ECE807: Critical Infrastructure Systems: Optical Networks

Oct 29th 2019

Outline

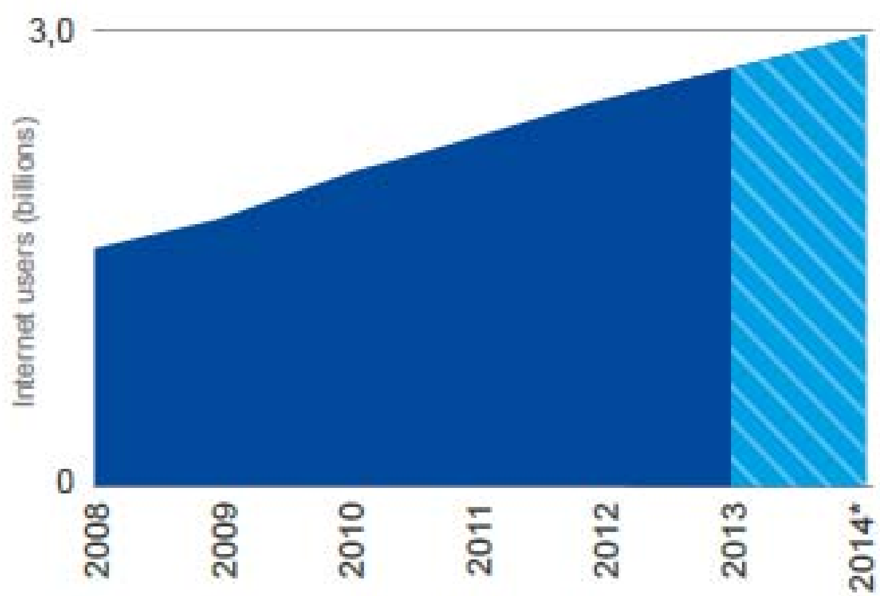
- Why Optical Networks?
- Connection Provisioning: Routing and Wavelength Assignment
- Fault Recovery Techniques

Why is Optical Networking needed ?

- **Desired Range of Applications :**
  - **Multiple services ranging from Mbps - Gbps**
  - **Include :**
    - **Data**
    - **Image transfers**
    - **Video Teleconferencing**
    - **Analog Video**
    - **Voice**

Why is Optical Networking needed ?

- What drives increased capacity?
  - Growth of Internet and WWW (number of users, amount of time taken by each user.)
  - Growing demand for high speed transmission of data for VR, the Internet of Things, cloud computing and other emerging technologies.



4,011,018,668

Internet Users

1,908,947,955

Total Number of Websites

as of 4:47pm CY time 3/9/2018 [Internetlivestats]

Traffic generated by different applications

- The increase in traffic is rapid, with a growth rate of 35% for the period 2013 to 2018.
- This is due to the global average traffic per connection being forecast to continue to grow significantly - reached an average 9.5GB per month per connection by 2018.
- This increase in traffic per connection results from the rise in average bandwidth associated with the move to higher bandwidth connections, in combination with the rise in data-heavy Internet applications using rich media such as video.

[Source: Internet Society Global Internet Report]

Traffic generated by different applications

263,707,930

Total online visits to MIT OpencourseWare as of July 2018

[source: MIT OpenCourseWare]

2,850,172

Apps available in Google Play
Sept 3 2018

[source: AppBrain]

3,205,573,592

Views of the “Gangnam Style” official Music video
Sept 3 2018

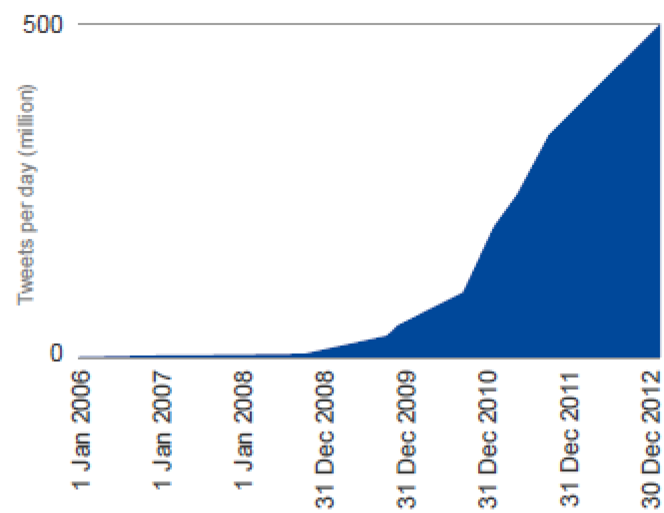
[source: Youtube]

Traffic generated by different applications

Apple iOS reached 170 billion downloads by May 2018 - Google play installs reached 94 billion in 2017 (with a record of 19B downloads in Q4 2017)
[Source: Internet Society Global Internet Report]

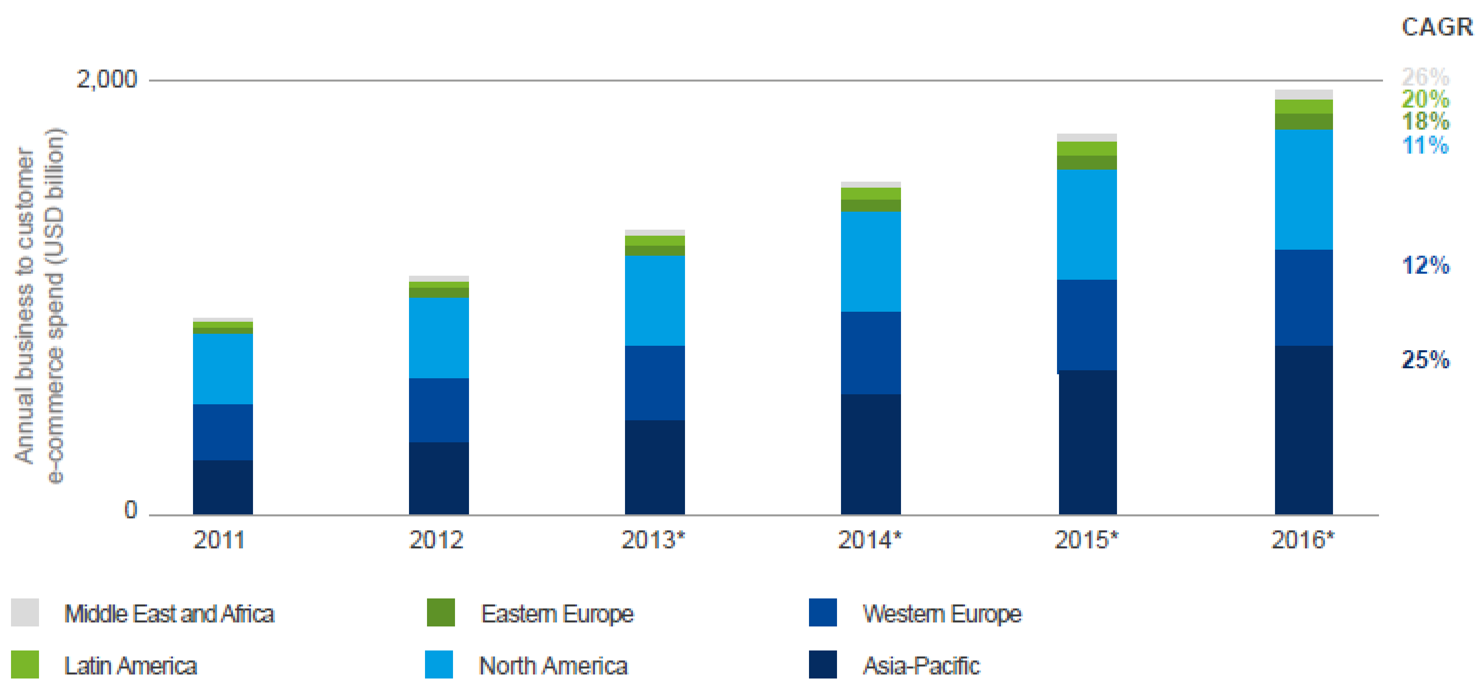
Twitter active users - 338,348,241
Tweets per day - 500 million tweets per day and around 200 billion tweets per year

[Source: internetlivestats.com]

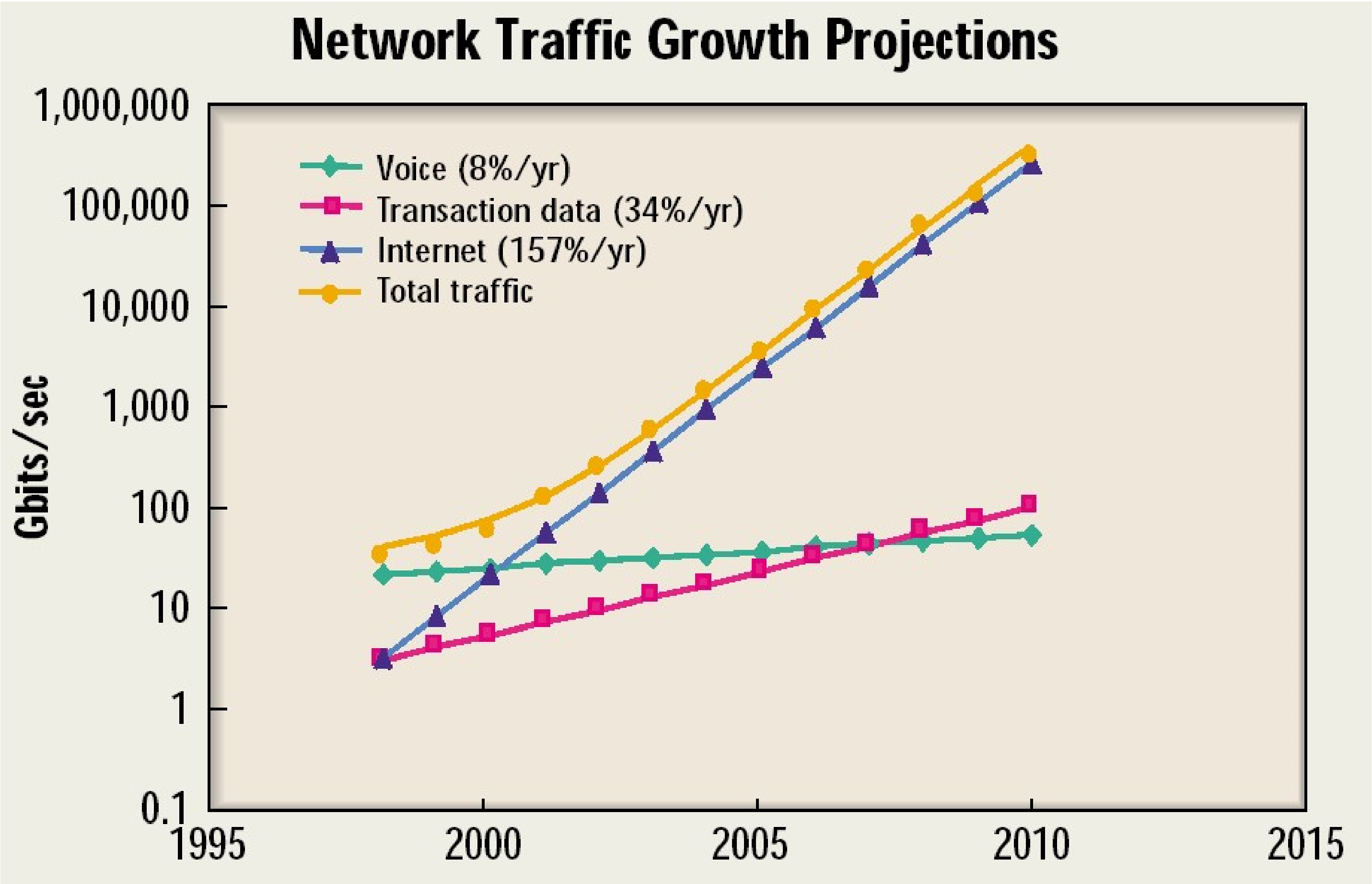


E-commerce

- Annual spending by each region
[source: eMarketer]

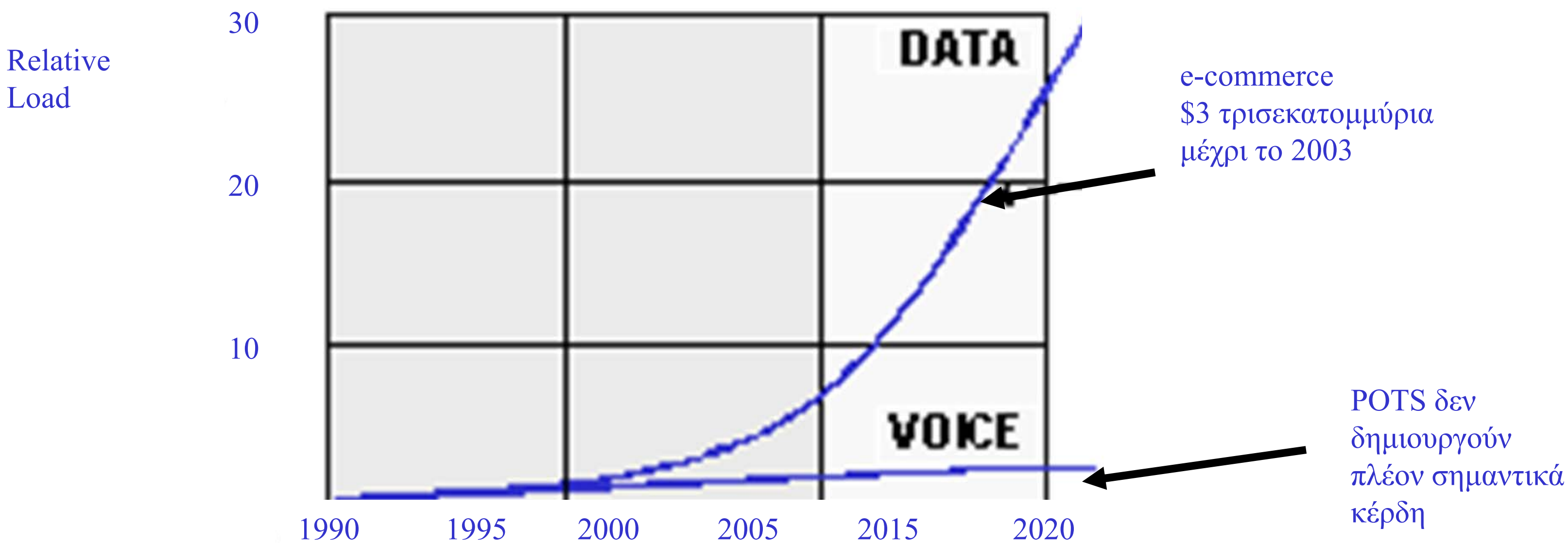


Increased Data Traffic



Source: Corning International Network Traffic Model

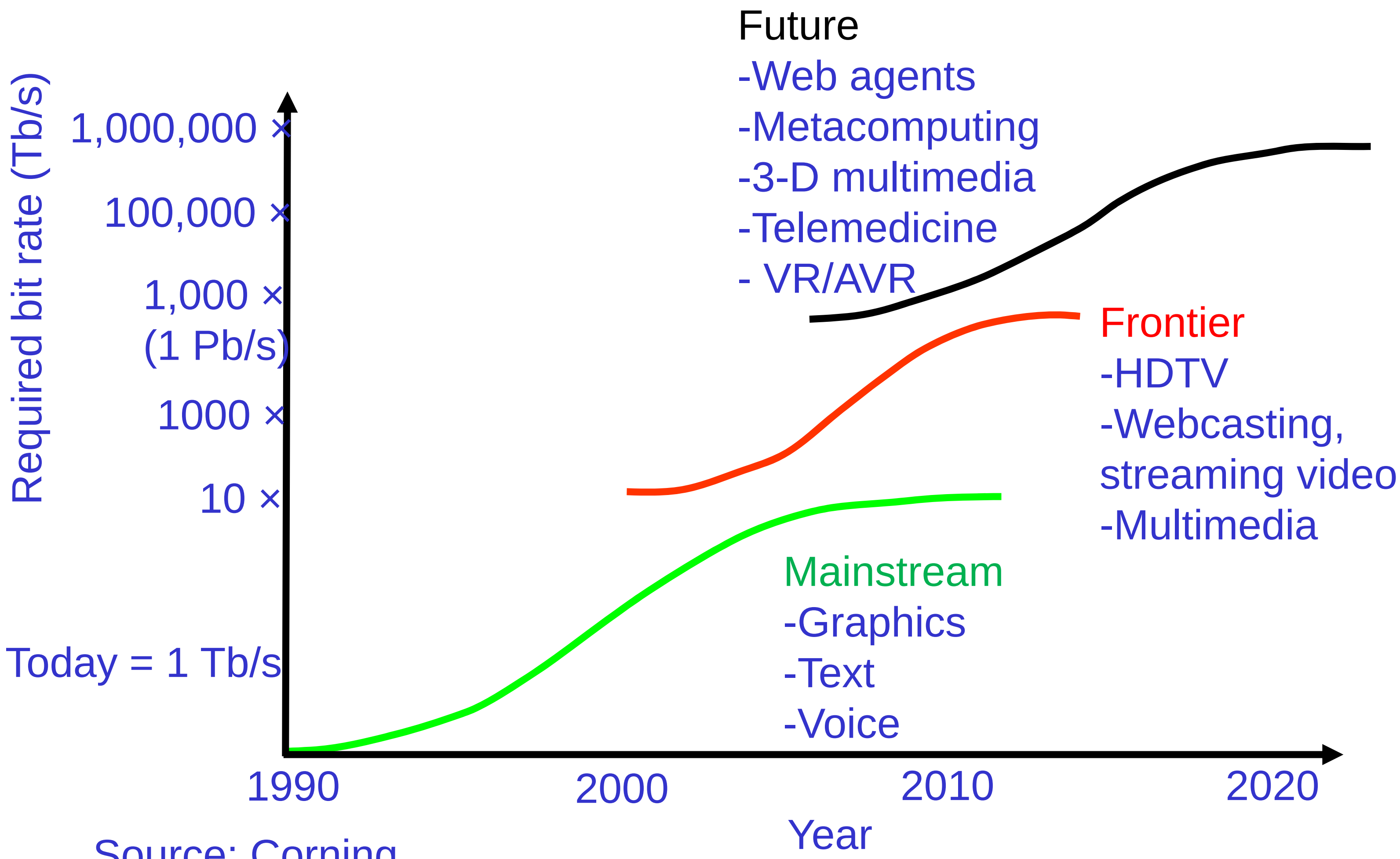
Increased Data Traffic



• Telecom is today the third largest sector in the world economy

•Cyprus mobile broadband penetration in 2017: 34% (no. 68 in the world)

Future Bandwidth Needs



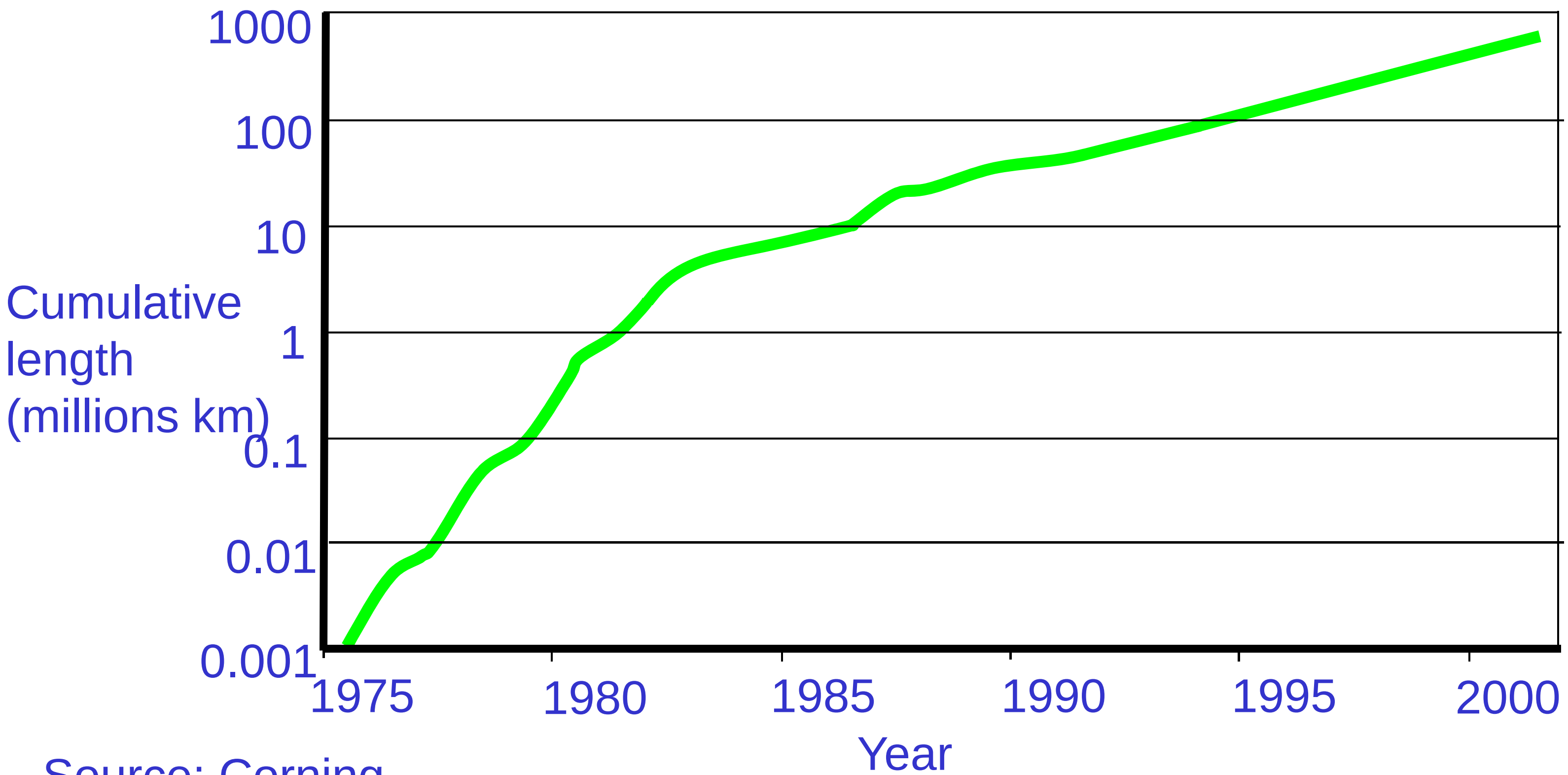
Source: Corning

Value of connectivity
Economic and social benefits

- Creation of additional jobs
- Decrease in extreme poverty in developing countries (Africa, Latin America, India)
- Increase in Productivity
- Health (access to medical information, medical advice, disease prevention)
- Education (open universities, more students online, teacher development, e-books and online resources).
- Economic, Environmental, and Social benefits: IoT Networks, smart cities
- ……

Optical Fibers Deployed

- Currently more than ***2 billion kilometers*** of optical fiber is deployed around the world, connecting people, businesses, communities, countries, and continents [source: Corning].
- Global demand for optical fibers is increasing - will reach 500 million FKM by the year 2018
- While 20 years ago we could only pick up the phone to connect with someone in real-time, today we have the technology to instantly and globally share voice, data, and video



Source: Corning

Available Capacity

Gilder’s Law

3x BW/year for 25 years

- **Today:**
  - **10/40/100 Gb/s per channel**
  - **4-192 channels per fiber**
  - **32 - 196 fibers per cable: > 1 Tb/s/cable**
  - **Theoretically 25 Tb/s per fiber (single core)**

- **Total BW doubles every 8 months!**

Available Capacity

- Today we are moving to multi-core optical fibers

- Experimental Results:

Mar 2014: 255 Tbps transmission in a single multicore optical fiber was demonstrated – close to the total sum of all traffic flowing across the Internet at peak time.

