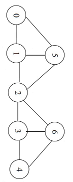


Lightpath $i \to j$	Load
1 → 4	0.78+0.8+1+0.7+0.6 = 3.88
4 → 1	0.65
2 → 1	0.75+0.32+0.7+0.6 = 2.37
4 → 2	0.78+0.8+0.64+0.55 = 2.77
2 → 3	0.8+0.8+0.55 = 2.15
3 → 2	0.32+0.72+0.6 = 1.64

Average weighted number of hops:
$$h_{ave} = \frac{\sum(h_{s,d} \times t^{s,d})}{\sum t^{s,d}} = \frac{13.46}{8.31} = 1.6197$$
Congestion:
$$f_{max} = \max f_{ij} = \max(3.88, 2.37, 2.15, 1.64, 0.65, 2.77) = 3.88$$

Q2 Consider a WDM network with 4 wavelengths per fiber as shown in Figure below. The wavelengths are labeled w0 through w3. The mean time to failure (MTTF) and mean time to repair (MTTR) of each link in the network are 9 and 1 unit, respectively. The MTTF and MTTR values are assumed to be independent for the links. Suppose that node 2 is provided with wavelength converters. The wavelength availability on different links is as stated in the table below.
(a) Calculate the availability of a link
(b) Which path and wavelength are chosen if it is required to set up a lightpath from node 0 to node 4 without requiring any wavelength conversion?
(c) What is the availability value for the path chosen in part Q2(b)?
(d) It is possible to improve the availability of a path by protecting one or more links, or segments on a path. What are the links and/or segments that can be protected on the path chosen in part Q2(b) to improve the path availability?. For each possible case of such protection, calculate the improved availability value. The wavelength converter can be used, if needed, for protection purpose.

Link	Wavelength availability
0-1	W_0, W_1, W_2
0-5	W_1, W_3
1-2	W_0, W_1
1-5	W_0
2-3	W_1, W_2
2-5	W_2
2-6	W_2
3-4	W_1, W_3
3-6	W_1
4-6	W_0, W_2



(a)
Availability is the probability that a system will work as required when required during the period of a mission:
$$Avilability = \frac{MTTF}{MTBF} = \frac{MTTF}{MTTF+MTTR} = 90\%$$
where MTTF = Mean Time To Failure, MTTR = Mean Time To Repair, MTBF = Mean Time Between failure = MTTF + MTTR.
(b)If it is required to set up a lightpath from node 0 to node 4 without requiring any wavelength conversion, the path is 0 → 1 → 2 → 3 → 4 with wavelength ω_1
(c)For path 0 → 1 → 2 → 3 → 4 the availability is:
$$Availability = \left(\frac{9}{9+1}\right)^4 = 65.61\%$$
(d) It is possible to improve the availability of a path by protecting one or more links, or segments on a path. Since it is given that only node 2 has converter, we can use the converter with protection path. Path 2 → 3 → 4 (ω_1) can be protected by path 2 → 6 →4 (ω_2):
$$fail_{2,3,4} = 1-(90\%)^2 = 19\%;$$
$$fail_{2,6,4} = 1-(90\%)^2 = 19\%$$
$$fail_{both} = 19\% \times 19\% = 3.61\%$$
$$Availability = 1-3.61\% = 96.39\%$$
The overall improved availability is:
$$Availability_{0,2} \times Availability_{2,4} = (90\%)^2 \times 96.39\% = 78.08\%$$

(a)For a step index fiber, with n1=1.5, n2=1.4, please estimate the upper limit ofBitrate-distance product.
$$BL < \frac{n_2}{n_1^2}\frac{c}{\Delta} = \frac{n_2}{n_1^2}\frac{c}{(n_1-n_2)/n_1} = \frac{n_2 c}{n_1(n_1-n_2)}$$
(b) For another step index fiber, with n1=1.5 and Δ=2.10-3, please estimate the upper limit of Bitrate-distance product.
$n_2 = (1-\Delta)n_1$ $BL < \frac{(1-\Delta)n_1}{n_1^2}\frac{c}{\Delta} = \frac{(1-\Delta)c}{n_1\Delta}$

