Optical Communication Networks

Transport networks

Transport networks (1)

- Transport networks
  - Evolution of TLC networks
  - Design of transmission layer
  - Unidirectional and bidirectional WDM systems
  - Long-haul networks
  - Submarine networks
  - Metro networks
  - All optical networks

Transport networks (2)

- Evolution towards ever increasing capacity networks
- Considerations taken into account by carriers
  - When a new network is installed
  - Or in case of upgrade of existing network
- Evolution of TLC networks
  - From the viewpoint of services delivered…
  - … hence of network infrastructure
- Architecture of next generation networks
  - Role of Sonet/SDH, IP, ATM
  - Role of optical layer
  - WDM vs. TDM vs. SDM – business considerations
- Metro vs. long-haul networks
  - Different requirements and technologies
- Search of trade-offs among different requirements
  - Use of complex design tools

Transport networks

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  - Evolution of TLC networks
  - Design of transmission layer
  - Unidirectional and bidirectional WDM systems
  - Long-haul networks
  - Submarine networks
  - Metro networks
  - All optical networks

Evolution of TLC networks (1)

- Traditional transport network based on Sonet/SDH
- Optical WDM layer introduced in these networks
- Evolution towards new architectures
  - Growth of network traffic
    - Doubles every year
  - Change of traffic type
    - Data traffic overcomes voice traffic
  - Increased competition in the TLC domain
- In the past
  - Long term contracts
  - Long deliver waits (weeks/months)
- Now
  - Lo long term committment contracts, low rates
  - Rapid delivery of requested bandwidth

Evolution of TLC networks (2)

- New carriers use different business model from incumbent carriers
  - Different business requires different architectures
- Incumbent carriers
  - Voice /telephone, renting of circuit-switched lines
- Other types of carriers
  - Carriers for connections among Internet providers
  - Carriers that provide bandwidth to other carriers
    - Bulk bandwidth (ex. 622 Mbps) to other carriers
  - …
- Each type of carrier has different needs…
  - … hence it requires different network architecture
- Fundamental quesiton…
  - What is the need of a carrier when it wants to install a new network technology?

Evolution of TLC networks(3)

- Each network evolution must guarantee…
  - Reduction of the cost of operating the network or…
  - … enable delivery of new revenue-bringing services
- Capital expenditures (CAPEX)
  - Cost necessary for installation of new devices
  - Cost of equipment, buildings necessary for energy supply and cooling, fibers…
  - Initial cost and costs necessary for upgrades
  - **Objective: minimize cost per transmitted bit per km**
- Operating expenditures (OPEX)
  - Cost necessary for network maintenance
  - Cost for renting equipment, cost for energy supply and cooling, maintenance of equipment…
- Operating costs prevail over capital cost…
  - Capital costs however are easier to quantify

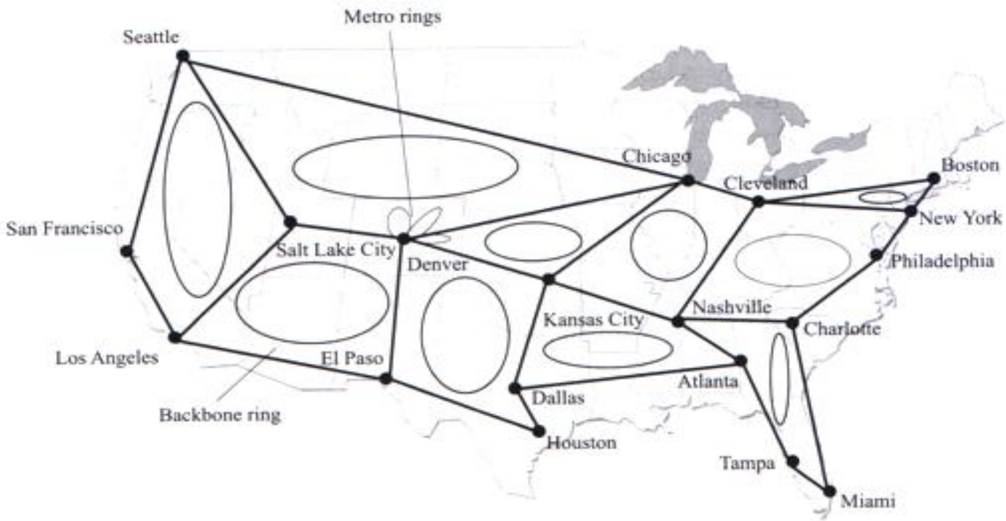
Evolution of TLC networks (4)