Jan. 2016: 1.125 terabits per second data transfer rate – e.g., at the quoted rate the entire HD series of the TV show Game of Thrones could be downloaded in less than one second

Aug. 2016: Chinese firm FiberHome developed an optical fiber that can transmit 400 Tbyte ps, breaking the world record for the amount of data that can be transmitted on optical fibers.
Such capacity would allow for simultaneous phone calls by 4.8 billion people and the transmission of 40,000 blue-ray high definition movies (10 gigabytes per movie) in one second

Optical Telecom System Categories

Free Space
e.g. intersatellite links

Guided

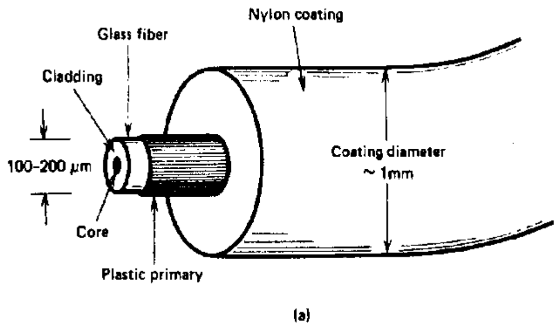
Optical Fibers

- Excellent transmission medium
- Dominates in long distance high bit-rate telecommunications

Integrated Optics

-Used for operation, e.g., Switching, muxing, splitting, etc

Optical Fiber Anatomy



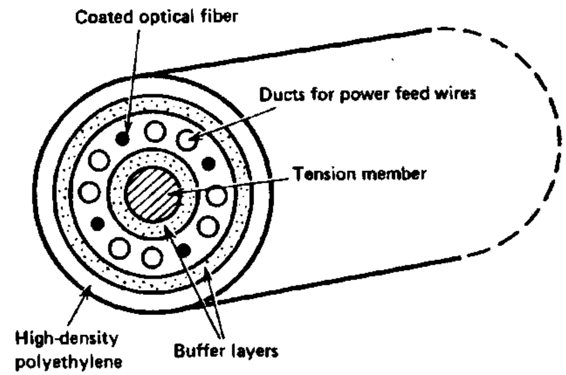


Figure 1.9. Optical fiber cable.

- **Diameter:**
  - **Single Mode Optical Fiber: 8 µm core, 125 µm cladding**
  - **Multimode Optical Fiber: 50, 62.5, 100 µm core, 125 µm cladding**

Fiber Optic Technology

FIBER IS A MEDIUM THAT CAN SUPPORT HIGH SPEED COMMUNICATIONS.

MAIN DESIRABLE FEATURES :

- ***Huge Bandwidth*** **(BW) - Terabits per second (1.3-1.6 μm bands)**
- ***Low signal attenuation*** **(0.2dB/Km) => Longer Repeater spacing**
- **Low signal distortion**
- **Low power requirements**

Fiber Optic Technology

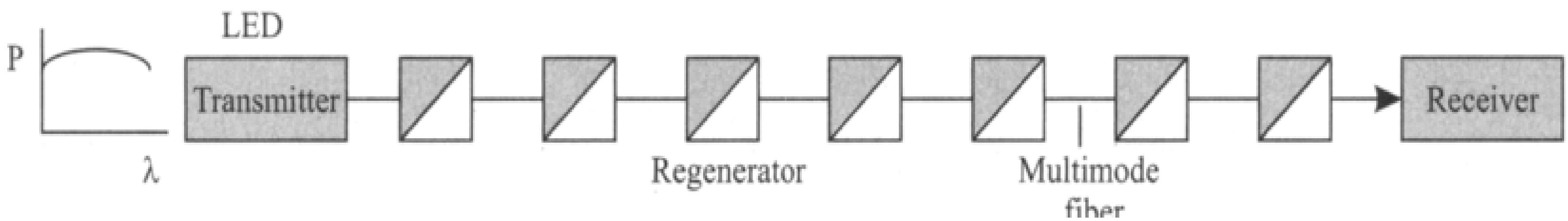
- **Small space requirements (small diameter, lightweight, flexible)**
- **Low Cost**
- ***Low Bit Error Rates* (BER <10E(-15))**
- **Low radiation => Security**
- **No grounding problems**
- **Immune to electromagnetic interference**

Fiber Optic Technology

- *Transparency*
  - Modulation format
  - Bit rate
  - Protocol format
  - Analog/digital signal

Lightwave Transmission Progress

- **Previously :**
  - **No high intensity light sources (LEDs)**
  - **No reliable medium (low-loss and low dispersion)**
    - **Pt-to-pt short distances**

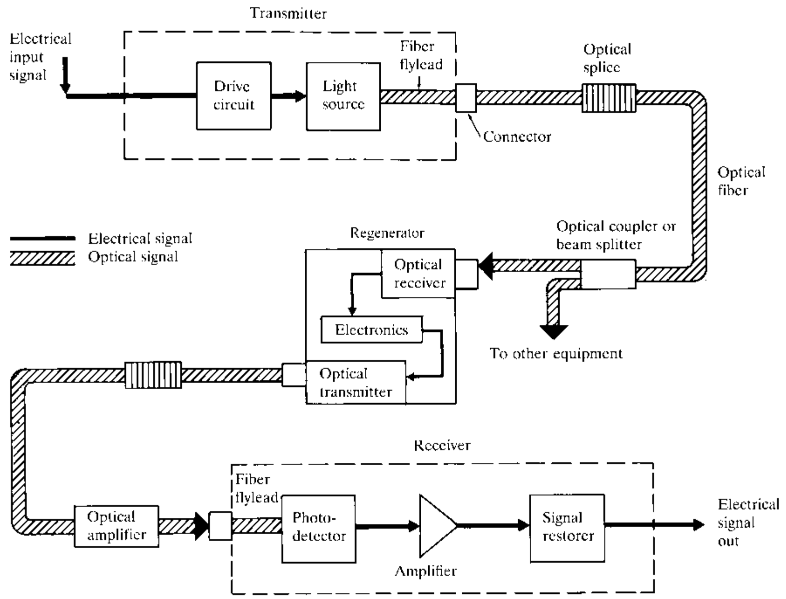


- **Three key developments during the last 30 years are responsible for optical communications**
    - **Invention of Laser**
    - **Fabrication of low-loss optical fiber**
    - **Introduction of semiconductor optical devices (including optical amplifiers)**

Lightwave Transmission Progress

- 1958 Invention of Laser
- 1960 First Lasers
- 1962 First Semiconductor Lasers
- 1966 Prediction of fiber telecommunications
- 1970 First Low Loss fiber and room temperature semiconductor laser
- 1974 First 1dB/Km fiber
- 1976-77 System Experiments and Trials
- 1987 Optical Amplifiers
- 1987-90 Introduction of DWDM
- 1990-98 First WDM prototype testbeds
- 1995 - Commercial WDM components
- 2000 - Deployment of WDM Networks

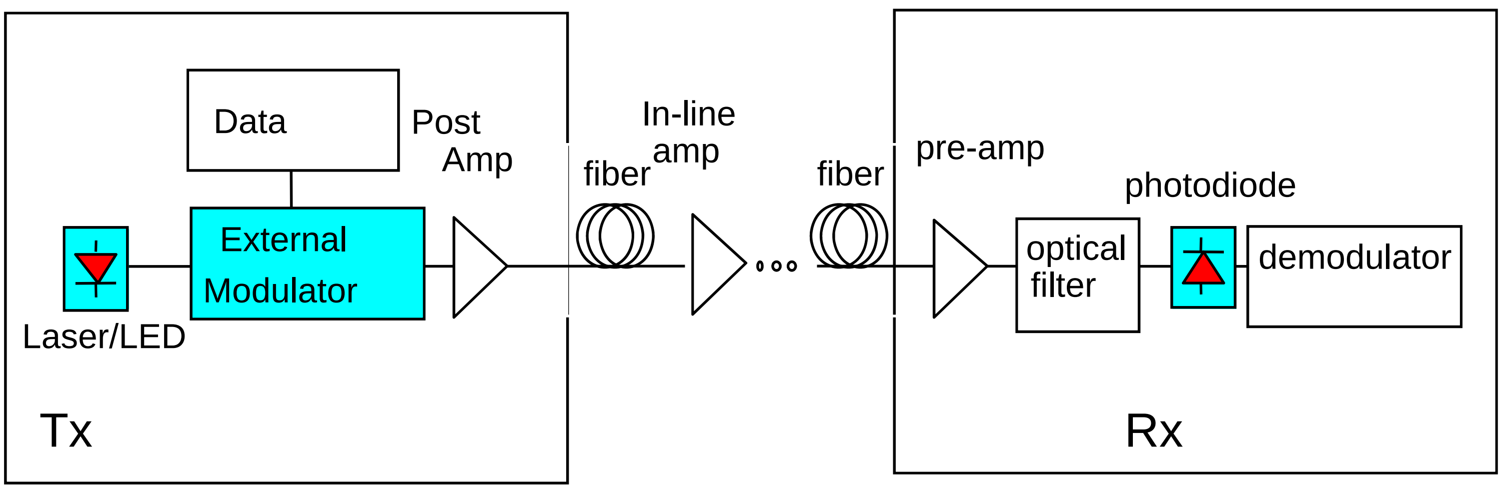
Lightwave Transmission



- **Transmitter :**
  - **LED (broad spectral width of several nm's - modulation at low bit rates (100-200 Mbps))**
  - **Lasers (high power, high bit rates (several Gbps), narrow spectral width)**
  - **How do you modulate the laser (i.e., how to send information ?)**
    Easiest way is to turn it on and off. You can also modulate the phase, freq., etc

Lightwave Transmission

- **Receiver :**
  - **pin - photodiode (Rx sensitivity around -19dBm)**
  - **APD receiver (Rx sensitivity around -29dBm)**



Lightwave Transmission

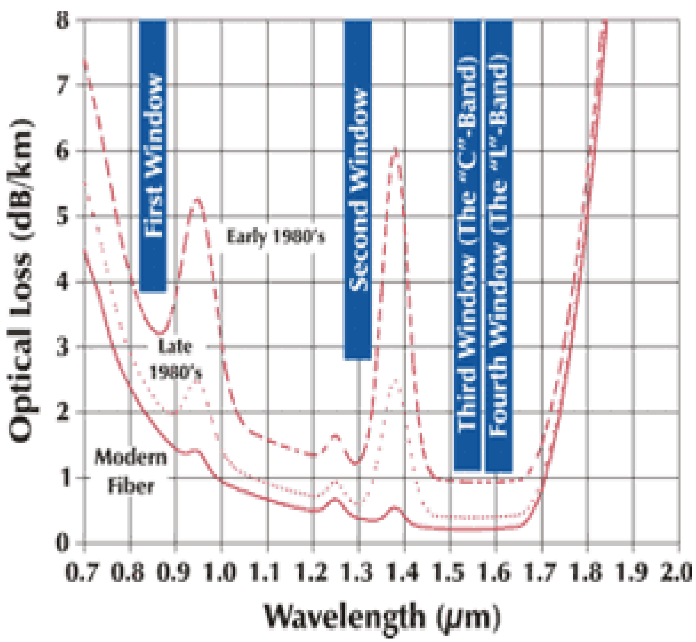
- **Fiber Medium Limitations**

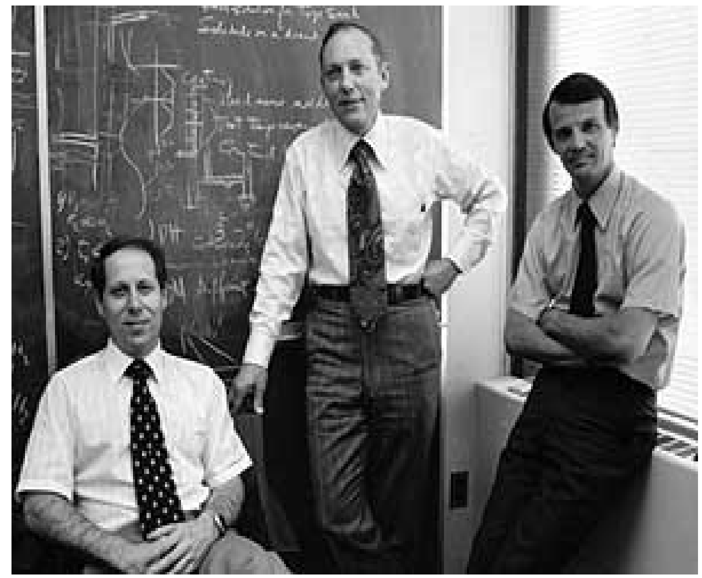
  - **Attenuation :**
    - **Absorption**
    - **Rayleigh Scattering**

  - **Pulse Broadening :**
    - **Chromatic dispersion**
    - **Polarization dispersion**
    - **Modal dispersion**

- **These are the two main causes of limitation in signal propagation distances**

Evolution of Optical Fiber Attenuation

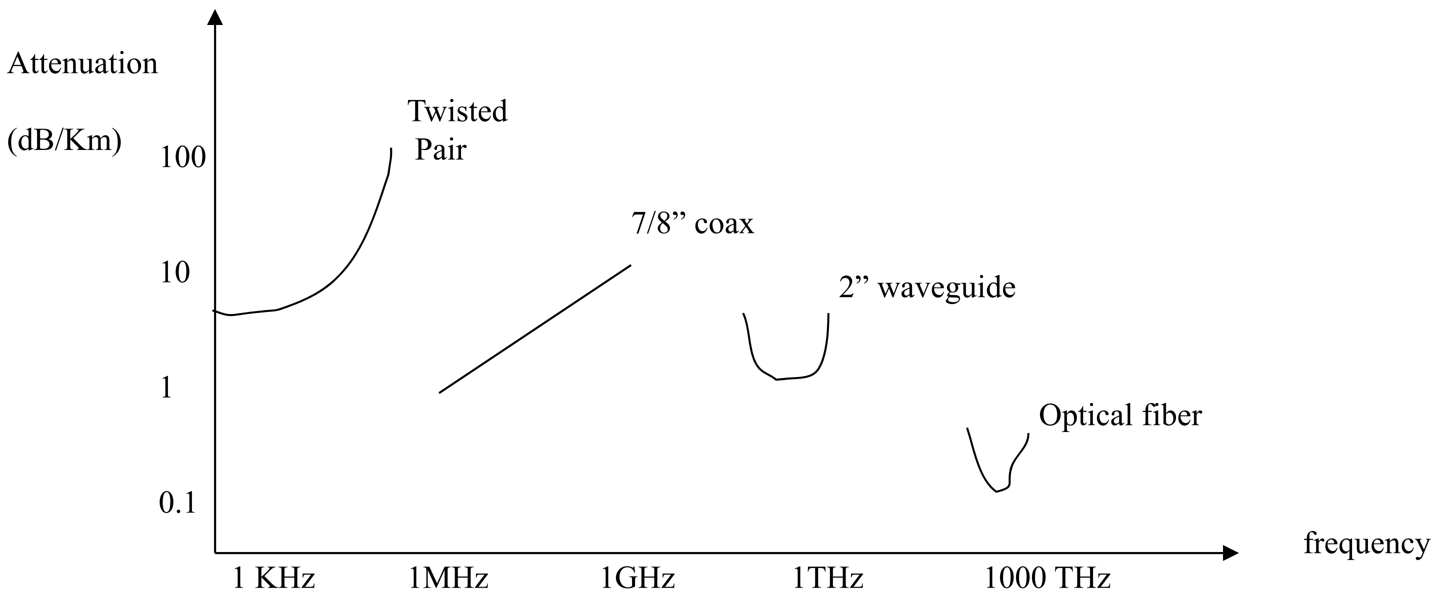




D. B. Keck, R. D. Maurer, P. C. Schultz
Corning, Inc.
Inventors of the first low-loss fiber (1970)

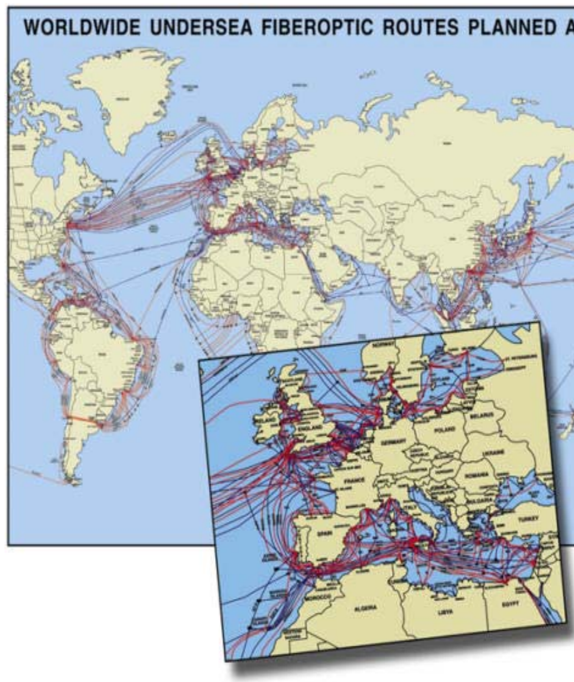
Lightwave Transmission

- **Comparison between types of transmission lines**



- **1.3-1.6 µm window (loss < 0.3dB/Km) => 300nm or 40THz available bandwidth !! (note that $\Delta f = (c\Delta\lambda/\lambda^2)$)**

Undersea Fiber Optic Systems



Undersea Fiber Optic Systems

Undersea cable laying ship, Cagayan de Oro beach landing

FLAG Atlantic

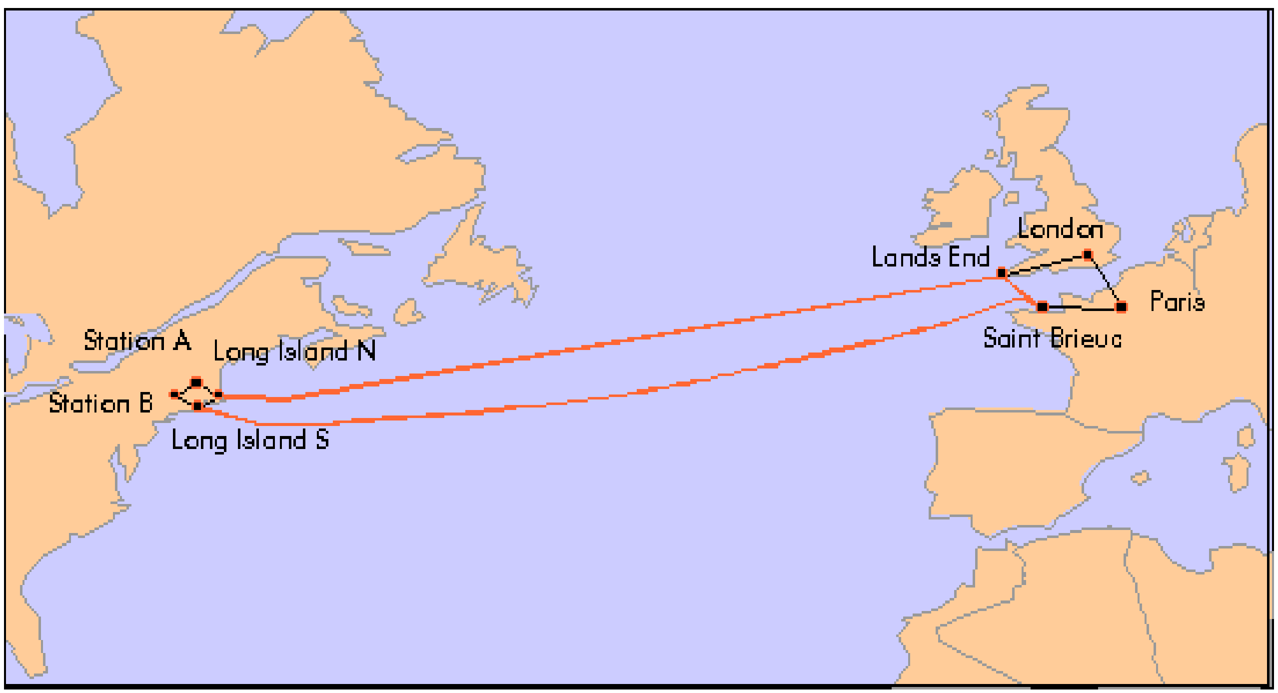
1997: The first undersea telephone cable (copper) in 1956 could carry 36 conversations; The first fiber-optic cable installed in 1988 could carry 8,000 channels (64 kb/s) in two fiber optic pairs. The Fiber-optic Link Around the Globe (FLAG) can carry 120,000 κανάλια (64-kb/s) in two fiber optic pairs

The initial FLAG system when it was completed (September 1997) was the longest system in the world (connecting England to Japan with fiber optic cables longer than 28,000 km (more than 2/3 of the earth's circumference)

2006: overseas satellite links accounted for only 1% of international traffic, while the remainder was carried by undersea cable. The reliability of submarine cables is high, especially when (as noted above) multiple paths are available in the event of a cable break. Also, the total carrying capacity of submarine cables is in the terabits per second. A typical multi-terabit, transoceanic submarine cable system costs several hundred million dollars to construct.