A multimode fiber with core radius of a=25 um, Δ=5.10-3, n1=1.45.
(a)How much is its normalized frequency at λ=1.3 μm and 1.55 μm, respectively?
(b) How many modes does it support at λ=1.3 μm and 1.55 μm, respectively?
$V = \frac{2\pi}{\lambda} a n_1 \sqrt{2\Delta}$ $M \approx V^2/2$

A conventional single-mode fiber has a dispersion of 16~18 ps/nm/km at 1550 nm. Suppose a very narrow optical pulse with a spectral bandwidth of 3 nm is launched at one end of a 2-km conventional single-mode fiber. After transmission, please estimate the pulse broadening in terms of ps.
$\Delta T = DL\Delta\lambda = (16\sim18)\times 2 \times 3$

For a silica glass, its Rayleigh scattering loss is 1.9 dB/km at 850 nm. Estimate its Rayleigh scattering loss at 1310 nm and 1550 nm.
Loss propotion to $1/\lambda^4$ $? = 1.9\frac{\lambda_1^4}{\lambda_2^4}$

(a)For a semiconductor alloy In0.74Ga0.26As0.57P0.43, please calculate its bandgap energy (in eV) of the material.
$In_{1-x}Ga_xAs_yP_{1-y}$ $Eg = 1.35 - 0.72y + 0.12y^2 (eV)$
(b) Calculate its peak emission wavelength.
$\lambda(\mu m) = 1.24/Eg(eV)$

For a semiconductor GaAs laser, it has cavity length of 0.8 mm, Fabry-Perot cavity. At 850 nm working wavelength, it has refractive index of 3.5. Please estimate its free-spectral range (FSR) in the unit of GHz.
$\Delta f = C/2nL = \frac{3\times10^8}{2\times3.5\times0.8\times10^{-3}} = 53.57GHz$

For a DFB laser, after solving the wave equation at its gain waveguide, the mode effective refractive index is found to be 1.59. If we would like to design the laser working at 1.55 μm, please calculate the grating period (under m=1)
$\Lambda_B = \frac{m\lambda}{2n} = \frac{1\times1.55}{2\times1.59} = 0.487um$

An EDFA is pumped at 980 nm, with 32 mWpump power. It provides signal gain at 1550 nm. The input 1550 nm signal optical power is 0.18 mW, please estimate the maximum signal optical power in mW.
$P_{s,out} \le P_{s,in} + \frac{\lambda_p}{\lambda_s}P_{p,in} = 0.18 + \frac{980}{1550}\times32 = 20.4mW$

A semiconductor LED has emission peak at 1.31 μm. Its radiative lifetime is 30 ns, and non-radiative lifetime is 90 ns. It needs a drive current of 30 mA. Please calculate (a) the bulk recombination lifetime; (b) the internal quantum efficiency (c) the internal power.
(a) $\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$ (b) $\eta_{int} = \frac{1}{1+\tau_r/\tau_{nr}} = \frac{1}{1+30/90} = 0.75$
(c) $P_{int} = \eta_{int}\frac{hcI}{q\lambda} = 0.75 \frac{6.626\times10^{-34}\times3\times10^8\times0.03}{1.6\times10^{-19}\times1.31\times10^{-6}}$

6.3×106 photons at 1310 nm is incident on a photodetector. 5.4×106 electron-hole pairs are generated. Calculate the quantum efficiency of this photodetector at 1310 nm.
η = electron-hole / incident photodetector = $\frac{5.4}{6.3}$

Calculate the responsivity of a PIN photodiode at 1.3 and 1.5 μmif the quantum efficiency is 80%. Why is the photodiode more responsive at 1.5 μm?,
$R = \frac{\eta\lambda}{1.24}(\mu m)$ λ↑ → Photo number ↑ for same power → R↑ until photon energy is enough to generate free carriers