- Revenue increase coming from
  - New services
  - Upgrade of existing services
- Ex. Installation of new network technologies that permit to provide rented lines within a few minutes
  - Reduction of service delivery time
  - Convenient *short-term* rates with no long-term obligations
  - Intensive and efficient usage of network resources
- Need of networks with
  - High capacity *scalability*
  - *Flexibile* delivery of services *where* needed *when* needed
- Optical layer permits to provide
  - Circuit-switching services at high bitrate
  - Transport of multiplexed packets at low bitrate

Sonet/SDH transport network (1)

- Tipical backbone of incumbent USA carrier (a)
  - Interconnected Sonet/SDH rings
    - Fed by metro rings
  - Capacity keeps growing: “stacked” rings
    - Multiple rings that connect the same nodes
      - Using different fibers, or a single fiber and WDM
- Schematic vision of a network node (b)
  - Multiple optical line terminals (OLT)
  - Each ring passing through the node requires an ADM
  - ADM connected to OLT
    - ADM operate at line rate OC-48 (2.5 Gbps) or OC-192 (10 Gbps)
    - Extraction of low bitrate fluxes
      - From DS3 fluxes (45 Mbps) to OC-12fluxes (622 Mbps)
    - Low bitrate traffic management by the DCS

Sonet/SDH transport network (2)



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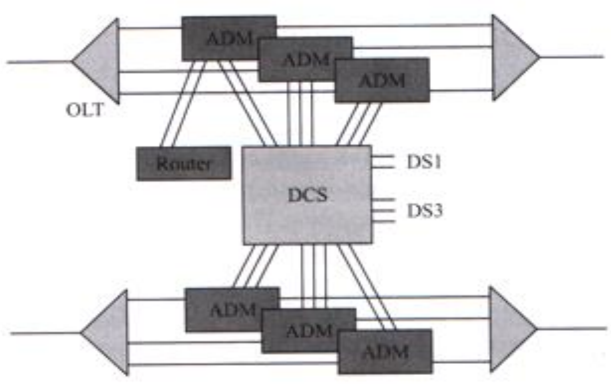

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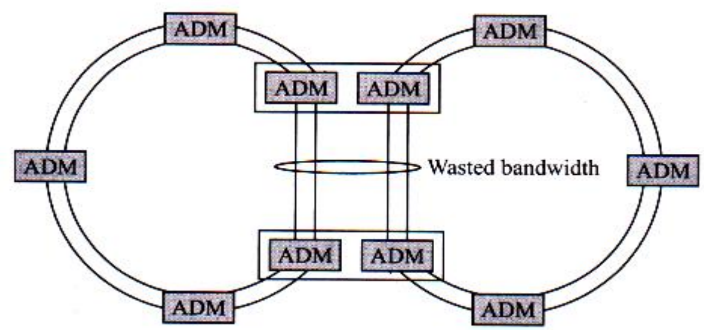


Sonet/SDH transport network (3)

- Private data lines enter the network as low bitrate fluxes, hence they are multiplexed via ADM and DCS
  - Private DS1, DS3 (E1, E3), or STS-N lines
  - Well defined and mapped signals in Sonet hierarchy
- IP or ATM data traffic
  - Enters the network as DS1/DS3 lines, or as high speed lines as OC-3 or OC-12
  - Transport via Sonet/SDH infrastructure
- **Network designed for voice traffic**
  - Circuit switching
  - Latency and bandwidth are well defined
  - High reliability, performance monitoring and faults recovered by Sonet protection
- Static network, the DCS provide switching hence they create the different connections
  - Connections last for months/years

Sonet/SDH transport network (4)

- Data traffic now dominates, optical layer becomes more and more complex, and some deficiencies of the architecture emerge
  - **Static rings, static bandwidth delivery**
    - Does not allow for the high speed delivery of services within seconds
  - **Traffic demand is typically of mesh type, rings are not well suited for this type of traffic**
    - Ring interconnection via DCS is complex
    - Half of the capacity on each ring for protection reasons
    - If two rings share a link (figure), separate protection on each ring (waste)
  - **All of the traffic is protected, there are no distinctions**
    - Protection is not necessary for best effort IP traffic
  - **Difficult coexistence between IP routers and Sonet network**
    - Data traffic at ever increasing bitrate…