FLAG Atlantic-1

- Bit rate(Tb/s):2.4/direction
- Length (km):   6250/direction
- Cost (billion d0llars):1.1
- Connecting: US, France, England

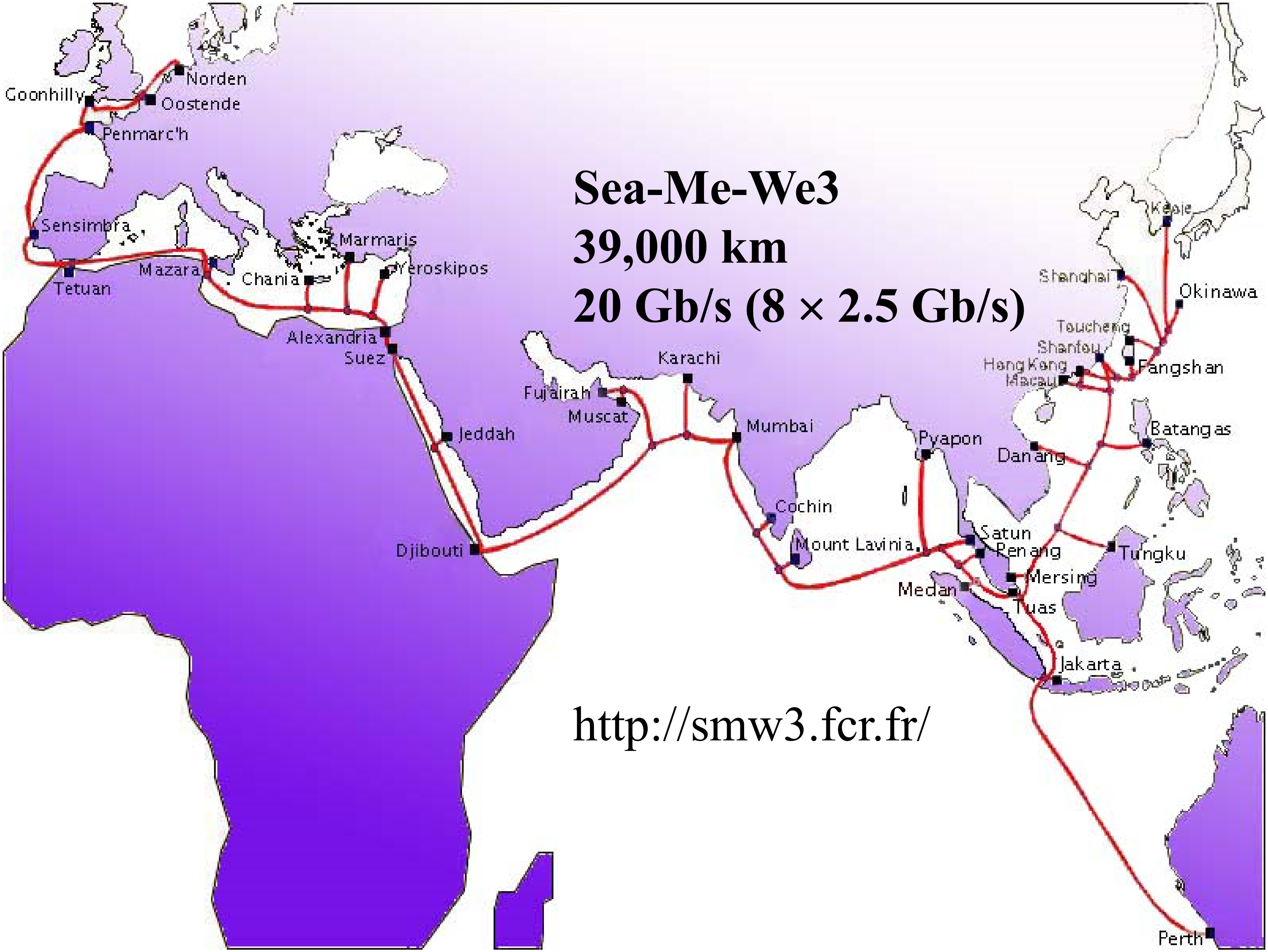


FLAG Atlantic-1

- **Equivalent to sending all the data in all the newspapers in the world in the last 300 years or approximately 30 million simultaneous phone calls in 1 second. (www.flagatlantic.com)**

Systems working with 8 Tb/s for distances greater than 6,500 km are now available with various companies

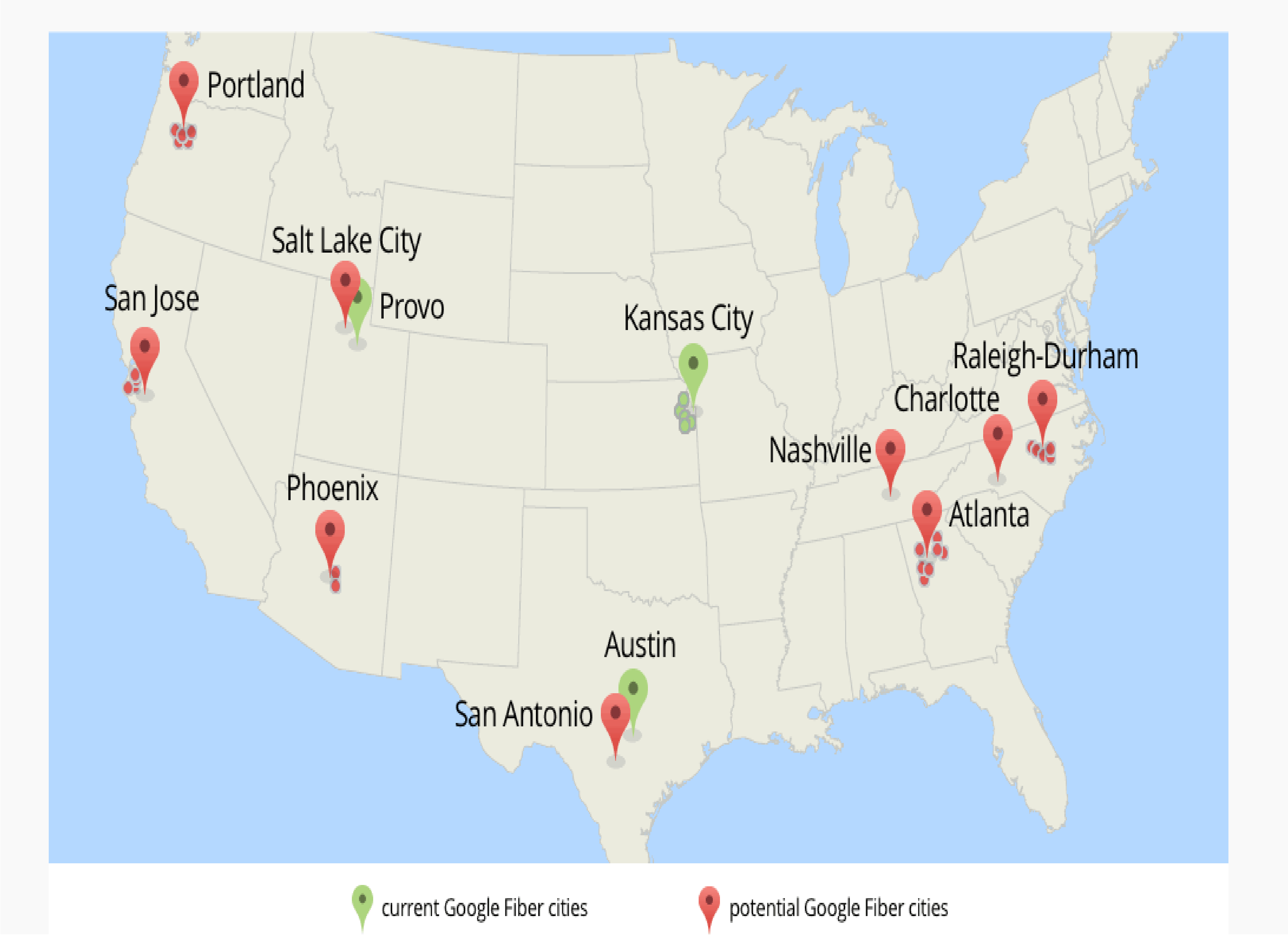
Sea-Me-We3
39,000 km
20 Gb/s (8 × 2.5 Gb/s)



http://smw3.fcr.fr/

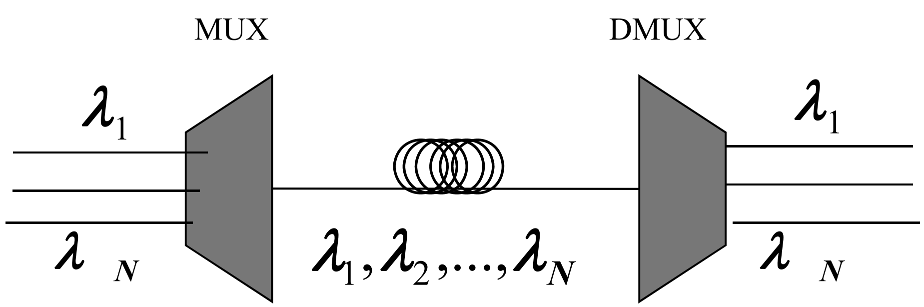
On-land Fiber Deployment Example - Google Fiber Project

- Google Fiber starts with a connection that is up to 100 times faster than today's average broadband speeds. Provides instant downloads, as well as crystal clear high definition TV.
- Streaming movies, storing files online, video chatting, online gaming were all enabled by broadband connections over a decade ago, and the next chapter of the web will run on even faster speeds.

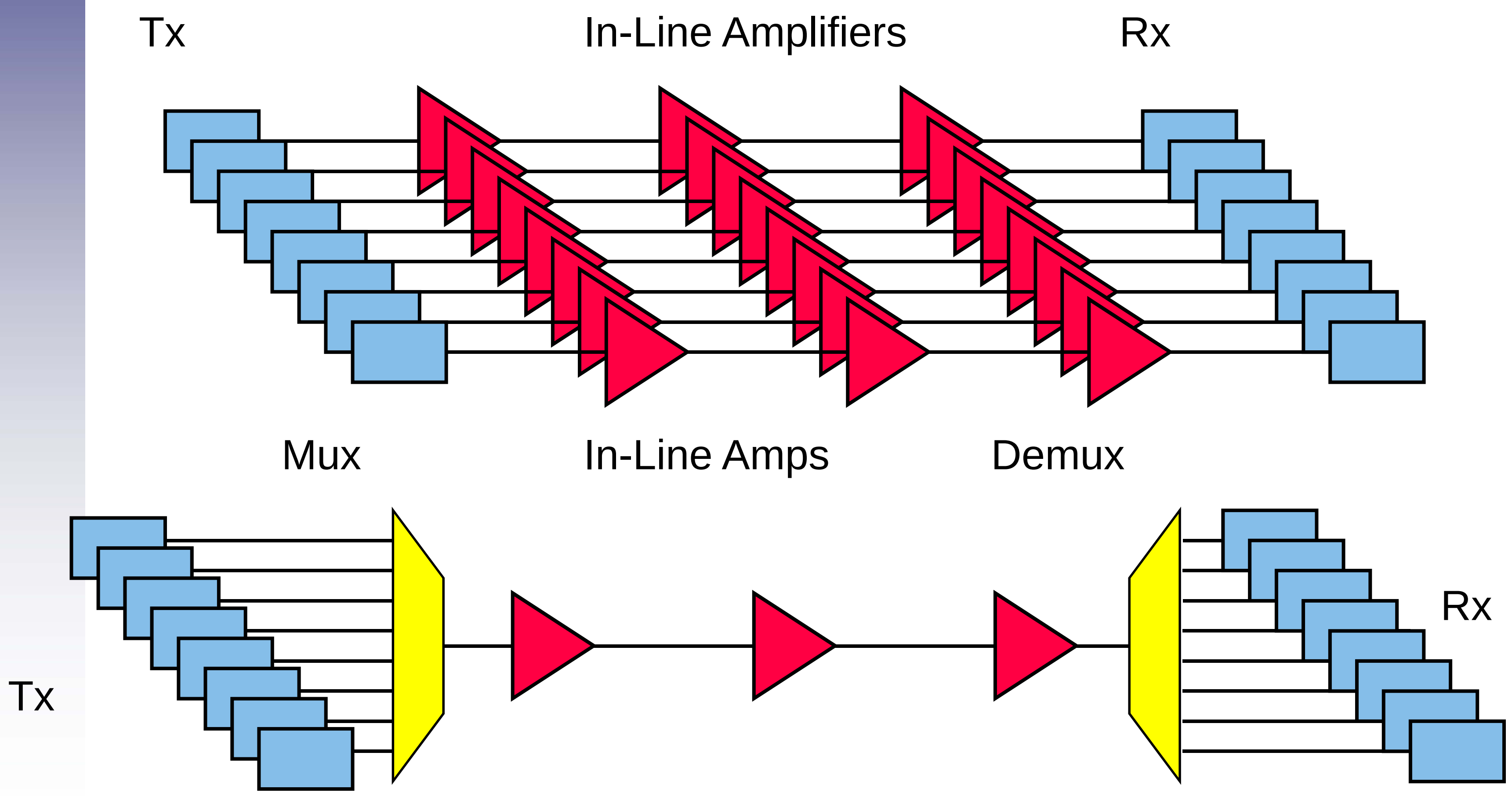

Portland
Salt Lake City
San Jose
Provo
Kansas City
Raleigh-Durham
Charlotte
Nashville
Atlanta
Phoenix
Austin
San Antonio
current Google Fiber cities
potential Google Fiber cities

Optical Networking

- **Optical networking is generally defined to include the use of :**
  - **Wavelength Division Multiplexing (WDM) to transport multiple signals independently on individual fibers.**
  - **Optical wavelength routing to achieve increased network capacity and increased flexibility relative to other approaches.**



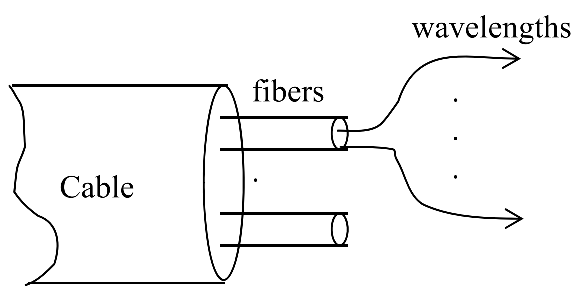
WDM

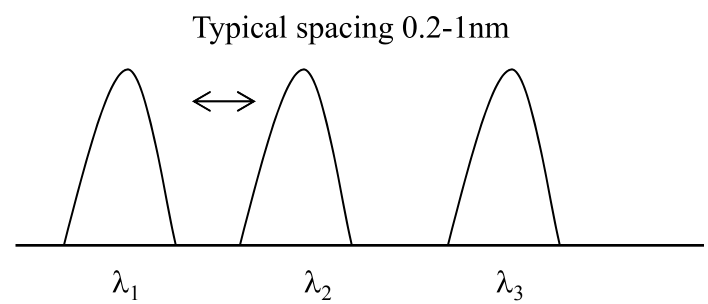


Wavelength Division Multiplexing (WDM)

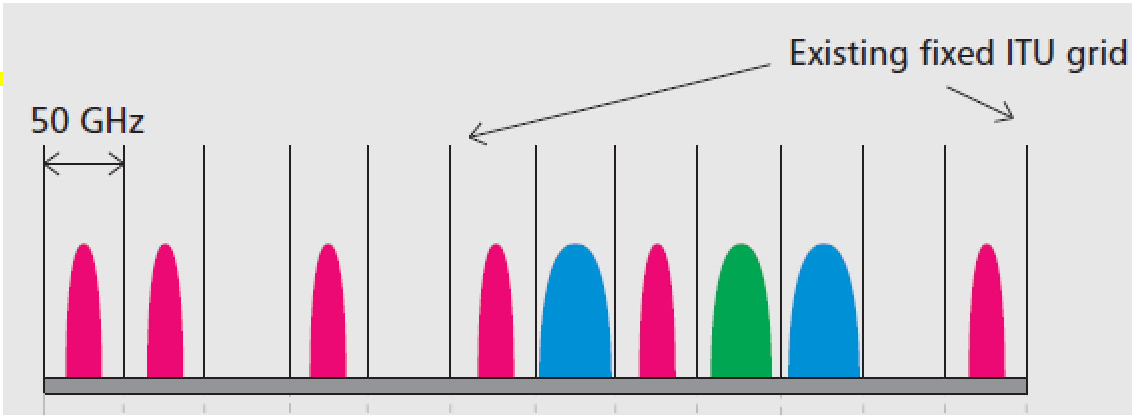
- Multiplex multiple WDM channels from different users on the same fiber

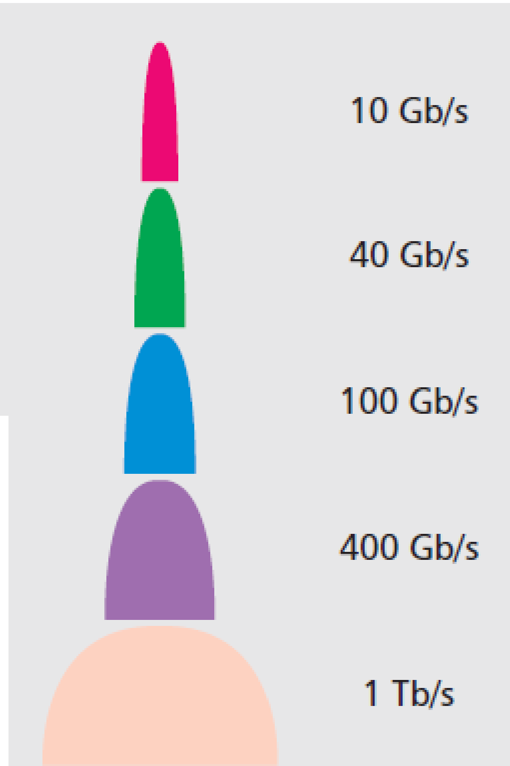
- The optical transmission spectrum is “carved-up” into a number of non-overlapping wavelength (or frequency) bands, with each wavelength supporting a single communication channel.





WDM with Traffic Grooming (TDM)

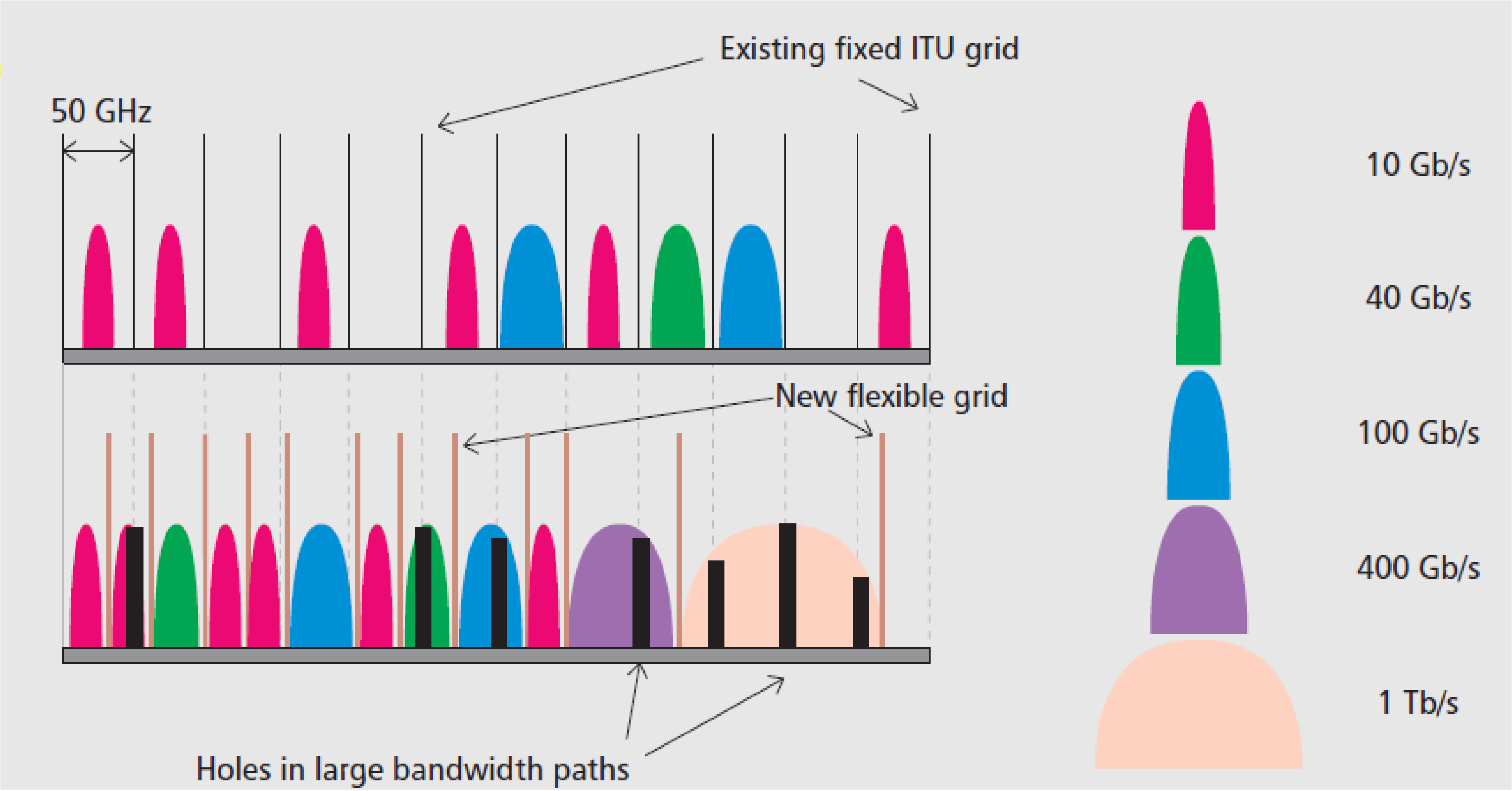




- **Traffic Grooming: Increases the bandwidth of an optical network, by grooming low-speed traffic demands into high-speed wavelength channels.**
- **Today, a typical connection request, requires bandwidth that is only a fraction of the wavelength bandwidth. (HDTV requires just 20 Mbps per channel, normal TV channel requires less than 2 Mbps per channel).**
- **If we have a wavelength with capacity 100Gbps, then ten connections with capacity 10Gbps can be groomed into the same wavelength.**

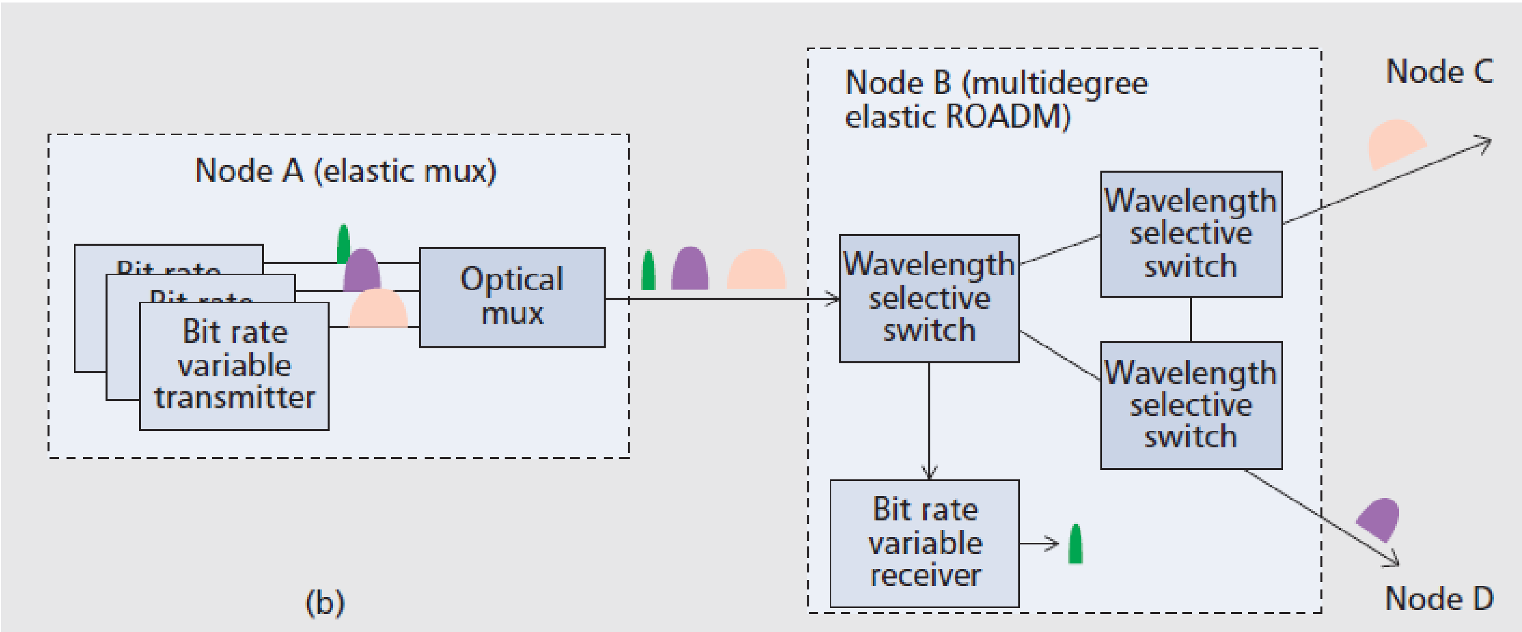
Elastic Optical Networking

[Source: O. Gerstel, M. Jinno, A. Lord, S.J.B Yoo, "Elastic optical networking: a new dawn for the optical layer?," IEEE *Communications Magazine*, 50(2):s12-s20, Feb. 2012]



- **OFDM:** The sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other, meaning that cross-talk between the sub-channels is eliminated and inter-carrier guard bands are not required.
- Since 100Gb/s and higher bit rates must be supported by the same network, it makes sense to "properly size" the spectrum for each demand based on its bit rate and the transmission distance (instead of forcing all demands to use more spectrum).