Photons at a rate of 1010/s are incident on an APD with responsivity of 6 A/W. Calculate the quantum efficiency and the photocurrent at the operating wavelength of 1.5 μmfor an APD gain of 10.
$\eta = \frac{hfR}{q} = hf(R_{APD}/M)/q = 1.24\times(R_{APD}/M)/\lambda$
Photons incident rate $R_{ate} = P_{in}/hf$ $P_{in} = hf\,R_{ate}$
$I_p = R_{APD}P_{in} = 6\times6.63\times10^{-34}\times3\times10^8/1.5\times10^{-6}\times10^{10}$

(a) An optical fiber has a length of 30 km and an attenuation of 0.4 dB/km. The output optical power from the fiber is 10 μW. Calculate the input optical power launched into the first optical fiber in terms of μW.
$Total\ loss = 30\times0.4 = 12dB = -10\log(\frac{P_{out}}{P_{in}}) P_{in} = \frac{P_{out}}{Total\ loss} = 158.49\mu W$
(b) A step-index fiber has a core diameter of 12-μm and a core refractive index of 1.445. The relative refractive index difference Δ is 0.18% at operating wavelength of 1.3-μm. Useful constants are given in Appendix.
(i) Estimate the normalized frequency of the fiber.
Normalized frequency: $V = k_0 a n_1\sqrt{2\Delta} = \frac{2\pi}{\lambda}an_1\sqrt{2\Delta}$. Therefore, V = 2.51Hz
(ii) Estimate the number of guided modes.
$M \approx V^2/2 = 3.16$, 3 mode
(iii) Determine the relative refractive index difference Δ required to make the fiber in single mode operation.
For single-mode operation, $V_{single} < 2.48048$
Since $V = k_0 a n_1\sqrt{2\Delta}$, $V_{single} = k_0 a n_1\sqrt{2\Delta_{single}} < 2.48048$
we have $\Delta_{single} < 0.165\%$

(a) A ruby laser contains a crystal with refractive index of 1.77 and length of 5 cm. The peak emission wavelength is 0.56 μm.
(i) Calculate the number of longitudinal modes.
For longitudinal modes: $M = \frac{2nL}{\lambda} = 316071$
(ii) Determine their frequency separation (free spectral range).
$$\Delta f = \frac{C}{2nL} = 1.69\times10^9 Hz$$
(b) Explain the spontaneous emission process and stimulated emission process and compare their differences. (hint: can use figures/drawings to explain)
A: Simulated emission has external photons. The emitted photon is coherent, with same properties, such as frequency, phase, polarization, and direction etc.
Spontaneous emission doesn't have external photons. The emitted photon is incoherent, with different properties.
(c) An avalanche photodiode (APD) is working with a quantum efficiency of 0.72 at 850 nm working under multiplication factor M=1. The APD is then biased to work under M=100, and the multiplied photocurrent is 500 nA. Calculate its incident optical power.
$R = \frac{\eta q}{hf} = \frac{\eta\lambda}{1.24} = 0.4935 R_{APD} = M\cdot R = 49.35 I_p = RP_{in} P_{in} = \frac{I_p}{R_{APD}} = 10.13nW$

(a) Consider a unidirectional WDM physical ring network with five nodes connected as 0→1→2→3→4→0. It is required to create six lightpaths for the node pairs P1: <0,2>, P2: <0,1>, P3:<3,0>, P4:<2,3>, P5: <1,4>, and P6: <4,0>.
(i) Route the lightpaths using shortest-path-first heuristic with fixed-order wavelength assignment policy, and list the path and wavelength assigned to each lightpath in the table format as shown below. Determine the number of wavelengths required.
(ii) Develop a better heuristic with fixed-order wavelength assignment policy and list the path and wavelength chosen for each lightpath in the table format as shown below. Your heuristic should require fewer wavelengths than that used in part (i) above. Explain the intuitive reason why your heuristic is doing better.
(iii) Construct a path graph and assign wavelengths for lightpaths using graph coloring method. Verify that this method requires the same number of wavelengths as in part (ii) above.
(iv) It is required to route 0.4, 0.5, and 0.6 units of client traffic flows for the node pairs (0,3), (2,1) and (1,2), respectively, through shortest paths over the virtual topology. Determine the routes and then tabulate the results in the format below. Compute the congestion and average weighted number of (virtual) hops.