Sonet/SDH transport network (5)

- IP routers connected to ADM Sonet ports, line rate must be higher than router rate
- Motivation: usually line rate of Sonet devices is larger than the rate of their input ports
  - Ex. router with OC-48c ports connected to Sonet ADM OC-192
- … Besides many Sonet versions reserve half of the bandwidth on each fiber for protection
  - Ex. 2 fiber OC-48 ring, each fiber may carry OC-24 traffic, concatenated flux cannot be split
- Big problem in modern networks
  - IP routers support ever increasing rates
    - Router with OC-192c ports mapped in ADM OC-768!!
    - Routers with ports working at bitrates larger than the maximum bitrate available with Sonet soon available
    - **Direct connection of IP routers with optical layer**

Sonet/SDH transport network (6)

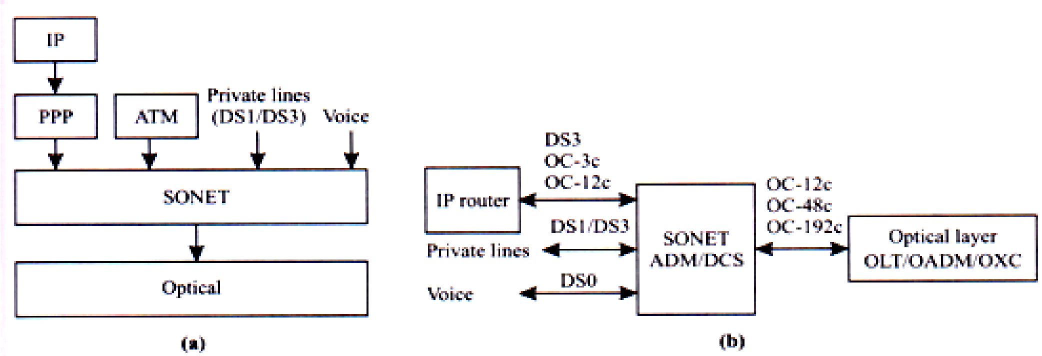
- **Sonet layer useless for best-effort services**
  - Sonet multiplexing and protection give no benefits for providers of high bitrate IP services
  - Cost savings if Sonet devices are eliminated
  - But still Sonet framing continues to be used
    - Widely used by IP and ATM devices
    - Common set of standard bitrates
    - Proper overhead to monitor performances and faults
- **Sonet does not include efficient mapping for all data signals**
  - Ex. Ethernet at 100 Mbps mapped in OC-3 link at 155 Mbps, bandwidth waste
- **Systems for managing and signaling for the setup of end-to-end connections are missing**
  - Each network element is separately installed
  - Connection setup is a long and manual process

Next generation networks

- Network architecture evolves in a significant manner
- Choice of new architecture depends on
  - Services that the carrier wants to offer
  - Existing network which may already be available
- **Transmission layer for next generation backbone: optical layer (OLT + OADM + OXC)**
  - Practically everybody accepts this choice
  - It is still debated the choice of technologies on the optical layer that provide services
    - In practice, this means which devices are to be installed
    - Possible options for the service layer
      - Sonet/SDH
      - ATM
      - IP