Elastic Optical Networking



- three demands of bit rates 40 Gb/s, 1 Tb/s, and 400 Gb/s connect node A to B, C, and D, respectively.

Promise of a WDM/Elastic Networking Layer

- **Increased aggregate capacity (avoid the electronics bottleneck and better utilize the capacity of the fiber)**
- **Transparency for a variety of services (switching, amplification, etc.)**
- **Flexible routing and configuration (Move from the electronic switching (bottleneck) and electronic regeneration to optical switching and optical amplifiers).**
- **Survivable Interconnectivity**

Optical Amplifiers

- Optical Amplifier is the Key Enabling Technology
- No O/E, E/O conversion - Amplify the optical signals in an optical medium => No electronic bottleneck associated with electronic repeaters (which are complex, expensive and provide no transparency)
- Larger BW than electronic repeaters (up to 100 Gbps)
- Insensitive to bit rates
- Transparent to modulation formats
- Simultaneous regeneration of multiple WDM signals
- Low cost and high reliability

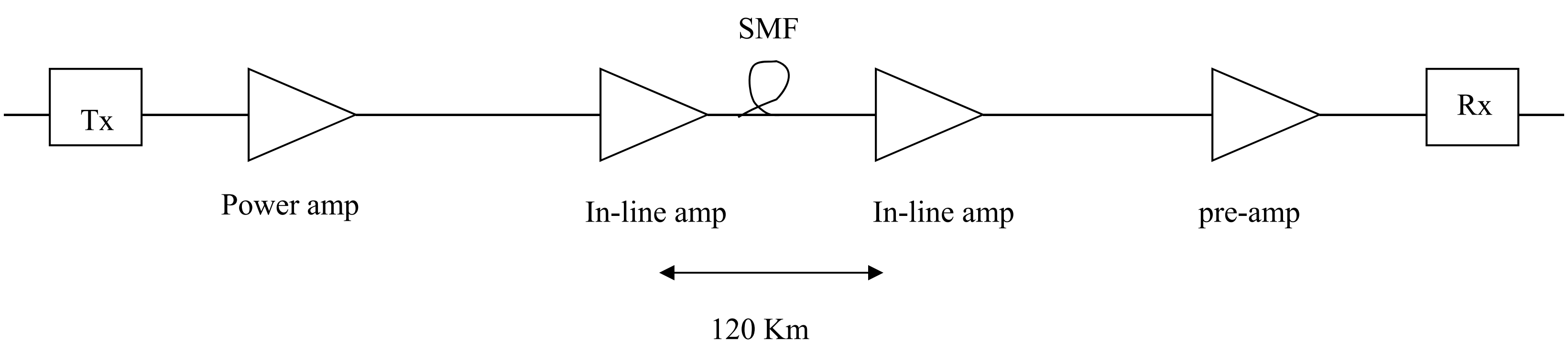
Optical Amplifiers

- Low noise, high gain.
- Very well suited for loss compensation of passive components in an optical transmission system
- Potential to create a universal lightpipe between terminals
- Potential for high bit rate applications through WDM

LONG-HAUL TELECOMMUNICATION APPLICATIONS

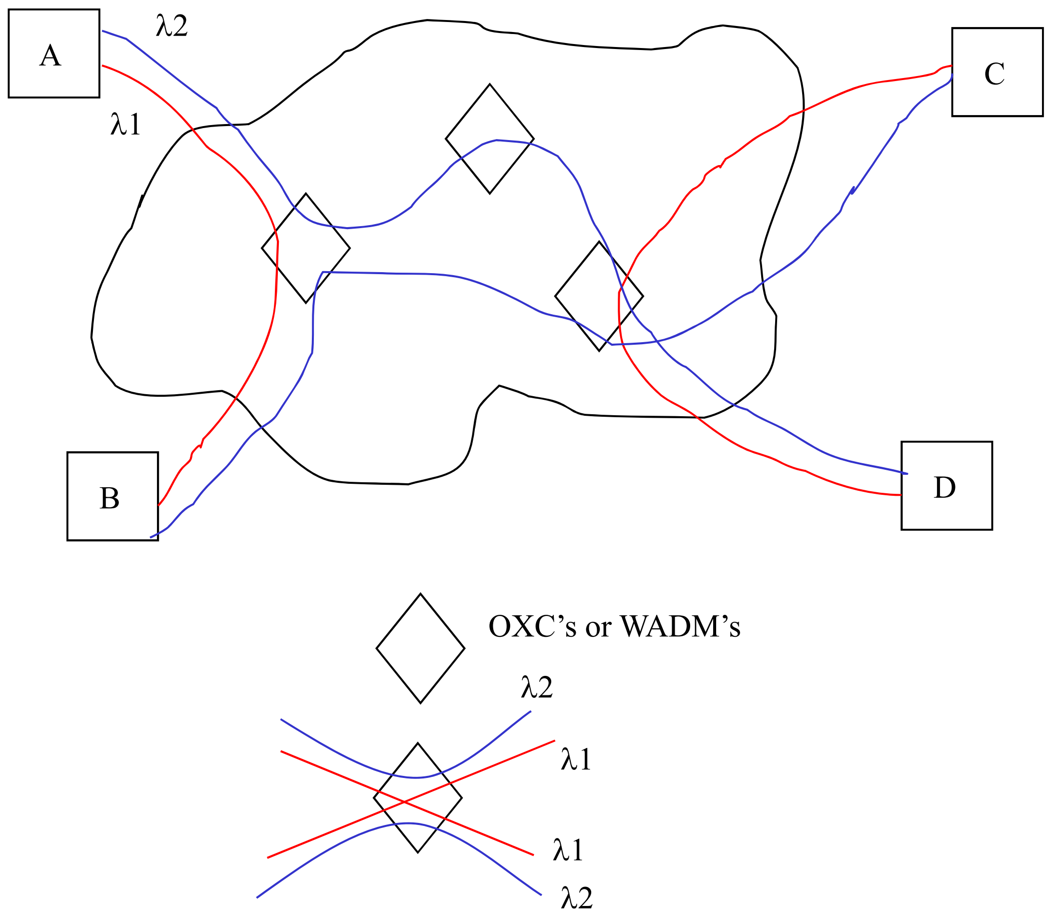
Optical Amplifiers

- Optical amplifiers can be used as :
  - Power amplifiers at the Transmitter (post-amplifiers)
  - Optical pre-amplifiers in high bit-rate Receivers
  - In line amplifiers to compensate loss in optical networks



Network Architectures

Wavelength Routing Networks (WRN's)



Network Architectures

Wavelength Routing Networks (WRN's)

- Wavelength Reuse
- Wavelength Continuity
- Transparency
- Wavelength Routing
- Dynamic Reconfiguration
- No splitting loss
- Scalable to large number of wavelengths and WAN's
- Switching provides connectivity, network resource sharing

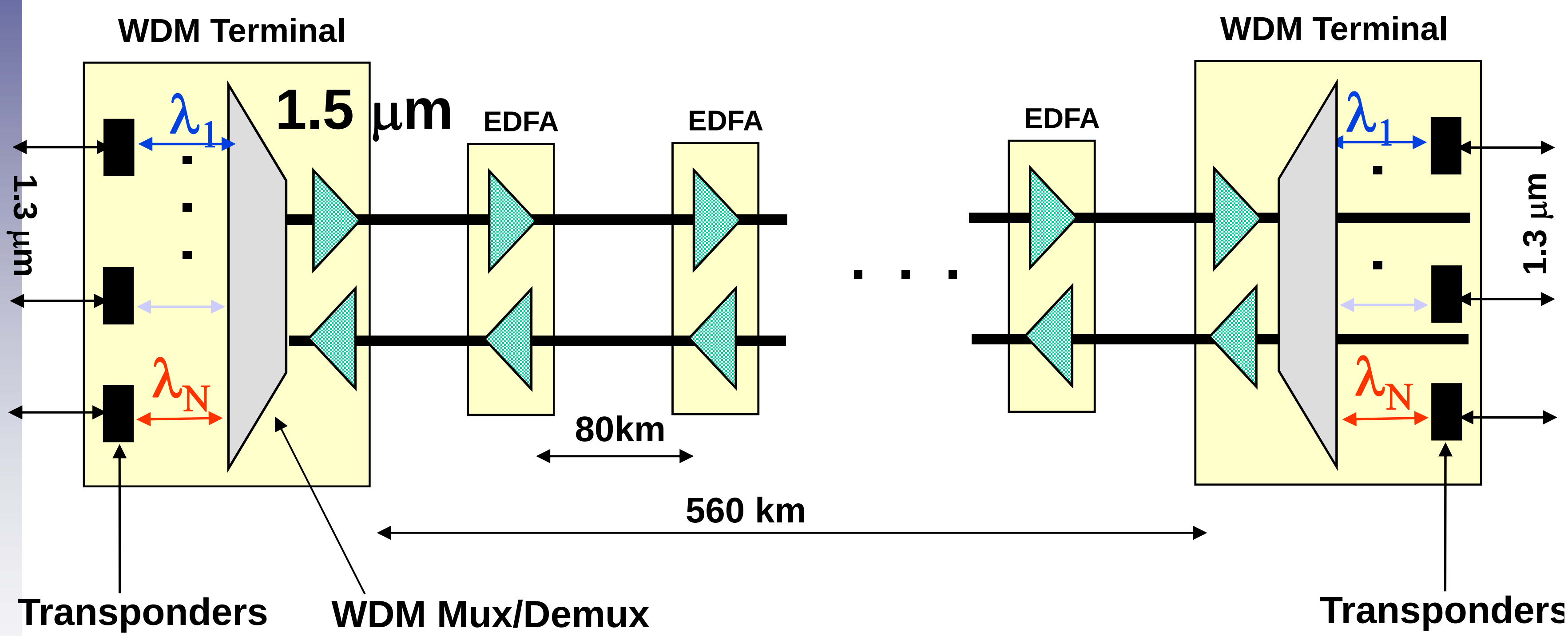
Network Architectures

- Wavelength Routed Networks
  - A lightpath (all-optical channel) is used to interconnect end-users.
  - A lightpath spans multiple fiber links to provide a "circuit-switched" interconnection between two nodes.
  - Normally a lightpath operates on the same wavelength across all fiber links (wavelength continuity constraint), unless a wavelength-converter is present.
  - Color Clash constraint : No two channels that have the same wavelength can share the same fiber link.
  - The number of wavelengths required in each network depends on the
    - network topology, traffic pattern, number of lightpaths terminating at each node, switching available in the network, wavelength converters

WDM Network Architectures

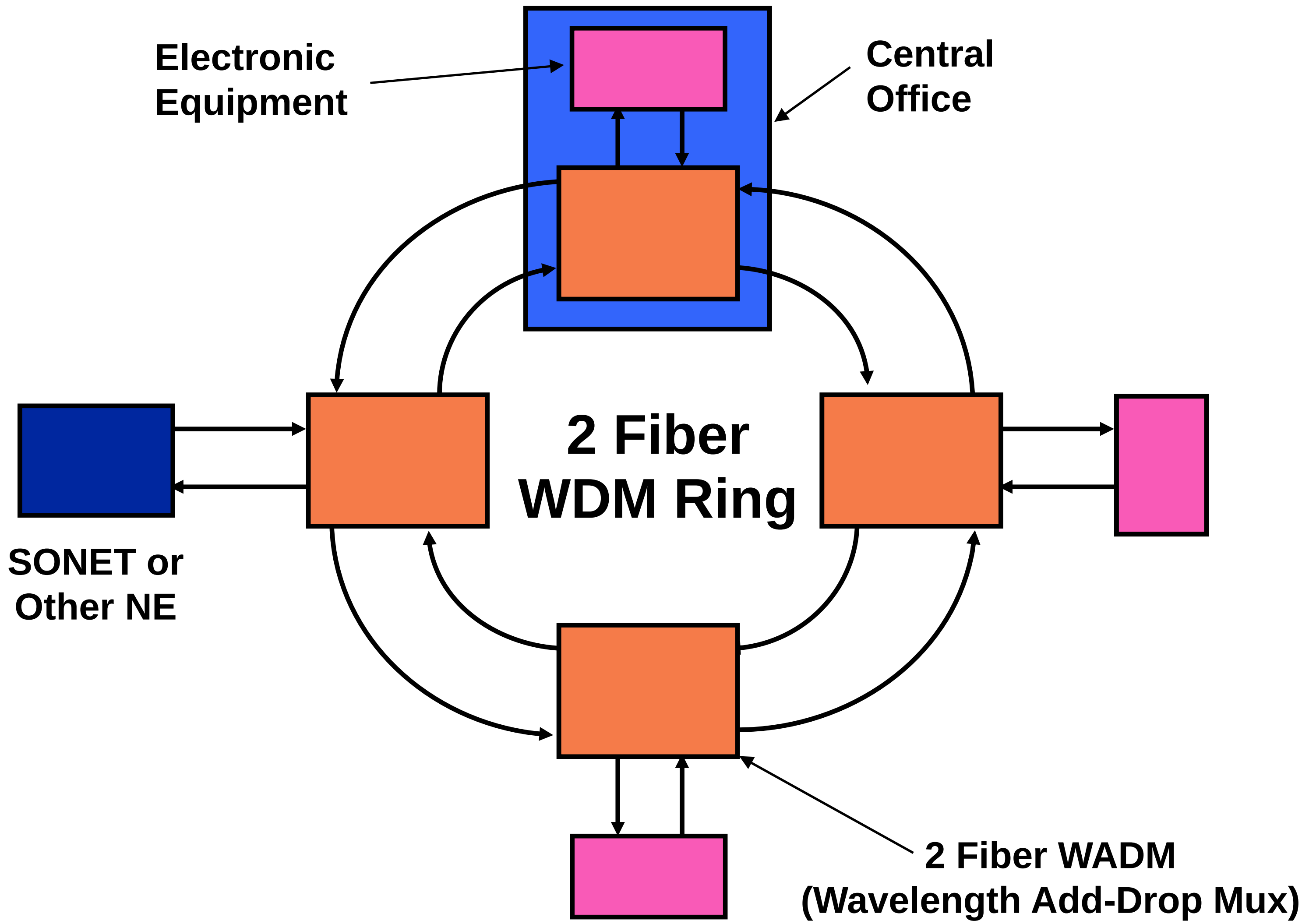
- Point-to-point WDM networks
- WDM Ring networks
- WDM Mesh networks