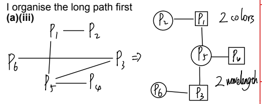
(a)(i)

Lightpath Pi	Physical Path	Wavelength
P2<0,1>	0 → 1	w_0
P4<2,3>	2 → 3	w_0
P6<4,0>	4 → 0	w_0
P1<0,2>	0 → 1 → 2	w_1
P3<3,0>	3 → 4 → 0	w_1
P5<1,4>	1 → 4 → 0	w_2

(a)(ii)

Lightpath Pi	Physical Path	Wavelength
P5<1,4>	1 → 2 → 3 → 4	w_0
P3<3,0>	3 → 4 → 0	w_1
P1<0,2>	0 → 1 → 2	w_1
P2<0,1>	0 → 1	w_0
P4<2,3>	2 → 3	w_1
P6<4,0>	4 → 0	w_0

I organise the long path first
(a)(iii)



(a)(iv)

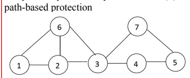
Traffic flow	Route on VT	No. of hops
<0,3>	0 → 2 → 3	2
<2,1>	2 → 3 → 0 → 1	1
<1,2>	1 → 4 → 0 → 2	3

Lighpath	Load
1 → 4	0.6
3 → 0	0.5
0 → 2	0.6 + 0.4 = 1
0 → 1	0.5
2 → 3	0.4 + 0.5 = 0.9
4 → 0	0.6

Average weighted:
h = 2x0.4 + 3x0.5 + 3x0.6 / 1.5 = 2.73
fmax = 1

(b) Briefly describe one advantage and one disadvantage of parallel route search when compared to sequential route search with forward wavelength reservation.
Answer:
Advantage: it can significantly reduce the time required to find feasible routes in large and complex networks, compared to sequential route search. This is because multiple routes can be explored simultaneously, which can result in faster convergence to an optimal solution.
Disadvantage: it can require a large amount of computational resources, including processing power and memory, especially when searching for a large number of routes or in networks with many nodes and links. Additionally, parallel route search can result in higher blocking probabilities compared to sequential route search with forward wavelength reservation, which reserves the necessary wavelengths as routes are discovered. This is because parallel route search may not always reserve the necessary wavelengths for all routes in a timely manner, resulting in conflicts and increased blocking probabilities.

(a) Consider a WDM network as shown in the figure below. A lightpath is set up from node 1 to node 5 in the path 1-2-3-4-5. List one set of possible backup paths in the cases of (i) failure-independent path-based protection and (ii) failure-dependent path-based protection

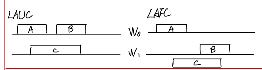


Assume the primary link is 1-2-3-4-5
(i) 1-6-3-7-5
(ii) 1-6-2-3-4-5 / 1-2-6-3-4-5 / 1-2-3-7-5

(b) Consider a hypothetical signaling protocol for EPON in which OLT assigns slots for the ONUs in a round-robin fashion for upstream operation. Here, OLT assigns x slots each to ONU1, ONU2, and so on, in a round robin fashion. Upon receiving the slot assignment, ONU1 transmits data for a maximum of x slots depending on how much data it needs to transmit. Upon completion, it notifies the OLT which then assigns x slots to ONU2. This procedure is repeated with other ONUs. Briefly discuss one advantage and one disadvantage of this protocol when compared with the MPCP protocol.
Answer:
Advantage: 1.Bandwidth allocation: EPON protocol uses a time-division multiplexing (TDM) scheme that allocates fixed time slots to each ONT (Optical Network Terminal) in the upstream direction. This enables better bandwidth utilization compared to MPCP, which uses a polling-based scheme that may result in some nodes being starved of bandwidth. 2.Cost-effectiveness: EPON is generally considered more cost-effective than MPCP because it uses a passive optical network that does not require any active components in the distribution network. This simplifies the network design and reduces the overall cost of deployment.
Disadvantage: 1.Limited scalability: EPON has a limited scalability because it uses a shared medium that is susceptible to collisions and interference. As the number of ONTs increases, the contention for the shared medium also increases, leading to lower network performance and longer delays. 2.Limited control: EPON protocol provides limited control over the upstream traffic because the ONTs can only transmit during their assigned time slots. This can lead to issues such as reduced flexibility in bandwidth allocation and limited support for real-time traffic.