Point-to-Point WDM Systems

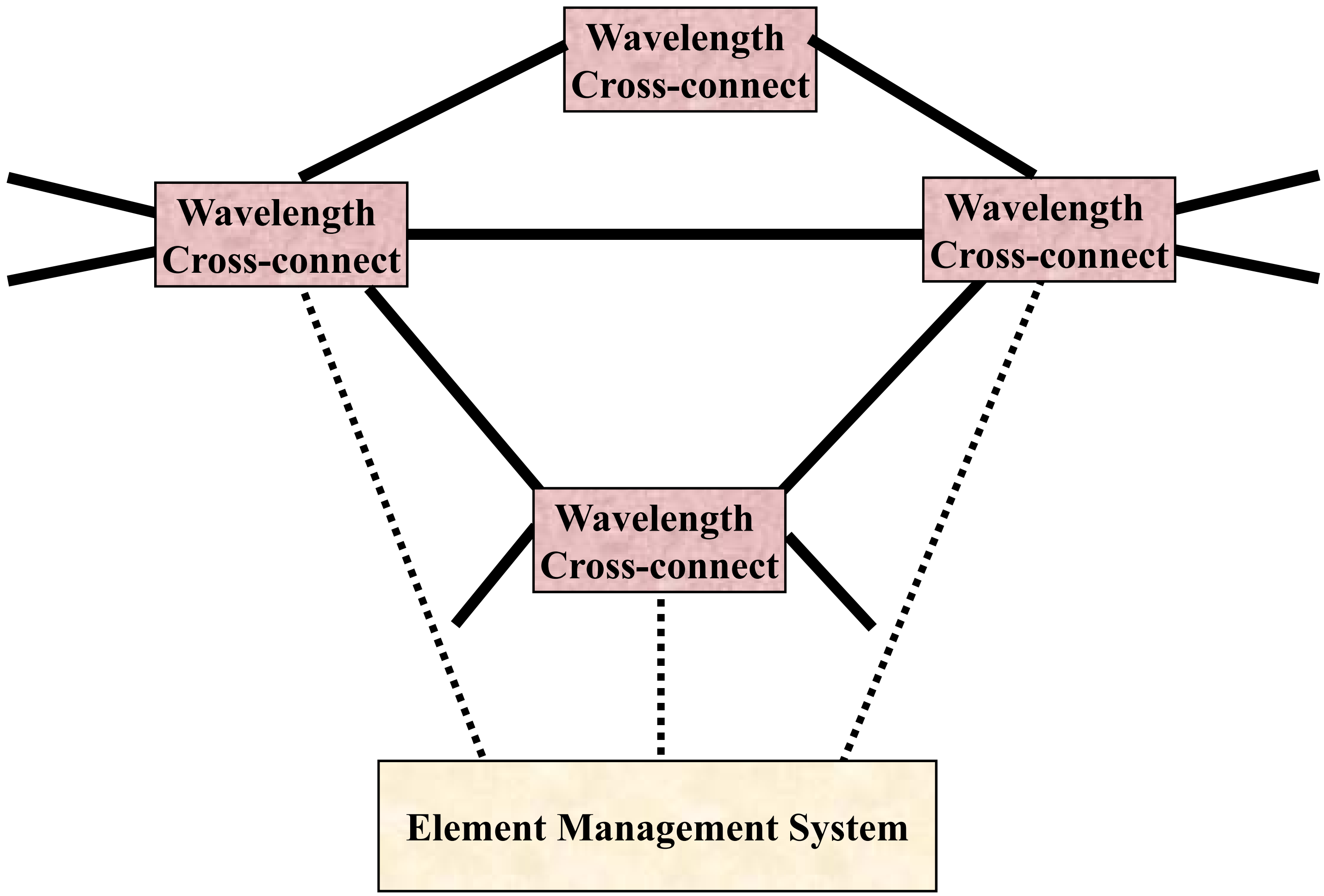


ITU defined freq separation at 50 GHz

WDM Ring Network Architecture

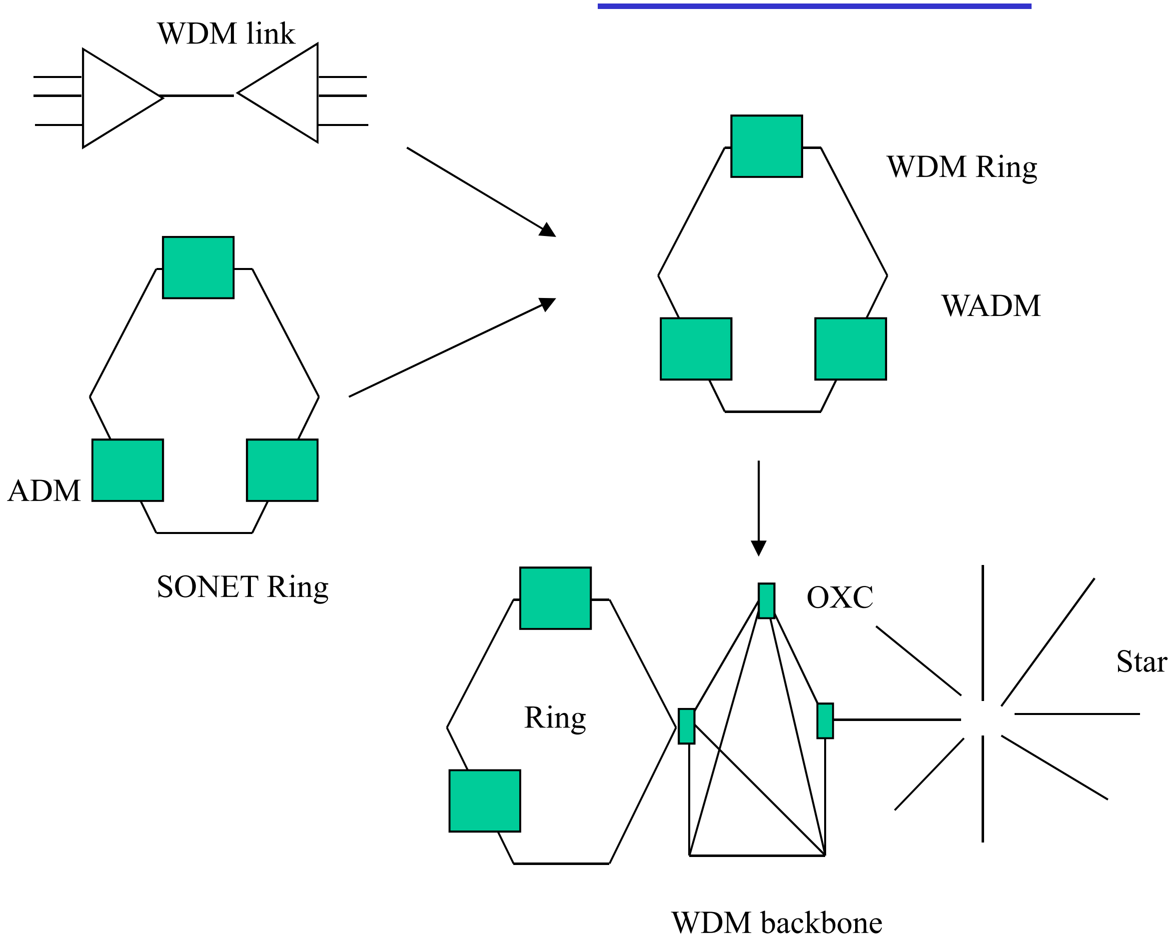


WDM Mesh Network Architecture



Network Architectures

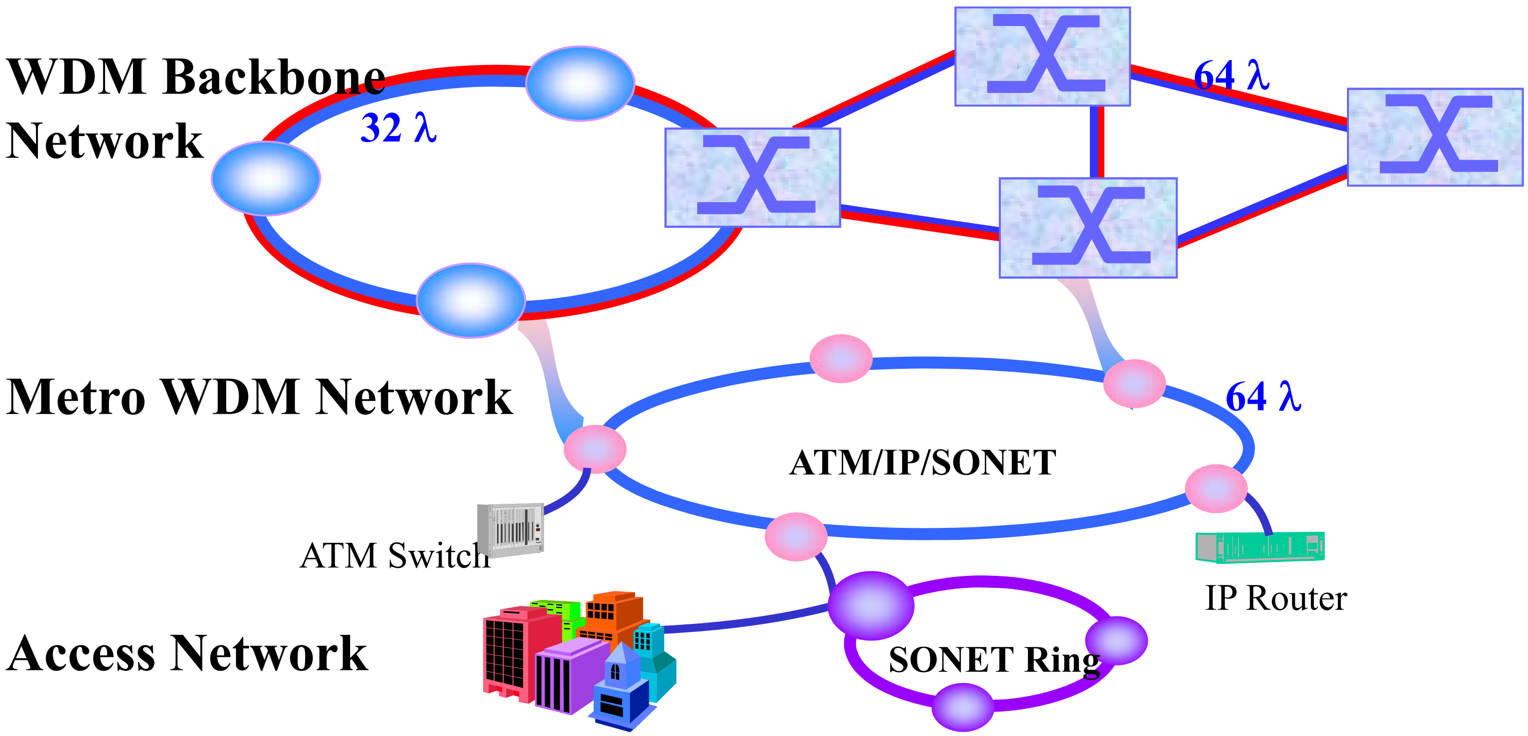
Evolution Scenario



Inter-office

1-2.5 Gbps/wavelength
8-32 wavelengths

Network Architecture



Provisioning: Routing and Wavelength Assignment - Heuristics

Routing and wavelength assignment

Wavelength-Routed Networks :

- **channel assignment involves allocating an available wavelength to the connection and tuning the Tx and Rx stations to the assigned wavelength**

- **Routing involves determining a suitable optical path for the assigned wavelength-channel and setting the switches in the network nodes to establish that path.**

- **Implementation of routing and wavelength assignment is a quite different problem depending on whether the optical connections are dedicated (static) or switched (dynamic).**

Routing and wavelength assignment

- Dedicated connections are assured to be held for a relatively long period of time.
- These connections are chosen at the design stage of the logical network and modified occasionally in response to changing traffic load conditions and/or equipment failures.
- Switched (demand assigned) connections are established and released on demand with holding times that might be as short as a minute or less.
- So we have a prescribed set of required connections for dedicated connections and a random sequence of connections for switched connections.

Routing and wavelength assignment

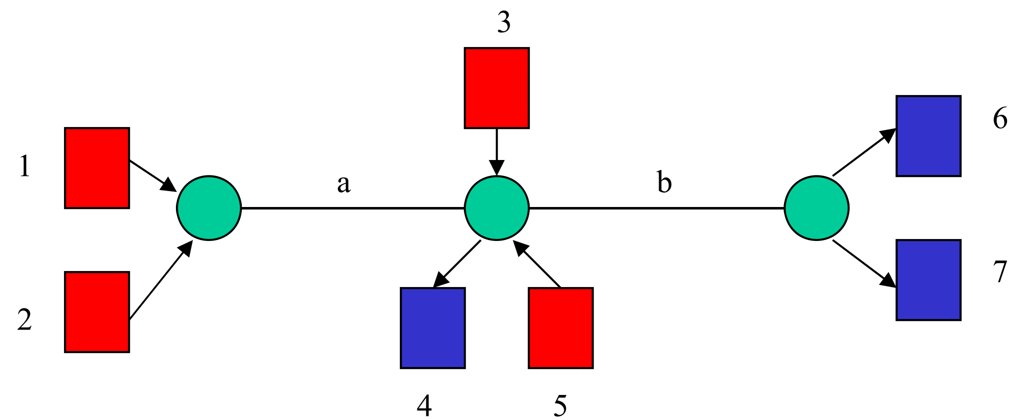
Channel assignment constraints :

- **Optical connections obey the wavelength continuity condition (in the absence of wavelength conversion). This is a condition imposed by the physics of the optical layer.**

- **Distinct Channel Allocation (DCA) condition ensures that the optical signals sharing a fiber do not interfere with each other at the Rx (use different wavelengths). When this condition is not met we have a Color Clash (two or more connections use the same wavelength in the same fiber)**

Routing and wavelength assignment

- **Example :**
  - 7 access stations and 3 optical switching nodes
  - Each link consists of a single pair of unidirectional fibers
  - physical topology is a tree, with only one possible optical path between pairs of stations (no routing decisions)
  - No wavelength conversion
  - two wavelengths and 3 connections to be established (2,4), (1,6), (5,7)



Routing and wavelength assignment

- **Dedicated Connections :**
  - (2,4) on wavelength 1, (1,6) on wavelength 2 and (5,7) on wavelength 1 is a feasible choice.

- **Switched Connections :**
  - Connection (2,4) enters the network and is assigned wavelength 1
  - Connections (3,6) and (5,7) enter the network and are assigned wavelengths 1 and 2 respectively
  - Connection (3,6) is terminated
  - Connection (1,6) enters the network => the connection is blocked.

Routing and wavelength assignment

- If it was possible to rearrange the active wavelength assignments to wavelength 1 for (2,4) and (5,7) then the new assignment could be accepted using wavelength 2.

- This is however impractical for two reasons :
  - requires momentary interruption of active connections which may be unacceptable to the users
  - finding a rearrangement which will “open up” the network to the new connection request typically requires solving an extremely complex combinatorial problem.

- We thus do not rearrange switched connections

Routing and wavelength assignment - WRNs

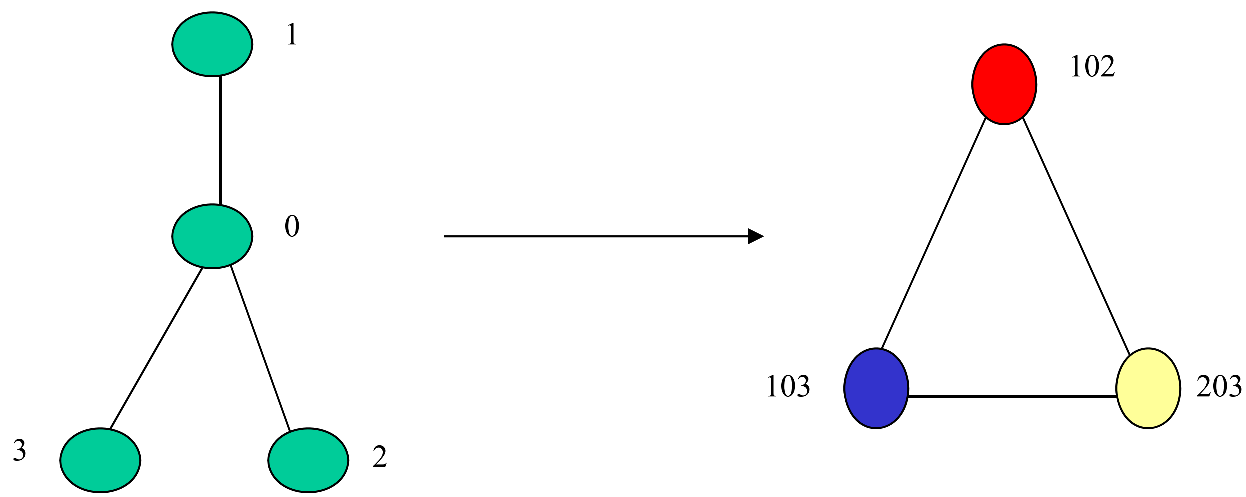
- **Relation of wavelength assignment to graph coloring :**
  - Transform graph G to graph P(G) : Each path becomes a node and there is a link between two nodes in P(G) if they share a common edge in their paths in G
  - Graph color graph P(G) : assign a color to each node of P(G) such that adjacent nodes are assigned distinct colors and the number of colors is minimum.
  - Minimum number of colors needed to color the nodes of a graph in this manner is called the chromatic number of a graph.
  - The minimum number of wavelengths to solve the WA problem of G is the chromatic number of P(G)

Routing and wavelength assignment

- **Example :**

Graph G :

Path Graph P(G) :

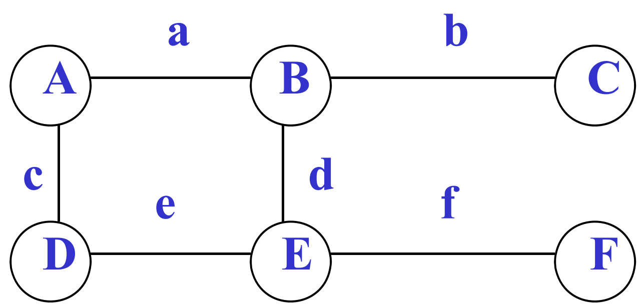


Paths (103), (102), (203)

Chromatic index = 3
# of wavelengths required = 3

Routing and wavelength assignment

- **Second Example :**



Connections (A,C), (A,F), (A,E), (C,E) requested

- **Only minimum hop paths are admissible.**

p1 = ab p2 = adf p3 = cef

p4 = ce p5 = ad p6 = bd

- **These are all the admissible fiber paths that support the required connections**

Routing and wavelength assignment

(A,C) is supported by p1

(A,F) is supported by p2 or p3

(A,E) is supported by p4 or p5

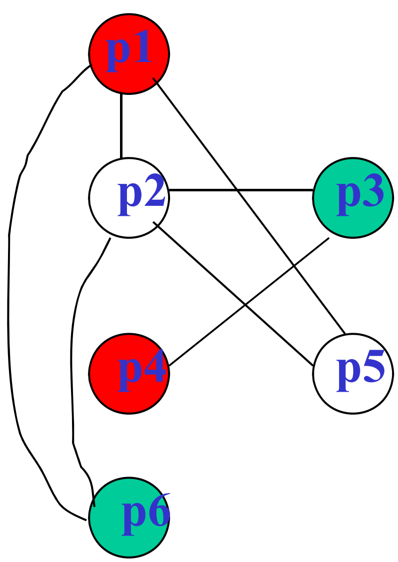
(C,E) is supported by p6

(A,C)

(A,F)

(A,E)

(C,E)



Minimum number of colors = 2 so the minimum number of wavelengths required is also 2

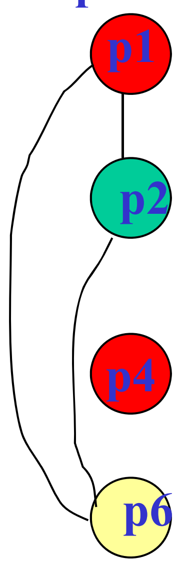
Routing and wavelength assignment

- In this case, the joint problem was solved by inspection.
- However, this is a very complex combinatorial problem.
- For example, consider the “brute force” approach :
  - Make an arbitrary choice of vertices of P(G) (a routing assignment) to satisfy the connection requirements. Form the subgraph P(G)’ induced by these vertices.
  - Determine the chromatic number of this subgraph
  - Repeat this process for all choices of vertices of P(G) and select a routing assignment that produces a subgraph with minimum chromatic number
  - Do a minimal vertex coloring (wavelength assignment) of the subgraph.

Routing and wavelength assignment

- Break the problem in two Routing and Channel Assignment (independent)

- Example : (Suppose I choose path with lowest indicator number) :



Number of colors to color all vertices is now 3

- In this case, 3 wavelengths instead of two are required to assign all connections (sub-optimal solution)

Routing and wavelength assignment

- Coloring an arbitrary graph is an NP-complete problem.
- It was also shown (by transformation) that the WA problem is also NP-complete.
- Exact solutions can be found for some topologies and approximate solutions for other using heuristics.

Heuristics for Static RWA

EXAMPLE :

- Separate RWA into its two sub-problems and confine all routes to shortest (minimum optical hop) paths

- Given a list of M prescribed logical connections among s-d node pairs, the routing algorithm attempts to minimize fiber congestion (number of paths using any one fiber), which tends to minimize the number of required wavelengths.

- Process can be adaptive or non-adaptive (fixed)

Heuristics for Static RWA

- **Adaptive routing schemes incorporate the current network state information to find a path and a wavelength assignment for a connection**

HEURISTIC 1 :

- **An adaptively sorted wavelength set is searched sequentially.**
- **On each wavelength, the algorithm searches for the shortest path available at the time of the connection establishment**
- **Once a path is found on some on some wavelength, the connection is established**
- **If after exhausting the wavelength set no path is found, the session is blocked**

Heuristics for Static RWA

- The wavelength set is sorted to implement one of four schemes :
  - Pack : Algorithm attempts to allocate the most utilized wavelength first in an attempt to maximize the utilization of the available wavelengths
  - Spread : Algorithm attempts to allocate the session to the least utilized wavelength first in order to achieve near-uniform distribution of the load over all wavelengths
  - Random : Algorithm searches the wavelength-set in a random order (all permutations of the wavelength set are equally likely)
  - Exhaustive : All wavelengths are searched for a shortest path, and the shortest path amongst them is selected

Heuristics for Static RWA

HEURISTIC 2 :

- List all connections in random order and compute all minimum hop paths for each connection
- Assign a minimum hop path to each connection
- For each connection on the list :
  - Substitute an alternative minimum hop path from the one previously assigned iff the number of connections (congestion) on the most loaded link in the alternate path is lower than the congestion of the most loaded link in the previously assigned path

Heuristics for Static RWA

- Repeat the previous step until no further substitutions are possible

- Once the paths are assigned, a wavelength assignment algorithm is executed making assignments to the longest paths first. The steps are as follows :

  - Group paths with same lengths into common sets, and rank the sets in decreasing order of length.
  - Assign a numerical order to the wavelengths
  - Randomly select a path from the first set
  - Assign to the selected path the lowest numbered wavelength previously unused on any link in the path
  - Continue this wavelength assignment process for all paths in the first set. Then repeat for the next and subsequent sets, until all assignments have been made.

Heuristics for Dynamic RWA

- Under dynamic traffic conditions, a sequence of connection requests arrives in a random fashion
- These requests may or may not be accommodated, depending on the current state of the network
- Network state consists of all active connections and their optical path (route and wavelength) assignments
- If a request cannot be accepted, it is blocked

Heuristics for Dynamic RWA

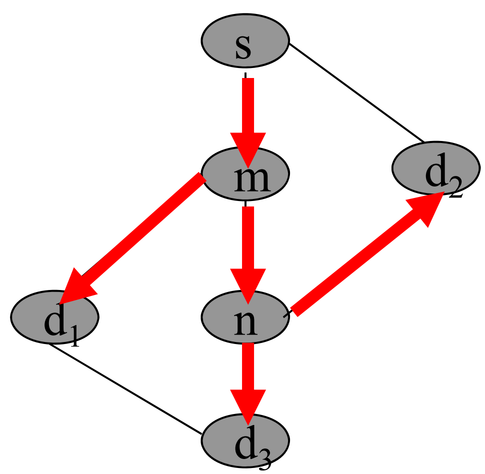
- **Virtually all dynamic algorithms are special cases of the following :**
  - **Arrange all admissible fiber paths for a given s-d pair in some prescribed order in a path list**
  - **Arrange all wavelengths in some prescribed order in a wavelength list**
  - **For each connection request, choose the first entry in the path list that is feasible given the network constraints and the current state of the network**
  - **Assign the first entry in the wavelength list that does not violate the DCA (assuming always wavelength continuity here) constraint for the chosen path.**

Heuristics for Dynamic RWA

- The paths can be listed in an increasing order of path lengths where the summation of the link weights over a path is defined as the path length
- Link weights can be assigned from a number of parameters, thus there is wide range of possibilities in selecting paths
- For example, the load (or interference) on a link (number of active connections sharing the link) can be used (Least Loaded Routing Alg.)
- Also, interference lengths of the paths sharing the link (number of hops of pairs of interfering paths) etc.

Multicasting in Wavelength-Routed Networks

- **Multicasting refers to one-to-many connectivity.**
- **A light-tree that spans the source and the destination set (on a specific wavelength) is used to serve the multicast request.**



• multicast connectivity is more efficient (light-trees) rather than using equivalent unicast connections for each destination:

- •no message replication.
- •less resources

Multicasting in Wavelength-Routed Networks

- **Finding the multicast tree is equivalent to finding the least-cost tree.**

- **The calculation of these least-cost multicast trees is a fundamental problem in graph theory called the "Steiner Minimal Tree" (SMT) problem.**

- **The SMT is an NP-complete problem when the multicast group has more than 2 members and less than the entire set of network nodes (as the spanning tree problem also has a polynomial time solution)**

Steiner Tree Heuristic

- **Finds a tree spanning the set $D=\{s, d_1, d_2, \ldots d_k\}$, where s is the starting node and $d_{1\text{-}n}$ the destination nodes.**
- **Several heuristics exists for finding the minimum Steiner tree.**
- **Time complexity (of the next heuristic) is O(kn^2) where k is the number of destination nodes and n is the number of nodes in the graph.**

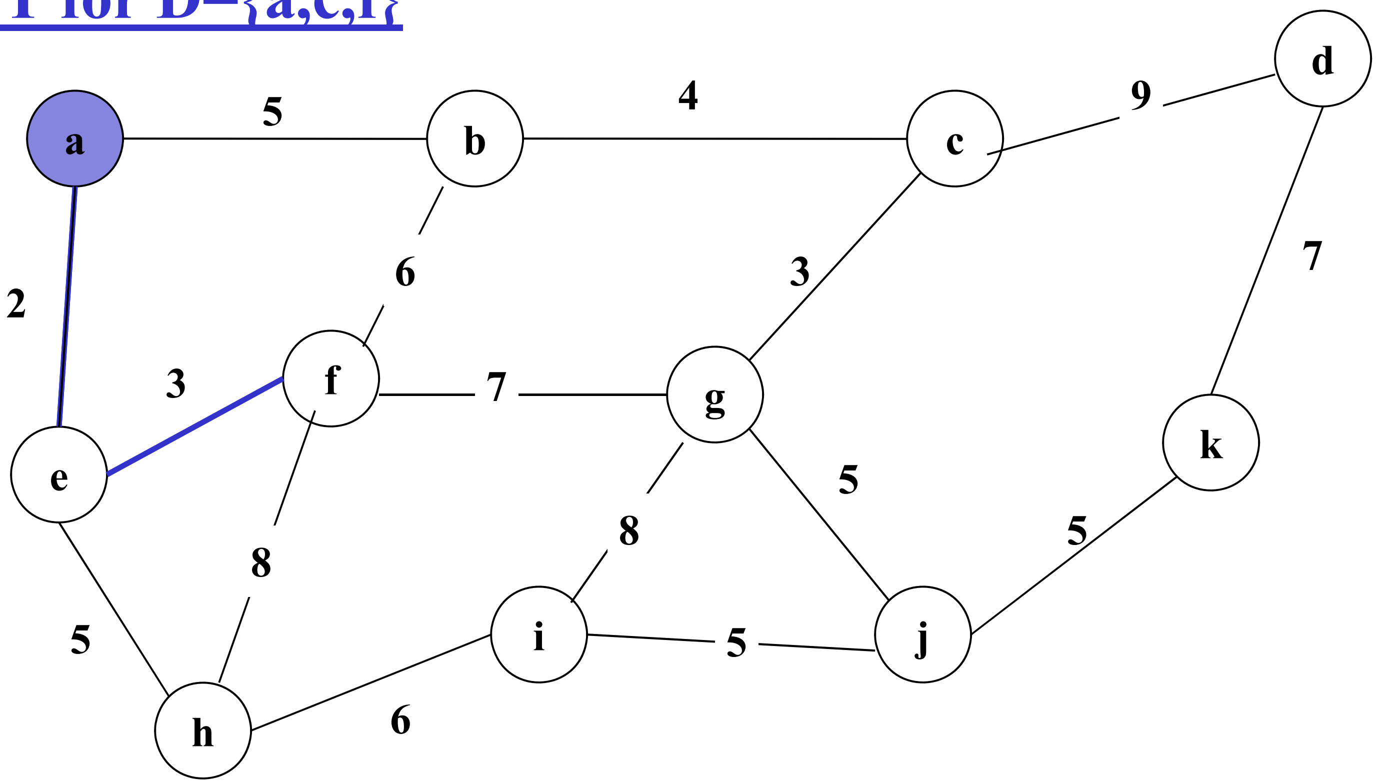
Steiner Tree Heuristic

- Input: G = (V,E), D=[s,d1,d2,…dk].
  Output: Tree T spanning the set D.

1. T={s}, m=0.
2. Calculate all shortest paths from every node in T to every destination node in D.
3. Choose the shortest path amongst them and add it to T
4. Identify node dj last added to T
5. Remove destination node dj from D
6. m = m + 1.
7. If m<k then repeat steps 2to 6.

Steiner Tree Heuristic Illustrated

ST for D={a,c,f}

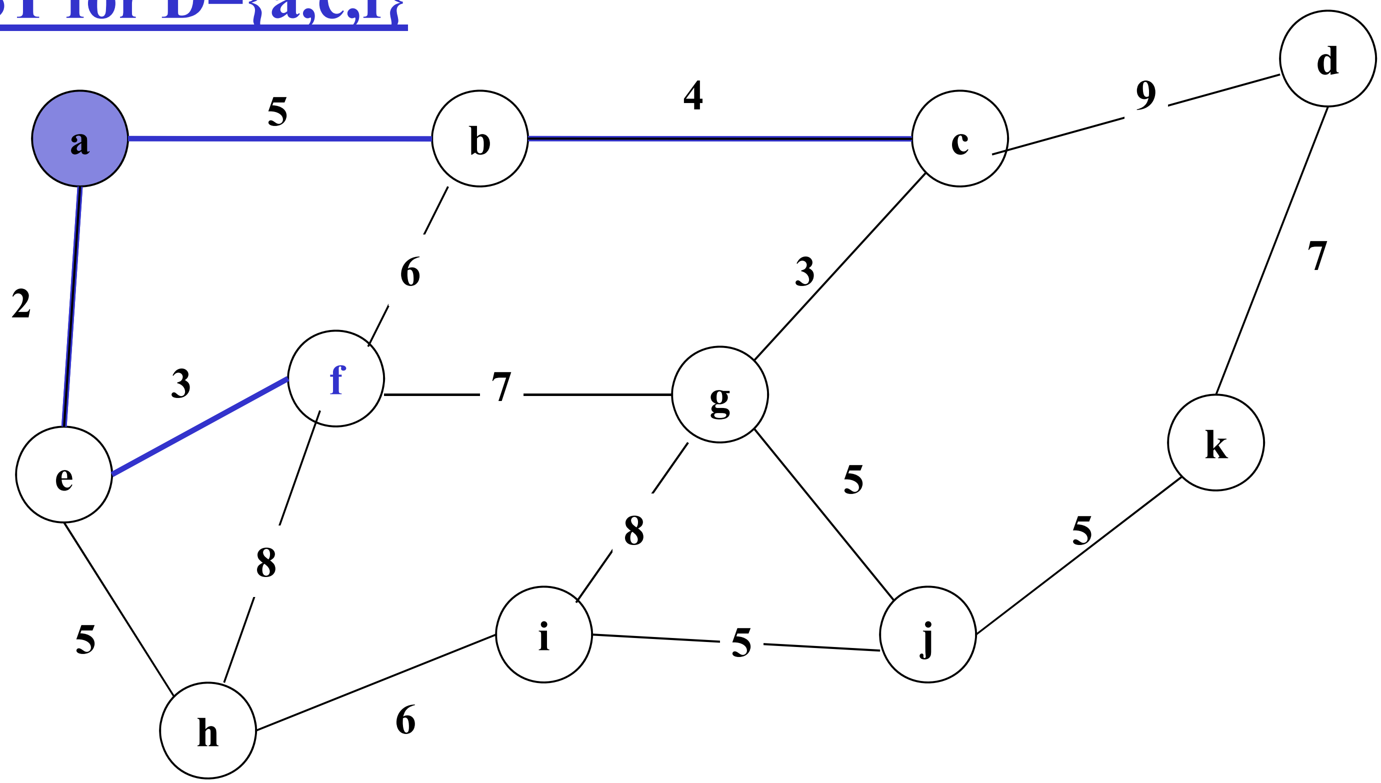


Shortest paths from T={a} to D={c,f} :
Path (a-c)={a,b,c} cost(a-c)=9
Path(a-f)={a,e,f} cost(a-f)=5

→ T={(a,e,f)}, D={c}

Steiner Tree Heuristic Illustrated

ST for D={a,c,f}



Shortest paths from T={(a,e,f)} to D={c} :
Path (a-c)={a,b,c} cost(a-c)=9
Path(e-c)={e,f,g,c} cost(e-c)=13
Path(f-c)={f,g,c} cost(f-c)=10

→ T={(a,e,f),(a,b,c)}, D={}

Failure Recovery – Protection/Restoration

Motivation (I)

- As we become more dependent on communication networks, it is crucial that we make these networks more reliable and the service supported on these networks more available
  - human-to-human, human-to-machine, machine-to-machine interaction
  - C2C, B2C, B2B
  - Social networking, entertainment, shopping, trading, searching, access to information; etc…
- Each self-recovery mechanism used for network survivability offers trade-offs in terms of availability, recovery latency, scalability, and cost.
  - We are looking for fault recovery methodologies that are fast and capacity efficient.

Motivation (II)

- Fiber-optic transmission systems are cable-based technologies that are subject to frequent damage

- Due to the introduction of WDM to commercial networks, each fiber can carry an extremely high volume of traffic. Thus, a failure can potentially affect a large number of customers causing devastating effects to the network.
  - For example, for 10Gb/sec/channel and 160 channels/fiber, we have 1.6Tb/sec/fiber. If a cable carries approximately 100 fibers, a cable cut will result in the loss of about 160Tb/sec
    - 10^9 (one billion!) voice equivalent circuits
  - Fiber cuts may be the result of a variety of reasons (construction work, rodents, fire, human error etc.)
    - FCC statistics: 13 cuts/1000 miles/year (metro); 3 cuts/1000 miles/year (long distance (LD))
    - Typical LD network with 30,000 route-miles of fiber experiences a fiber cut every 4 days on average

- Equipment failure can also occur and in general they affect many more customers than cable cuts
  - Equipment failures can result from earthquakes, floods, fires, hardware degradation or human error

Motivation (III)

- 1988 fire that destroyed Illinois Bell's Hinsdale switching office
  - happened on one of the busiest days of the year (Mother's day)
  - took more than a month to completely repair
- 1987 fire that damaged New York Telephone's Brunswick switching office
- 1987 AT&T switching computer failure in Dallas.
- Destruction of a key Verizon call and data-switching center in lower Manhattan on September 11, 2001.
  - 200,000 voice lines for homes and small businesses
  - 100,000 voice lines for several large businesses
  - data services with a capacity equivalent to 3.5 million circuits.
  - 500 copper and fiber-optic cables originated or passed-through the center
  - 300 copper and fiber-optic cables were damaged
- Several undersea cable failures in the past few years
  - December 27, 2006: Due to Taiwan Earthquake
  - January 30, 2008: In Mediterranean Region
  - December 19, 2008: Again in Mediterranean Region

Motivation (IV)

[source: Internet Society Global Internet Report 2014]

•2011 an elderly woman in Georgia inadvertently severed the main terrestrial fiber cable link to Armenia, cutting off the Internet in the country for five hours.

• A cut in the SEA-ME-WE 4 cable near Alexandria, Egypt, resulted in a significant slowdown of the Internet in Africa, the Middle East, and parts of Asia. In this case, there are multiple cables providing resilience, but several were being maintained, and thus could not provide diversity when needed.

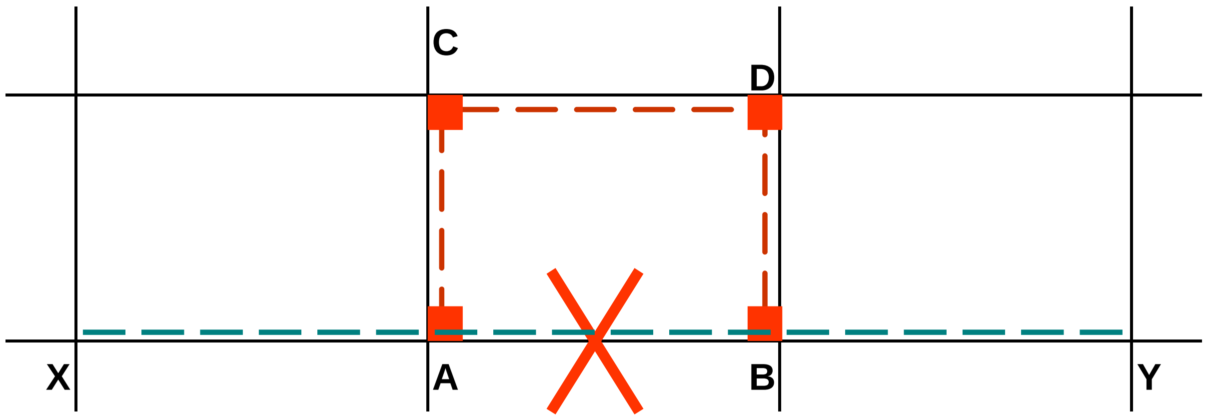
Motivation (V)

- Failures cost companies millions of dollars in business
  - Revenue losses by their customers during the outage
  - Diminished customer confidence in the companies' services

- Carriers are now bound to service-level agreements (SLAs) with their customers guaranteeing that the customer will be provided with services with a prescribed service availability
  - 99.999% availability - equivalent to less than 5 minutes of down time per year
  - Financial penalties if the availability SLA is not met (typically credit for the monthly price of the service, or ability to cancel the contract without penalty if carrier fails to meet SLA several months in a row)

Industry	Average Loss Per Hour
Brokerage Operations	$6,450,000
Credit Card Authorizations	$2,600,000
eCommerce	$240,000
Package Shipping Services	$150,250
Home Shopping Channels	$113,750
Catalog Sales Center	$90,000
Airline Reservation Center	$89,500
Cellular Service Activation	$41,000
ATM Service Fees	$14,500
Source: Contingency Planning Association Research	

Basic Recovery Concepts



- **Recovery Requires**
  - **Fault detection**
    - **Loss of Light (LoL), Loss of Signal (LoS), BER threshold**
  - **Spare capacity**
    - **How much ?**
  - **Switch fabric to put failed circuits on spare capacity**
  - **Control logic to reroute failed circuits**
    - **Protection vs. restoration**

Fault Detection/Isolation

- Problem : In transparent optical networks the effect of a failure propagates from the primary source of failure downstream to all the nodes that are participating in paths using the faulty node
- Faults propagate quickly to different paths of the network raising a large number of alarms.
- Given this set of alarms we are looking for methods to identify the fault quickly.
- Deterministic and probabilistic approaches have been proposed.

Fault Protection vs Restoration

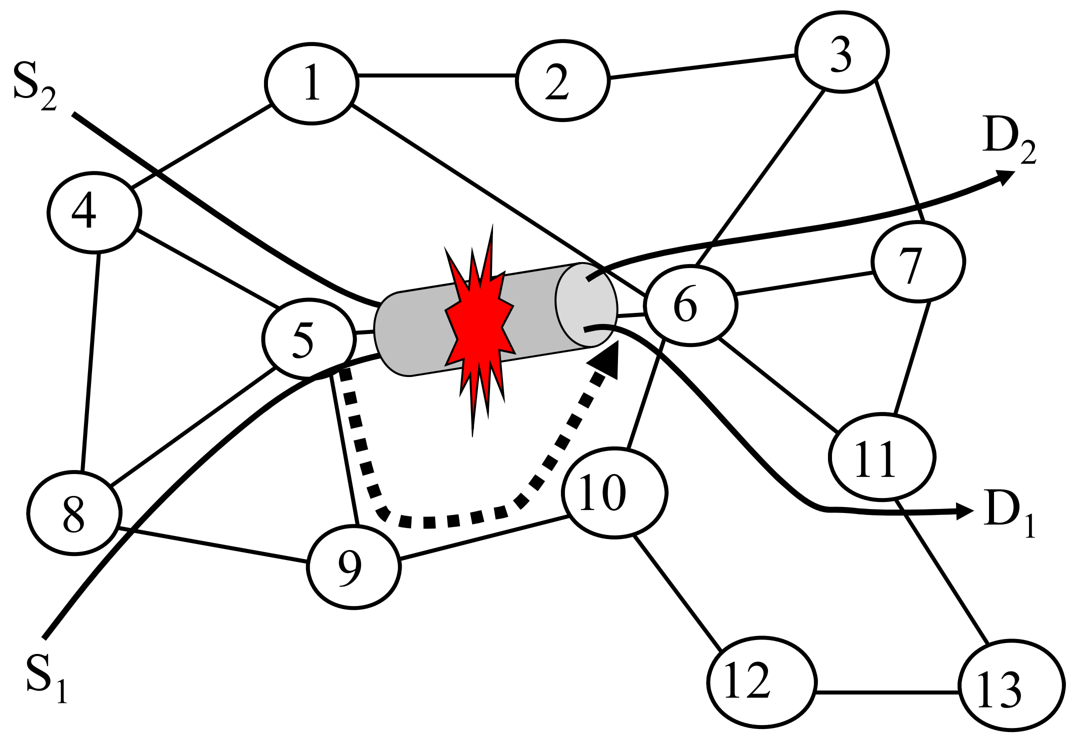
- **Protection** refers to a pre-planned system where a protection path is pre-computed for each potential failure (before the failure occurs) and the path uses pre-assigned resources for failure restoration (dedicated for specific failure scenarios or shared among different failure scenarios).

- **Protection** signifies that it is based on 100% redundancy and physical layer Automatic Protection Switching (APS) is used to automatically switch the traffic to protection facilities

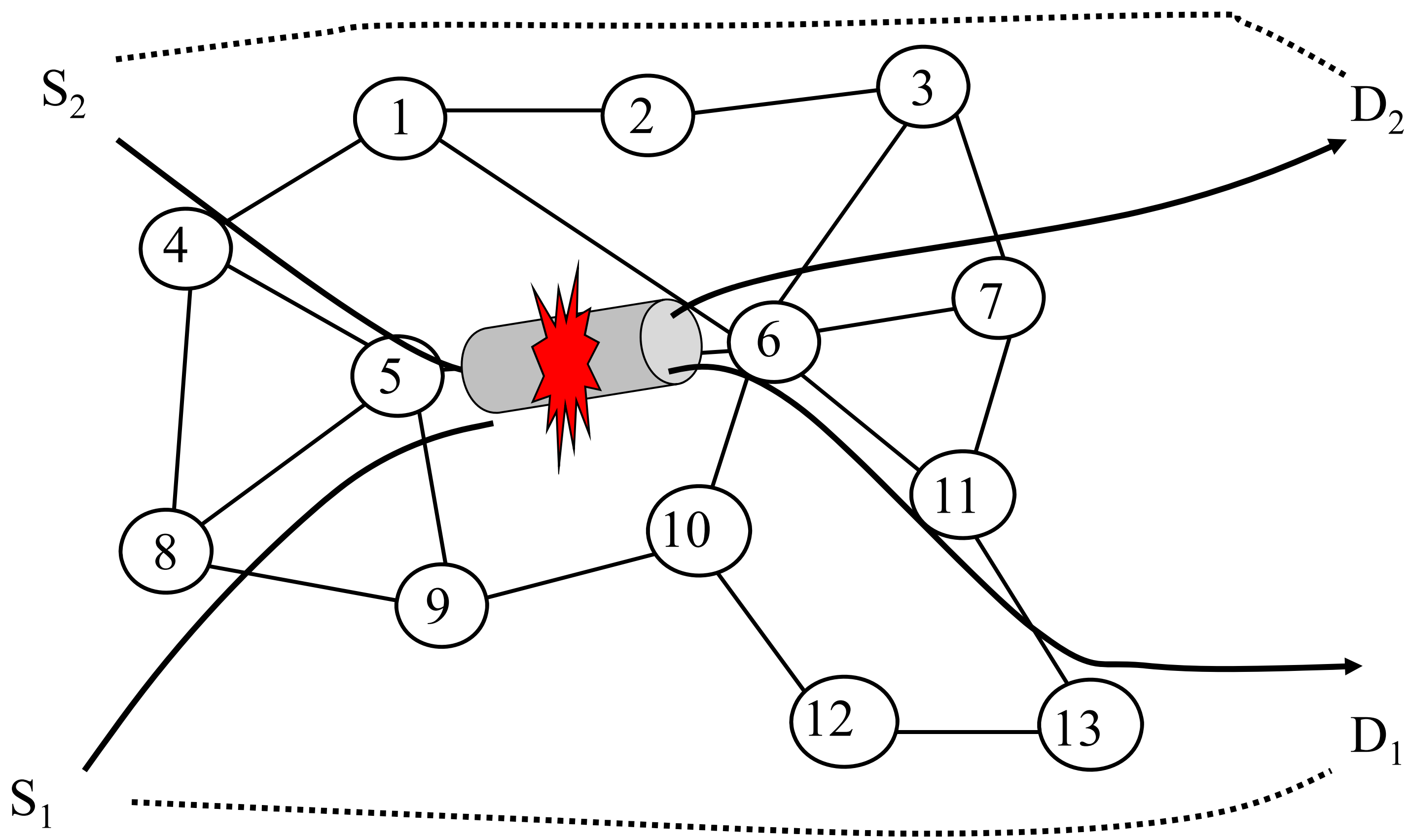
- In **restoration**, the protection route is computed in real time (after the failure occurs) and spare capacity available in the network is used to reroute traffic around the failure

- **Restoration** signifies that it is based on reconfigurable cross-connects (switching equipment and spare capacity in conjunction with a re-routing scheme are used to re-route traffic in (mainly) mesh networks in the event of a failure)

Line-based Recovery



Path-based Recovery



Line- vs. Path-based Recovery

- Characteristics of line-based recovery
  - Generally recovers link failures only.
  - All traffic carried on failed link is recovered as a single unit.
  - 100% reserved recovery capacity is generally required (e.g. in ring- or cycle based protection).
  - Recovery is simple and fast.
  - Signaling and processing overhead is very low or non-existent.

- Characteristics of path-based recovery
  - Recovers both link and node failures.
  - Each connection carried on failed link/node is recovered individually.
  - Working and protection paths must be disjoint from source to destination.
  - Usually requires less than 100% reserved recovery capacity (if recovery capacity is shared).
  - Recovery is complex and slow.
  - Signaling and processing overhead is high.

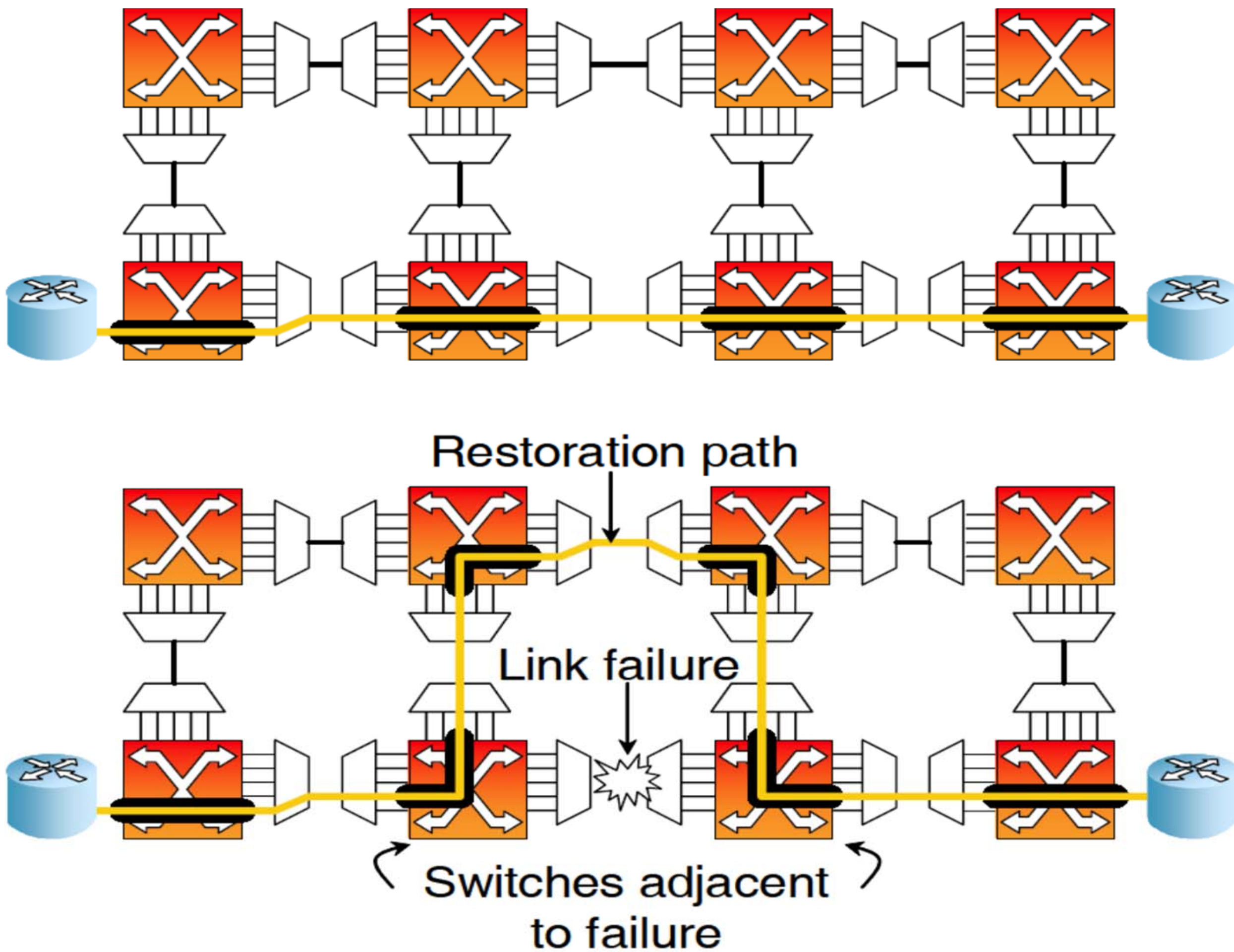
Line (Link) Recovery in Mesh Networks - Disadvantages

- It has the disadvantage of requiring 100% redundancy (1 protection fiber for one working fiber)
- Require different processes for link and node failures
- Difficult to provide recovery from a node failure
- Does not allow for shared mesh recovery (share the redundant capacity among a number of different connections)

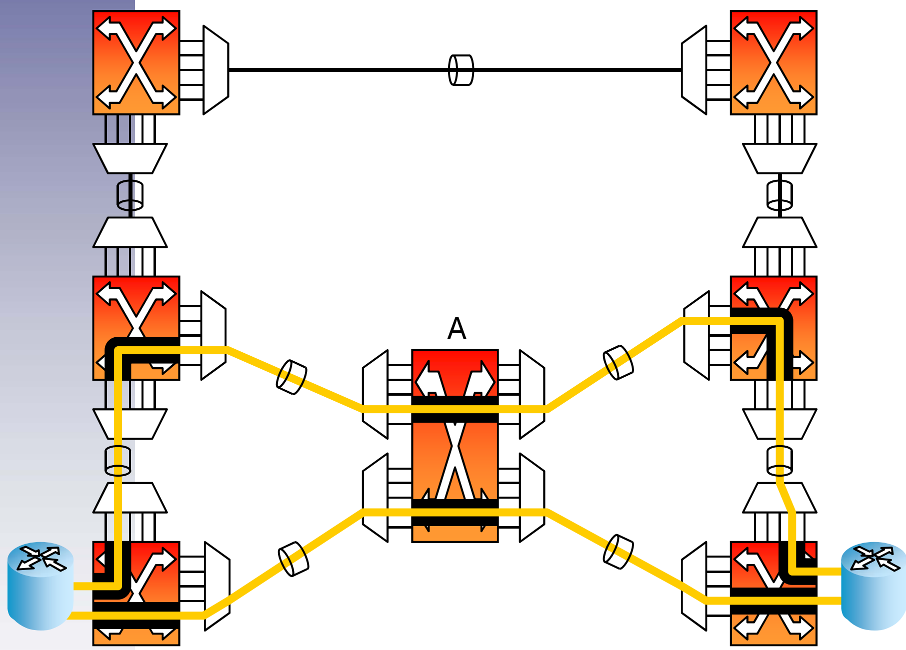
Path Recovery

- Restoration is performed on a per-wavelength basis, allowing for a finer recovery granularity.
- The path-switched approach performs better in terms of network switch failures.
- Allows for shared-mesh recovery.
- Same recovery process for link and node failures.
- Redundant capacity required is much less compared to the line-switched approach.