(c)Briefly discuss one advantage and one disadvantage of MPCP protocol when compared with the EPON protocol.
Answer:
Advantage: it provides better bandwidth utilization. MPCP is designed to prioritize time-sensitive data, which allows for more efficient allocation of bandwidth. As a result, the network can handle more data traffic with fewer delays.
Disadvantage: it requires a centralized controller, which can be a single point of failure. If the controller fails, the network can experience significant disruptions. Additionally, MPCP requires more complex hardware and software, which can increase costs and maintenance requirements.

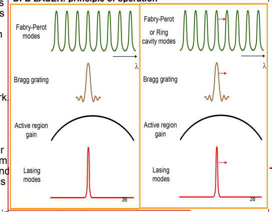
(d) A burst scheduling algorithm called Latest Used Channel First (LUCF) chooses the wavelength channel on which latest number of bursts are currently active among the possible wavelength channels for a new burst. Show with an example that LUCF performs poorly when compared to the Latest Available Unscheduled Channel (LAUC) algorithm. In your example, choose a burst-switching network with 2 wavelengths w0 and w1 per fiber and three bursts, and show that LAUC can schedule all the three bursts, but LUCF can schedule only the first two bursts.



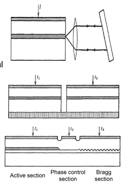
(e) Consider a wavelength-convertible WDM network with 6 wavelengths per fiber and each node having conversion capability of degree 2. Suppose that a wavelength is occupied on a fiber with probability 0.15. The above event is assumed to be independent of the use of other wavelengths on the fiber and is also independent of the use of the same and other wavelengths on other fibers. (i) What is the equivalent multi-fiber network for the above convertible network from the perspective of blocking performance? (ii) Use the above equivalence and calculate the blocking probability of a request for a 3-hop path (i.e., a path traversing 3 links).
Answer:
(i) a multi-fiber network with 2 fibres and 3 wavelength in a fiber
(ii) pnew = p^2 = 0.0225
Pf= [1 - (1 - p^w)]^H = [1 - (1 - p^3)]^3 = 2.87e-4