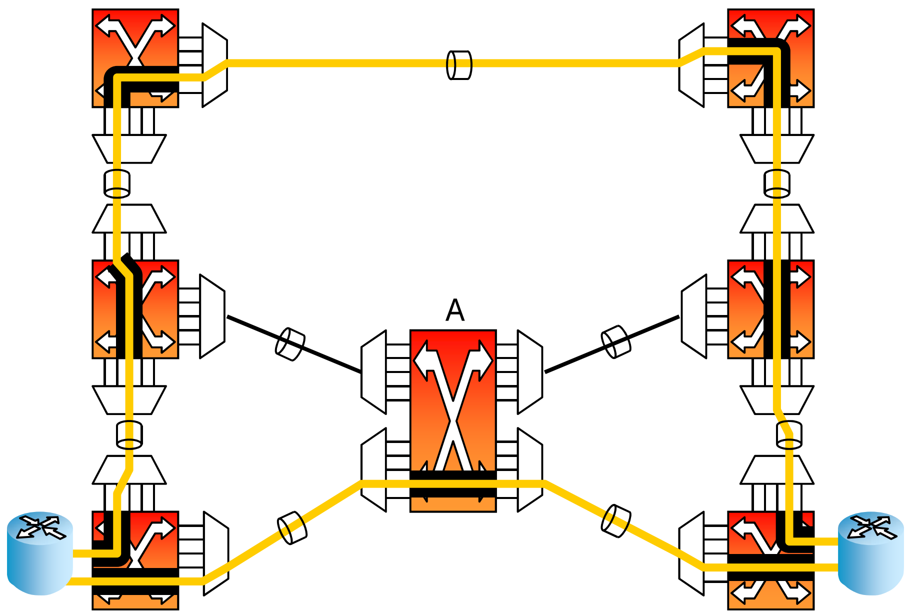
Link-Based Protection



Path-Based Protection – Path Diversity

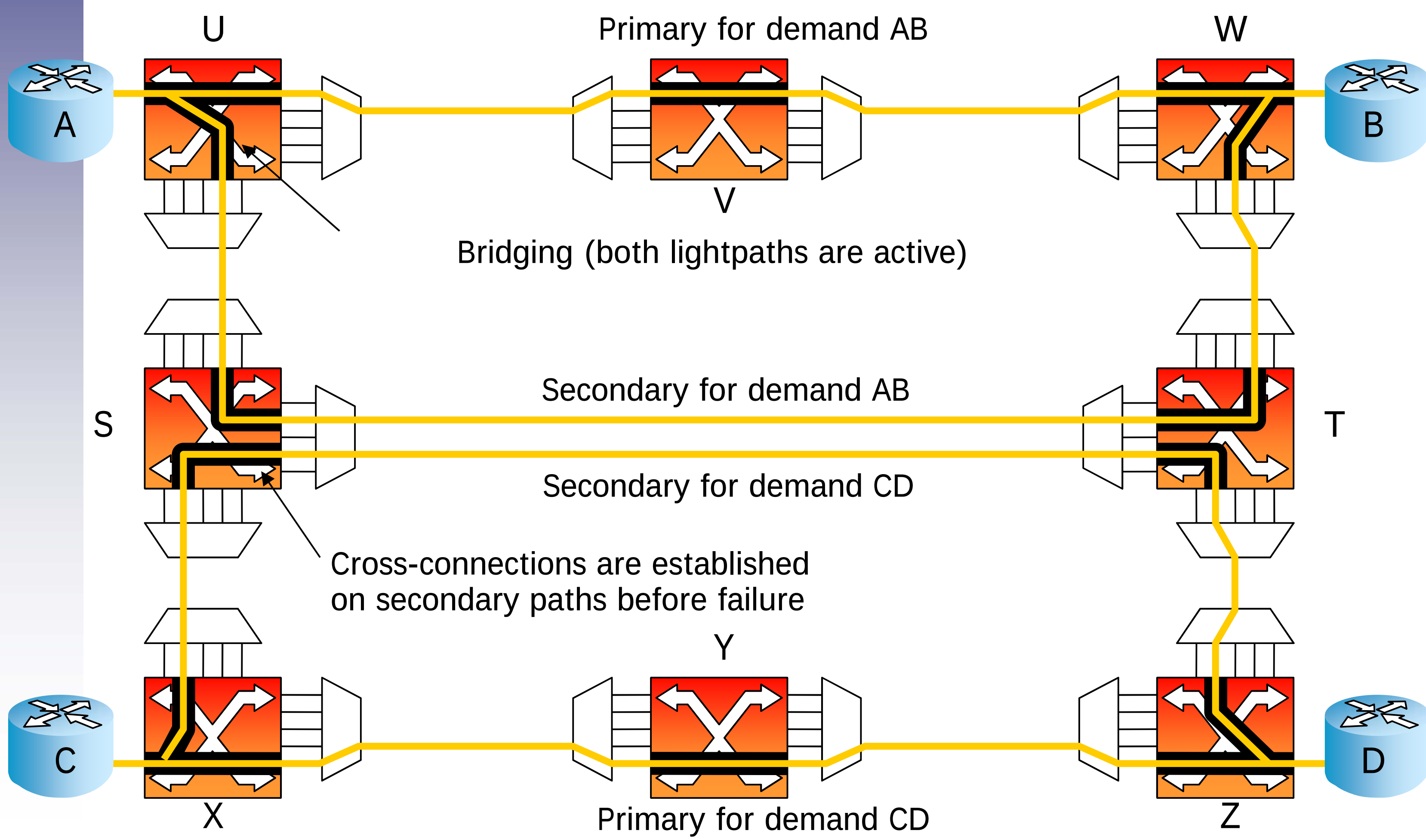


Link-diverse paths

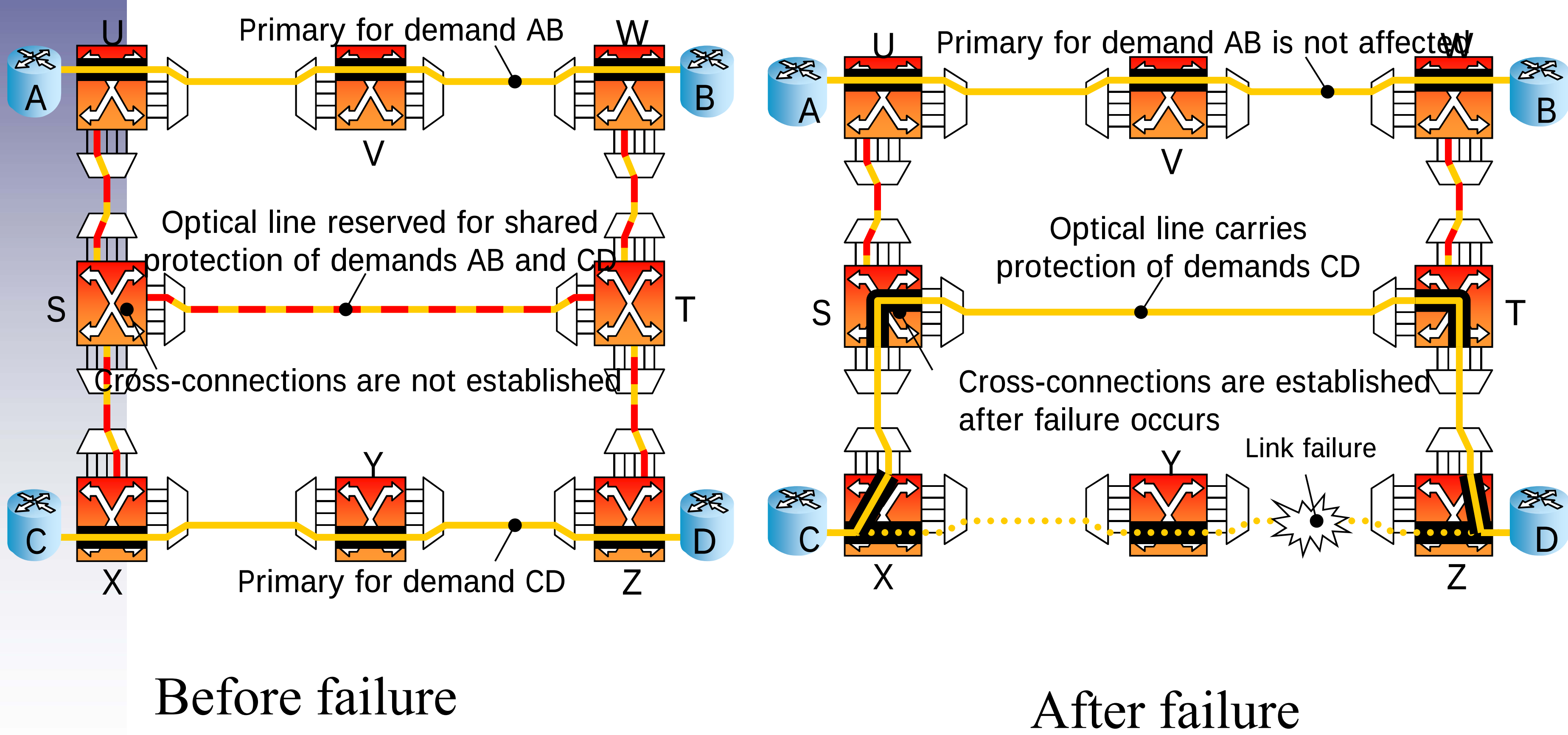


Node-diverse paths

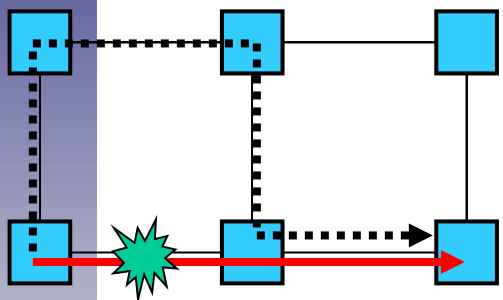
Path-Based Protection
Dedicated Backup Path



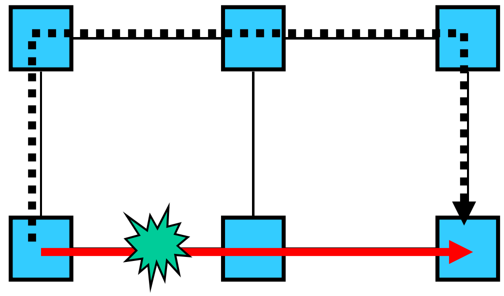
Path-Based Protection
Shared Backup Path



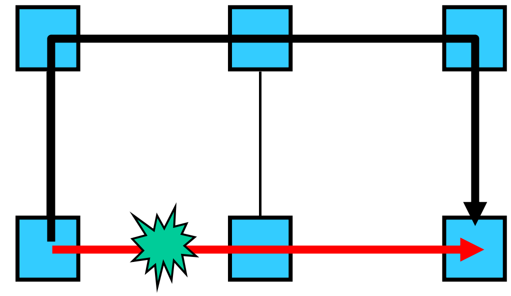
Path vs. Segment Protection



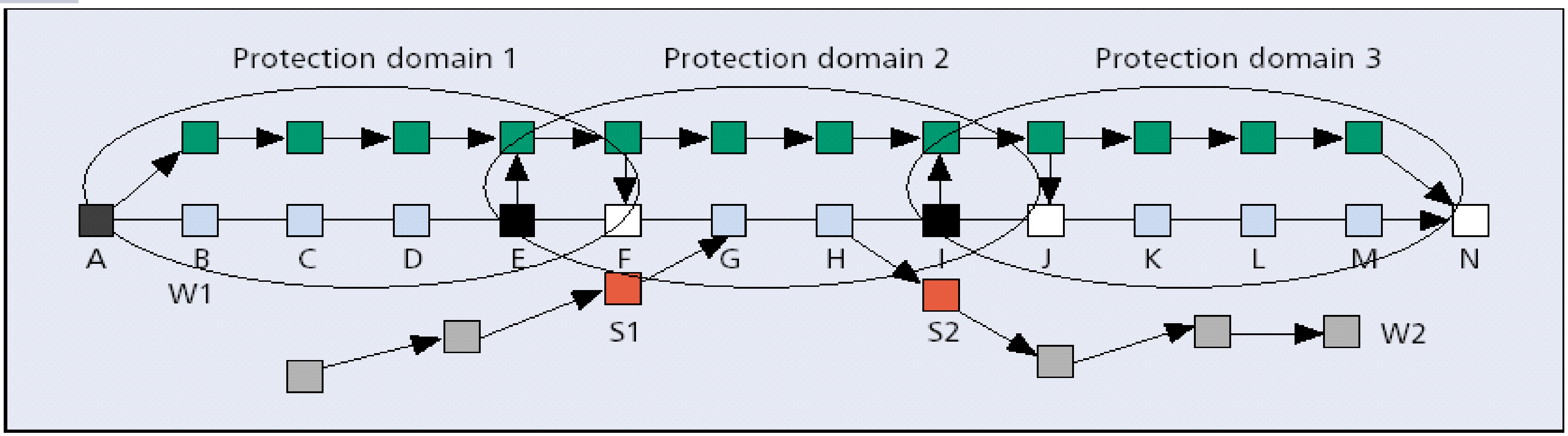
(a) Link Recovery



(b) Shared Backup Path Protection



(c) Dedicated Backup Path Protection

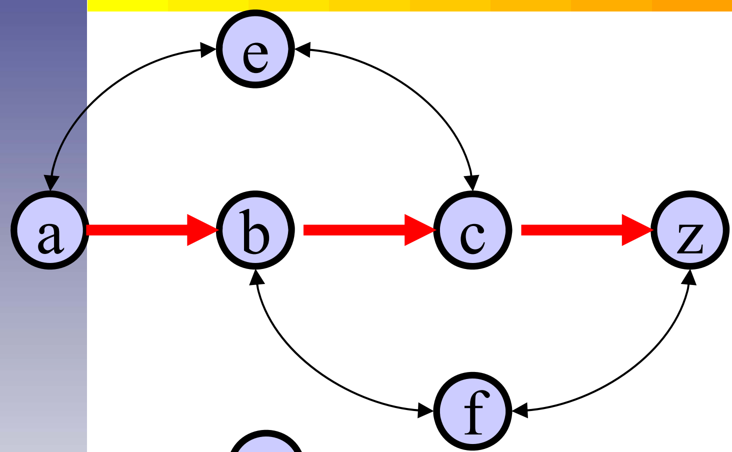


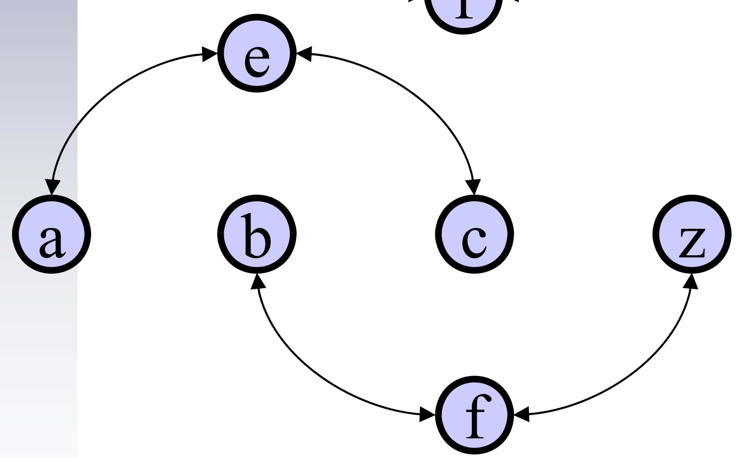
(d) Segment Protection

Diverse-Path Routing – Edge Diverse Paths

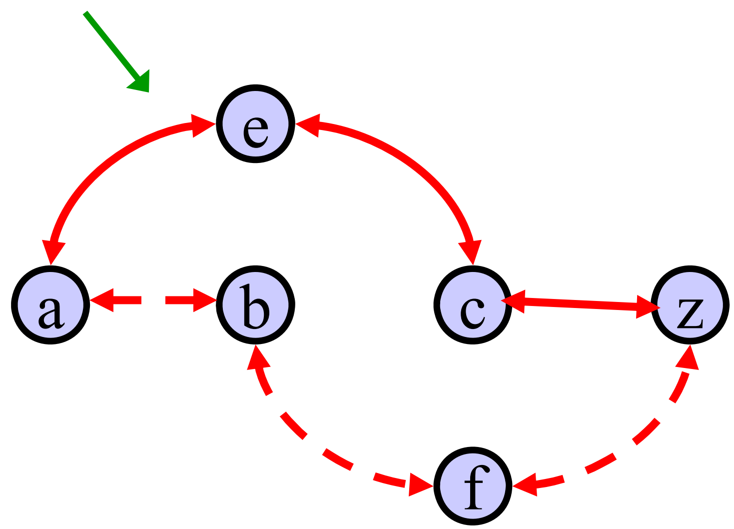
- Often, it is necessary for each circuit to find an alternate backup path onto which the circuit can be deviated if a failure occurs along the working path
- The backup path should be diverse as much as possible from the working path in order to limit the risks that both become simultaneously affected by a same failure
- Simple two-step method - compute a working path, then compute a disjoint backup path – does not always return the most cost efficient solution, and sometime even fails to return one
- Suurballe algorithm finds the working and backup paths with minimum aggregated weight if such a pair exists
- Suurballe algorithm uses an augmenting flow method similar to Ford-Fulkerson's, with unit flows and capacities

Diverse-Path Routing –
Drawbacks of Two-Steps Methods





After computing the working path using a shortest path algorithm, and removing the edges to compute the backup. The residual graph becomes disconnected, and we find no corresponding backup path even though one exists.



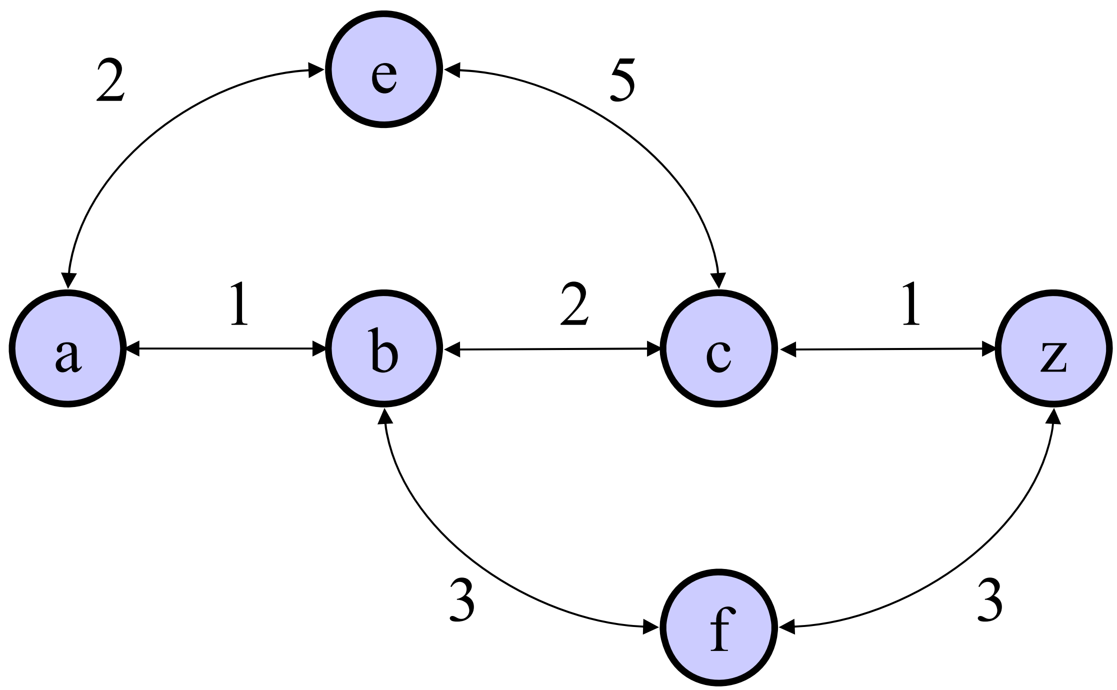
Diverse-Path Routing – Suurballe Algorithm

<u>**Suurballe(a,z,G)**</u>

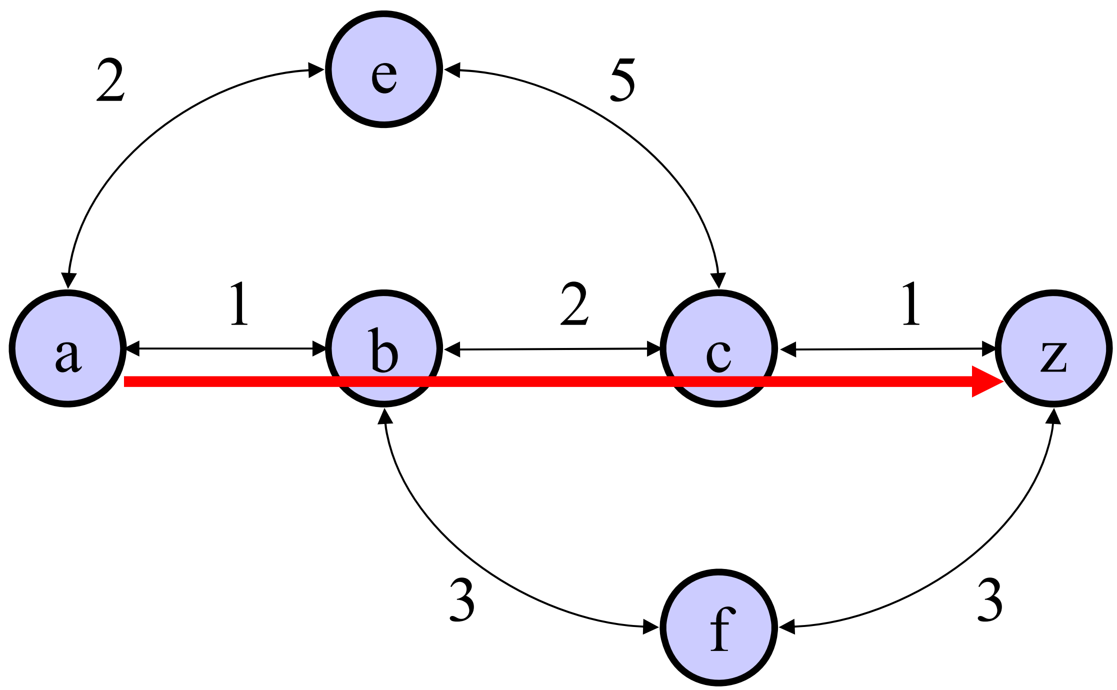
1. P_w = Dijkstra(a,z,G).
2. Create G’ from G as follow: orient all edges traversed by P_w to the direction opposed to P_w, and reverse the sign of their weight.
3. P_b = BellmanFord(a,z,G’).
4. Create G” from G’ as follow:
   - orient all edges traversed by P_b to the direction opposed to P_b, and reverse the sign of their weight.
   - Remove all edges that have positive weights.
5. Apply simple “two-step” BFS(z,a,G”) to construct the working then the backup path.

(without loss of generality, assume undirected graph)

Diverse-Path Routing – Suurballe algorithm Illustrated

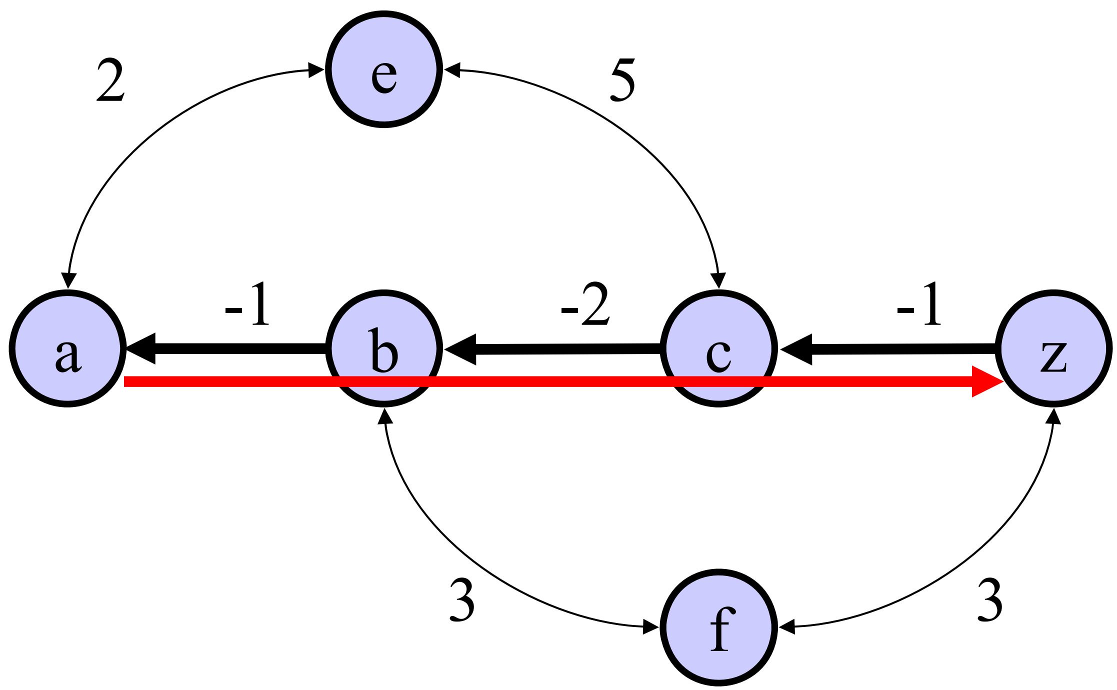


Diverse-Path Routing – Suurballe algorithm Illustrated



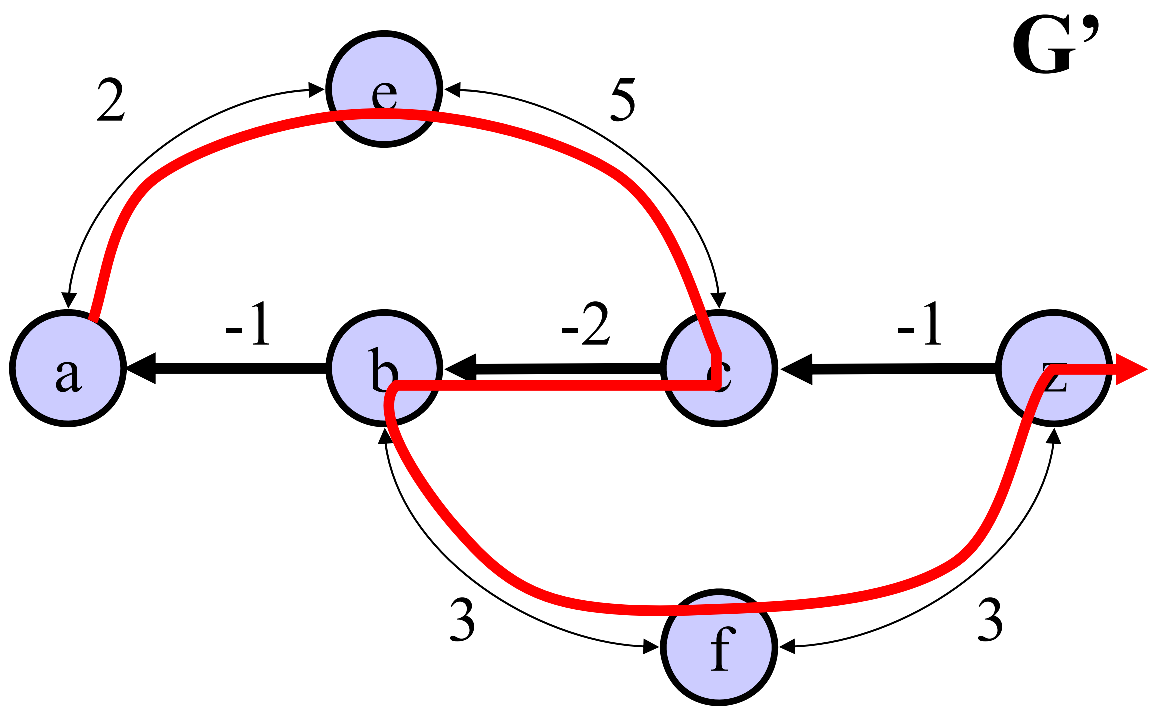
Compute min weight working path (a,z) = (a,b)+(b,c)+(c,z) Total weight of path=1+2+1=4.

Diverse-Path Routing – Suurballe algorithm Illustrated



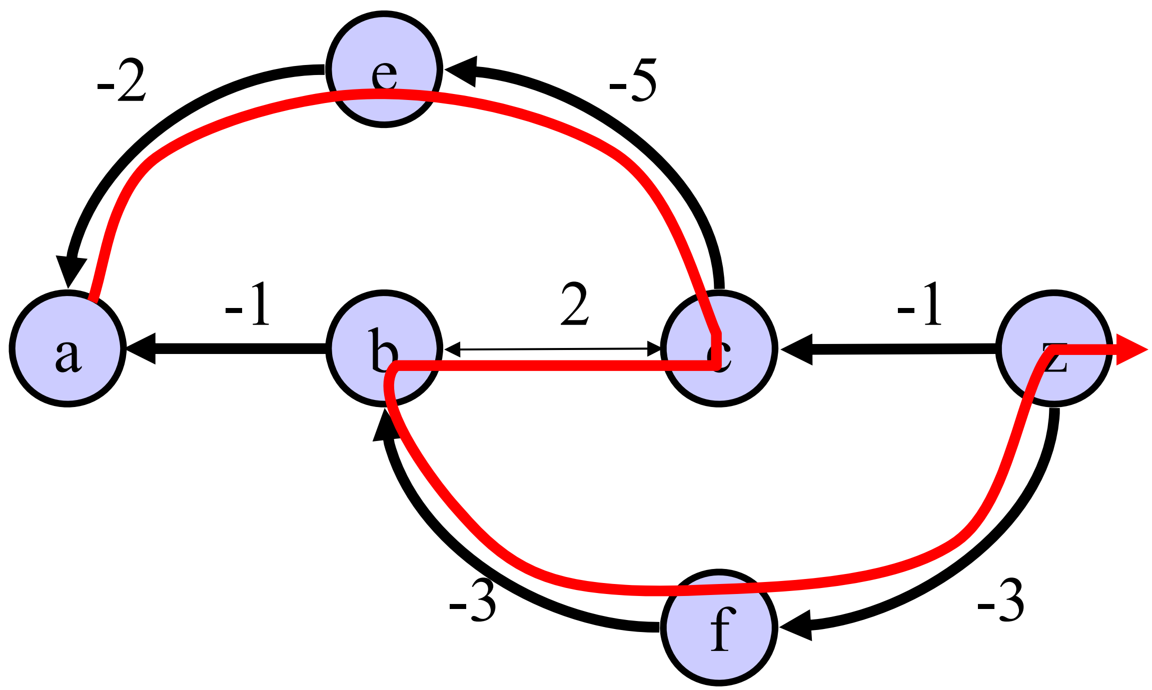
Edges (a,b), (b,c) and (c,z) are oriented backward, and the sign of their weights is reversed.

Diverse-Path Routing – Suurballe algorithm Illustrated



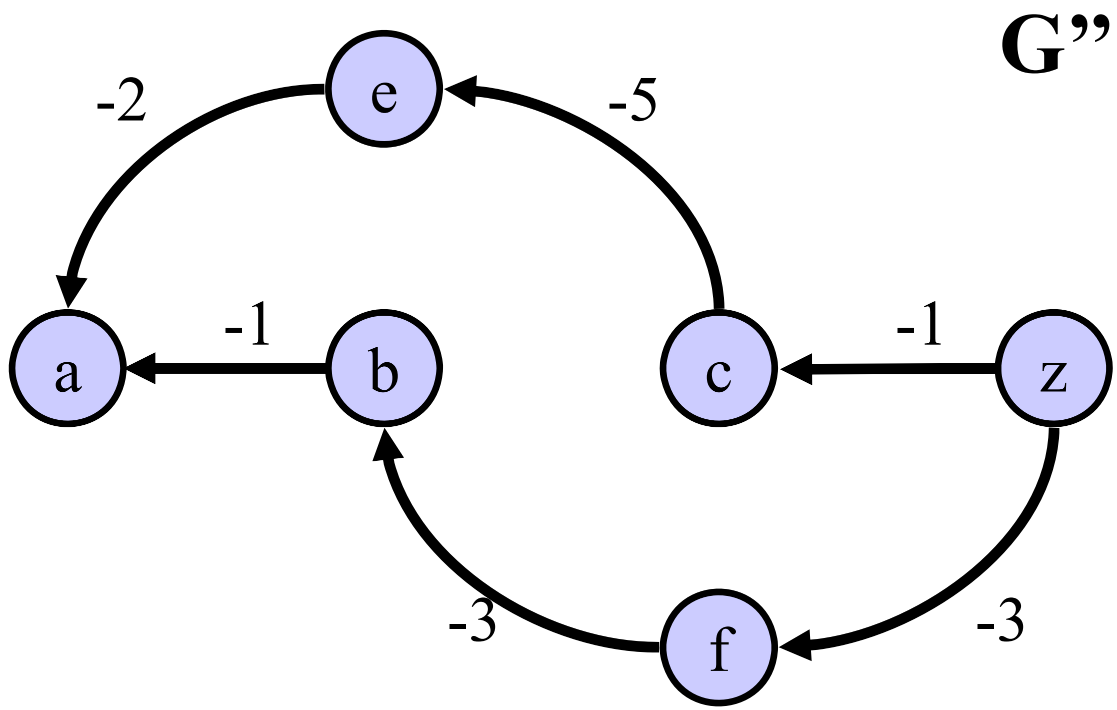
Compute min weight backup path (a,z) = (a,e)+(e,c)+(c,b)+(b,f)+(f,z)
Total weight of path=2+5-2+3+3=11. The negative weight indicates that the edge is "removed" from the working+backup path solution.

Diverse-Path Routing – Suurballe algorithm Illustrated



Edges (a,e), (e,c), (c,b), (b,f) and (f,z) are oriented backward, and the sign of their weights is reversed. Edge (b,c) was negative, therefore its weight becomes positive and thus is removed.

Diverse-Path Routing – Suurballe algorithm Illustrated



Construct G” by removing all edges that have positive weights.
Apply two-step BFS(z,a) in graph G”.

Diverse-Path Routing – Suurballe Algorithm Summary

- Guaranteed to find the minimum weighted working + edge diverse backup path if one exist
- Can be adapted to compute node-diverse backup path by way of pre-and post-routing graph-transformations
- Requires that edges have same weights for working and backup paths. Solution is sub-optimal if weights are asymmetric
- Finds a pair of edge diverse paths, or finds nothing. Not suitable for a “best-effort” solution which minimizes diversity violations
- Not appropriate for computing diverse paths through arbitrary sets of edges or nodes, known as Shared Risk Groups (SRG), that are susceptible to be affected by a common equipment failure

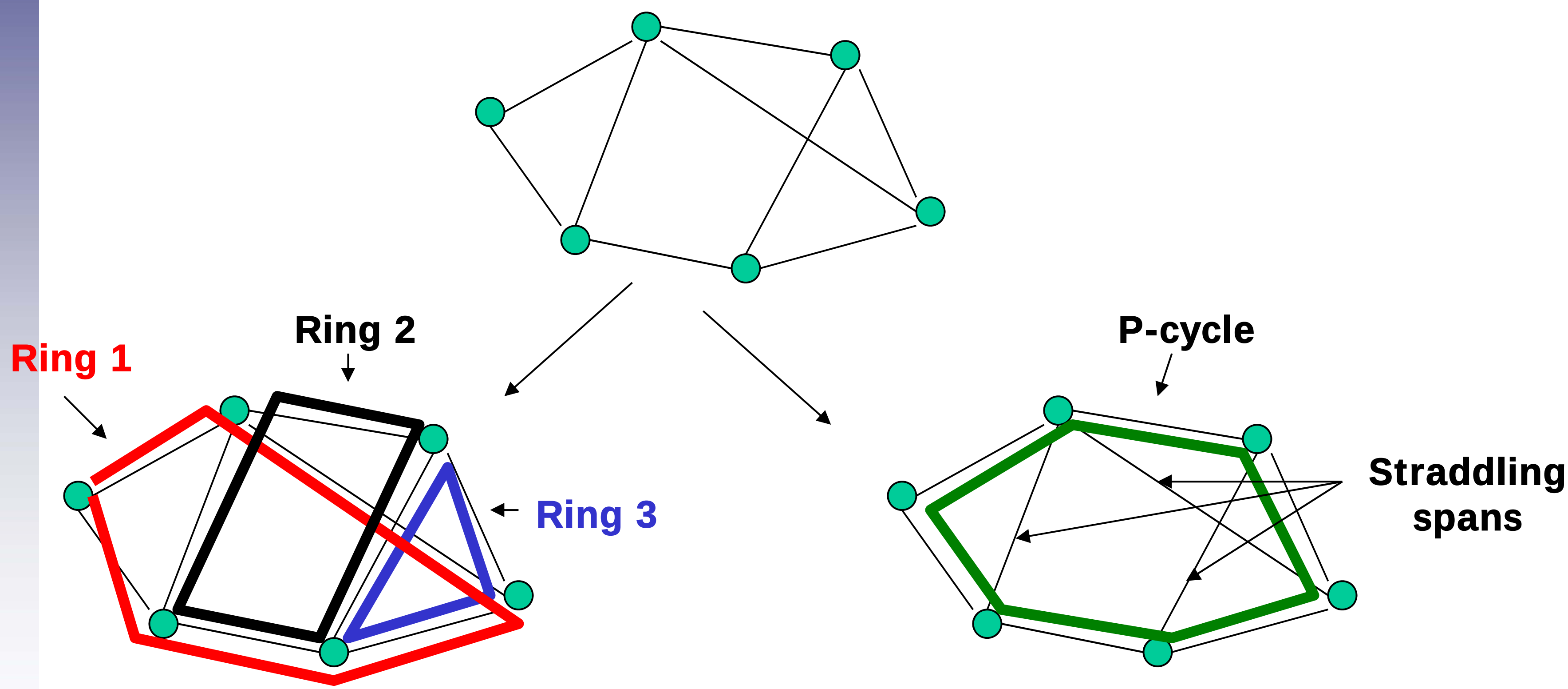
Fault Protection in WDM - Mesh Topologies - Ring Covers

- Ring Cover technique involves finding a ring cover for the mesh network, and treats each cycle in the ring cover as a self-healing ring.
- A number of ring covers can be found for each network, so the goal of this approach would be to minimize the length of the ring cover (which in turn will minimize the extra capacity required in the network).
- Definition : Given an undirected graph G, a cycle cover (or ring cover) of G is defined as a set of (not necessarily distinct) cycles C = (C1, …, Cm), $m \geq 1$, of G, such that each edge of G belongs to at least one cycle of C.
- The length of a cycle is defined as the number of edges it contains. The cycle cover length is the sum of the lengths of all cycles in the cycle cover set C.

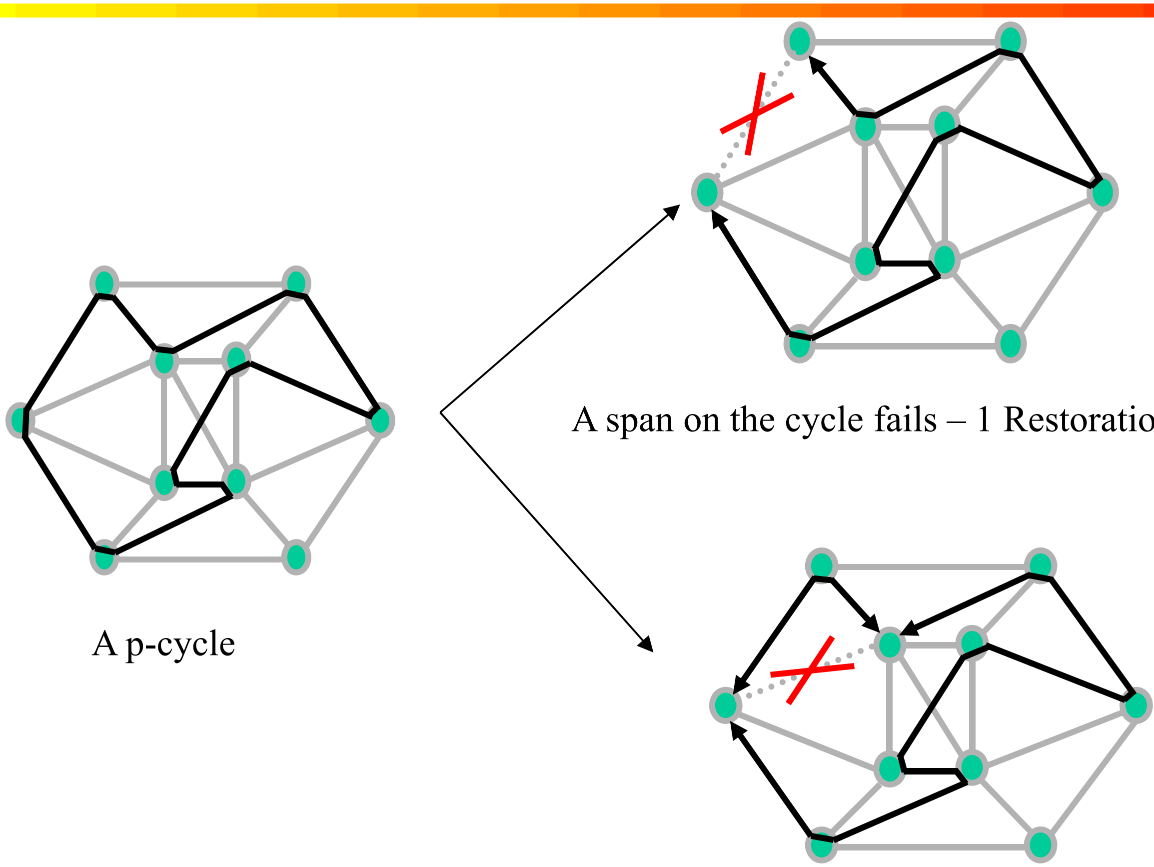
Ring-Based Protection – p-cycles

- Ring-like protection with addition of protection of *straddling* failure spans.
- A straddling span is one that has its end-nodes on the p-cycle but is not itself part of the p-cycle
  - Like a chord on a circle
- Two types of protection
  - Usual ring-like loopback protection of spans on the ring: "on-cycle" failures.
  - Two protection paths on the p-cycle ring for failure of a straddling span

Protection Using p-cycles



Protection Using p-cycles



A p-cycle

A span on the cycle fails – 1 Restoration Path, BLSR-like

A span off the p-cycle fails – 2 Restoration Paths, Mesh-like

- Less than 100% redundancy is required to protect the mesh network against any link failure as the straddling links have working capacity but require zero units of protection capacity.

Ring-Based Protection – p-cycles

- **p-cycle-based protection achieves ring-like protection in terms of recovery speed, with mesh-like high efficiency in the use of spare capacity.**
  - **Achieves fast recovery times since**
    - **p-cycles are preconfigured**
    - **Signaling only between the nodes of the failing link is required for the identification of the failing link and its protection.**
  - **Achieves high capacity efficiency since a p-cycle can protect both on-cycle links and straddling links.**

Literature
Fiber-Optic Communication Systems

- G. P. Agrawal, *Συστήματα επικοινωνιών με οπτικές Ίνες*, 2η έκδοση, 2000.
- Gerd Keiser, Optical fiber communication, McGraw-Hill, 2000.
- J. Senior, Optical Fiber Communications: Principles and Practice, 2009.
- G. Agrawal, Fiber-Optic Communication Systems 4th Edition, 2010.

Additional Books on Optical Networks

- Rajiv Ramaswami, Kumar Sivarajan, Galen Sasaki, Optical Networks: A Practical Perspective, 3rd edition, 2009.
- Biswanath Mukherjee, Optical Communication Networks, McGraw-Hill, 2006.
- Hussein T. Mouftah and Pin-Han Ho, Optical Networks: Architecture and Survivability, Kluwer Academic Publishers, 2002.
- Hui Zang, WDM Mesh Networks: Management and Survivability, Kluwer, 2003.
- G. Bernstein, B. Rajagopalan, D. Saha, Optical Network Control, Addison Wesley, 2004.
- W. Grover, Mesh-Based Survivable Networks, Prentice Hall, 2004.
- ….