(a) Calculate the transmission distance for a fiber link with an attenuation of 0.52 dB/km, under the condition that the power launched in is 1.2 mW, and power at the receiver end is 48 μW.
$P_{in} = 10\log1.2 = 0.7918dBm$
$P_{out} = 10\log(48\times10^{-3}) = -13.1876dBm$
$P_{out} - P_{in} = L\times Attenuation = -13.9794dBm, L = 26.88km$
(b) Assume a multimode step-index fiber with a core diameter of 84 μm and a relative index difference Δ = 1.5%. It works at 850 nm wavelength. Its core index is 1.47. Estimate (i) The normalized frequency of the fiber (ii) The number of guided modes.
$a = 42\mu m\ n_1 = 1.47$
$V = \frac{2\pi}{\lambda}an_1\sqrt{2\Delta} = \frac{2\pi}{850\times10^{-9}}\times42\times10^{-6}\times1.47\sqrt{2\times0.015} = 79Hz$
$M \approx \frac{V^2}{2} = 3124.25$ 3124mode
(c) List out different types of dispersions in optical fiber, and explain the cause of each type.
Answer:
1.Modal dispersion (inter-modal dispersion)
Different fiber modes travel at different velocities;
Only at multi-mode fibers;
2.Chromatic dispersion (intra-modal dispersion)
Also called group-velocity dispersion (GVD);
GVD has two contributions:
Material dispersion: due to l-dependence of fiber material
Waveguide dispersion: due to waveguide design;
3.Polarization-mode dispersion
Different polarization components of a pulse travel at different velocities.
(d) An optical fiber has a length of 1.2 km. It is a multimode step-index fiber, with n1 = 1.48, n2 = 1.465, and Δ = 0.01. Calculate the model delay of this optical fiber
$$\Delta T = \frac{L}{c}\frac{n_1^2}{n_2}\Delta = 5.98\times10^{-8}s$$
(a) Explain three key optical processes within a semiconductor laser. (hint: can use figures/drawings to explain).
Absorption / Spontaneous emission / Stimulated emission
(b) A DFB laser has a Bragg grating period of 221 nm. Its waveguide has an effective refractive index of 3.5. Calculate its Bragg wavelength (assuming a first order grating).
$$\Lambda_B = \frac{m\lambda}{2n} \quad m = 1\ n = 3.5$$
$$\lambda = \frac{2n\Lambda_B}{m} = 1.547\mu m$$
(c) A silicon-based PIN photodiode has a light receiving area with diameter of 0.42 mm. Under the radiation at 700 nm with intensity of 0.12 mW/cm-2, the photodiode generates a photocurrent of 74 nA. (i)Calculate its responsivity. (ii) Find its quantum efficiency at 700 nm
$r = 0.21mm\ P_{in} = \pi r^2 I = 1.66\times10^{-4}mW$
$R = \frac{I_p}{P_{in}} = 0.445\ A/W$
$\eta \approx \frac{1.24R}{\lambda(\mu m)} = 78.8\%$
(d) A silicon-based APD has a quantum efficiency of 0.7 at 830 nm under M=1. The APD is then biased to work under M=120. Calculate its photocurrent with incident optical power of 8 nW.
$R = \frac{\eta\lambda}{1.24M} \approx 0.4685$ $R_{APD} = MR = 56.23$
$I_p = R_{APD}P_{in} = 0.4498\ \mu A$

DFB LASER: principle of operation



Tunable Semiconductor Laser
Tunable: Desirable feature for lasers used in WDM lightwave system
1.External cavity semiconductor laser;
2.Tuning by rotating the grating;
3.Mechanically unstable for optical transmitter.
1.Cleaved-coupled cavity laser;
2.Tuning by varying injection current in one of the cavity sections;
3.Carrier induced index change;
4.Tuning is not continuous (mode hopping of 2 nm).
1.Multi-section DFB and DBR laser;
2.Carrier induced index change;
3.Continues tuning by controlling the phase and Bragg sections.



Erbium Doped Fiber Amplifiers (EDFA)
1.A simplified schematic of an EDFA;
2.A 980 nm pump is fed into the erbium doped fiber through a coupler;
3.Amplified spontaneous emission (ASE);
4.Gain can be flattened in spectrum by using an optical filter with transmission loss mimic the gain profile.
5.Energy conservation:
$$P_{s,out} \le P_{s,in} + \frac{\lambda_p}{\lambda_s}P_{p,in}$$

Raman Amplifiers
1.Fiber based Raman amplifiers make use of stimulated Raman scattering (SRS);
2.Figure above is a Raman amplifier in the forward-pumping configuration;
3.A pump photon gives up the energy to create another photon of reduced energy at the signal frequency;
4.The remaining energy is absorbed by the silica in the form of molecular vibrations (optical phonons).
5.The broadband nature of the Raman spectrum is due to the amorphous structure of glass.
6.The vibrational energy levels of silica molecules merges to form wide energy bands.

Light Emitting Diodes (LED)
1.In some local-area networks, the coherent source is not required;
2.LED is an option that is less expensive, longer-lasting optical source;
3.The structure of LED is similar to semiconductor laser
(1)Employ an active layer in between two cladding layers,
(2)Pumped using the forward bias p-n junction.
4.LED is different from Laser in the following aspects:
(1)Stimulated emission does not happen, since population inversion is not reached.
(2)Radiative recombination of electron-hole pair generate photons through spontaneous emission.
(3)The photons can be coupled into optical fiber.
(4)The emitted light is incoherent, with relatively large spectral width of 30-60 nm.

Bandwidth (BW) of a photodetector:
$$\Delta f = [2\pi(\tau_{tr} + \tau_{RC})]^{-1}$$
both τ_{tr} and τ_{RC} should be reduced to <10 ps for photodetectors working at bit rate of >10 Gb/s within a lightwave system.
Dark current: current generated in a PD in the absence of optical signal, from stray light or thermally generated electron-hole pairs.
For a good photodetector, the dark current should be negligible (<10nA).

Photocurrent of PIN Detector
$$P(z) = P_{in}(1-R_F)\exp(-\alpha z)$$
P_{in}: Incident optical power
α: Absorption coefficient
R_F: Fresnel reflectance
$$R_F = \left(\frac{n-1}{n+1}\right)^2$$
Refraction index of material

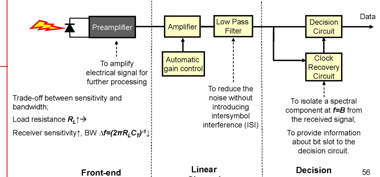
Photo-current, $I_p = q\left[\frac{P_{in}}{h\cdot f}\right](1-R_F)[1-\exp(-\alpha W)]$
Incident photon flux | Fraction transmitted into detector | Fraction absorbed in detection region
W: Length of the Depletion region

The **cut-off wavelength** is dependent on the bandgap energy E_g of the material:
$$\lambda_c(\mu m) = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}$$
The current gain or the multiplication factor *M* of the APD is defined as I_M/I_{pri}, where I_M is the average value of total output current and I_{pri} is the primary un-multiplied photocurrent.
The multiplication factor enhances the responsivity of APD. Thus, it can be written as
$$R_{APD} = M\frac{\eta\cdot q}{h\cdot f} = M\cdot R$$

Optical Receivers

❑ Most lightwave systems employ **binary intensity modulation**, we focus on **Digital Optical Receivers**.

Digital Receiver



Light Emitting Diodes (LED)

Radiative recombination rate
$$\eta_{int} = \frac{R_r}{R} = \frac{R_r}{R_r + R_{nr}} = \frac{1}{1+\tau_r/\tau_{nr}} = \frac{\tau}{\tau_r}$$
Fraction of the electron-hole pairs that recombine radiatively
Non-radiative recombination rate
❑ For exponential decay of excess carriers, the radiative recombination lifetime is $\tau_r = \frac{n}{R_r}$ and the non-radiative recombination lifetime is $\tau_{nr} = \frac{n}{R_{nr}}$
❑ The **bulk recombination lifetime** is shown in the following expression:
$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$
❑ If the current injected into the LED is I, then the total number of recombination per second can be expressed as:
$$R = R_r + R_{nr} = I/q$$
Electron charge
❑ The optical power generated internally can be expressed as:
$$P_{int} = R_r h\nu = (\eta_{int}\frac{I}{q})h\nu = \eta_{int}\frac{hcI}{q\lambda}$$
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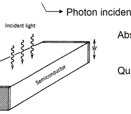
Responsivity and Quantum Efficiency

❑ The photo-current I_p is proportional to the incident optical power P_{in}. Thus,
$$I_p = RP_{in}$$
where *R* is the responsivity of the photo-detector (in units of A / W)
❑ The quantum efficiency of the photo-detector is defined as the ratio between the number of electron-hole pairs generated and the number of incident photons and is expressed as:
Electron-generation rate
$$\eta = \frac{I_p/q}{P_{in}/(h\cdot f)} = \frac{h\cdot f}{q}R$$
Photon incident rate
q: electric charge
h: Planck's constant
f: Frequency of light
$$R = \frac{\eta q}{hf} \approx \frac{\eta\lambda}{1.24}$$
$$R = \frac{\eta q}{hf} \approx \frac{\eta\lambda}{1.24}$$
η : Quantum efficiency
q : Electric charge
h : Planck constant
f : Frequency
λ↑
Photon number ↑ (for the same power)
R↑ until **photon energy** is not enough to generate free carriers



Absorbed power:
$$P_{abs} = P_{in} - P_{tr} = (1 - e^{-\alpha W})P_{in}$$
Quantum efficiency:
$$\eta = \frac{P_{abs}}{P_{in}} = 1 - e^{-\alpha W}$$
45