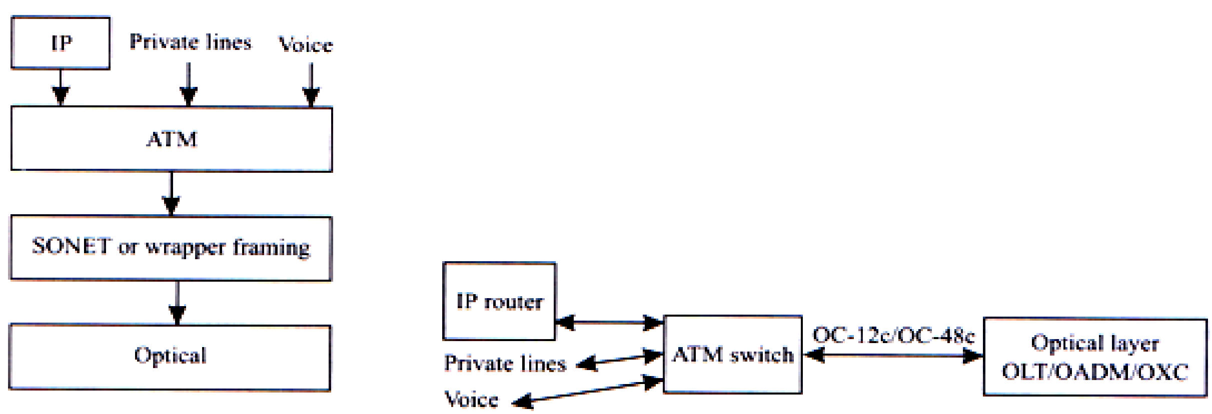
Sonet/SDH transport network

- Sonet/SDH is common layer over optical layer
- Other services (IP, ATM, private lines, voice) trasported by Sonet/SDH layer
- Trasport of IP traffic
  - Packets are enclosed in PPP frame for “link by link” safe and efficient transport
  - Framing using Sonet/SDH
  - Operations are carried out internally within the router
  - Router connected to ADM, who muxes connections
- Inefficient architecture (see previous slides)



ATM transport network (1)

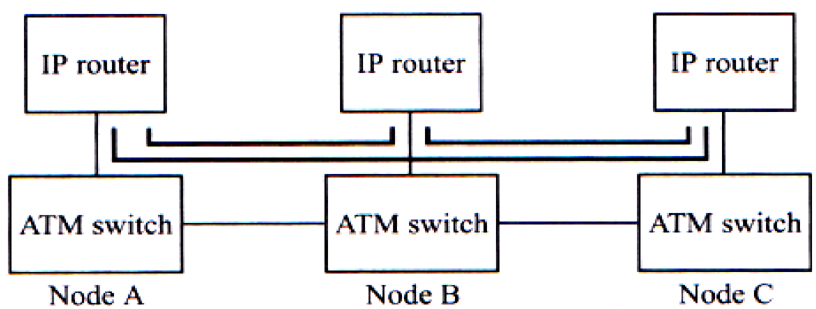
- ATM as common level (data-link level) for all services that are provides
  - ATM switches are directly connected to the optical layer
  - Sonet framing used for cell transmission
    - Data adaptation at the physical level
    - Addition of the proper overhead, advanced management
    - Commercial chipsets are integrated in the ATM switch
    - No separate ADM used



(a) (b)

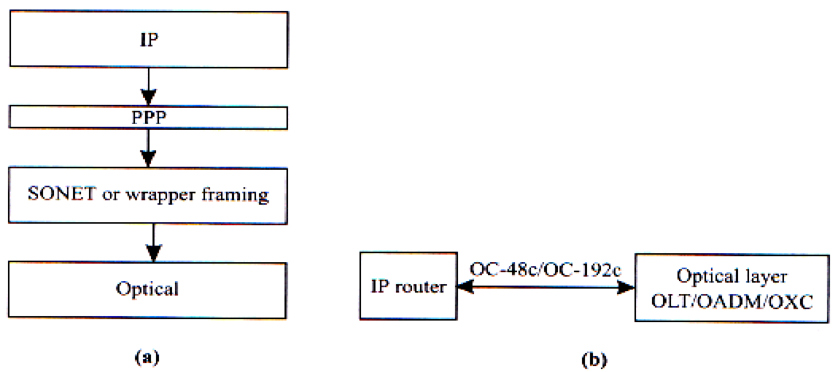
ATM transport network (2)

- Many carriers invest on ATM networks
- ATM able to provide QoS (bandwidth, low latency…)
  - Ex. Circuit emulation
    - Provide *virtual* DS1 o DS3 services
  - Protection switching at Sonet level or at optical level
- Trasport of IP traffic
  - Frame relay interface in ATM network
  - Best solution with respect to the use of private networks
    - Cost reduction, QoS guaranteed by private lines is not necessary
  - Direct virtual connection among routers via VC
    - Traffic from A to C without passing through router B
    - Improvement of IP traffic QoS
- **MPLS** may substitute ATM for these functionalities



IP transport network (1)

- The IP layer lives over the optical layer
- IP is level 3 layer, with MPLS has also level 2 functions
- This architecture foresees direct connection of the IP router to the optical layer
- Sonet framing for the usual reasons, implemented by a circuit within the router
- **No Sonet devices are used in the network**
  - Big cost savings



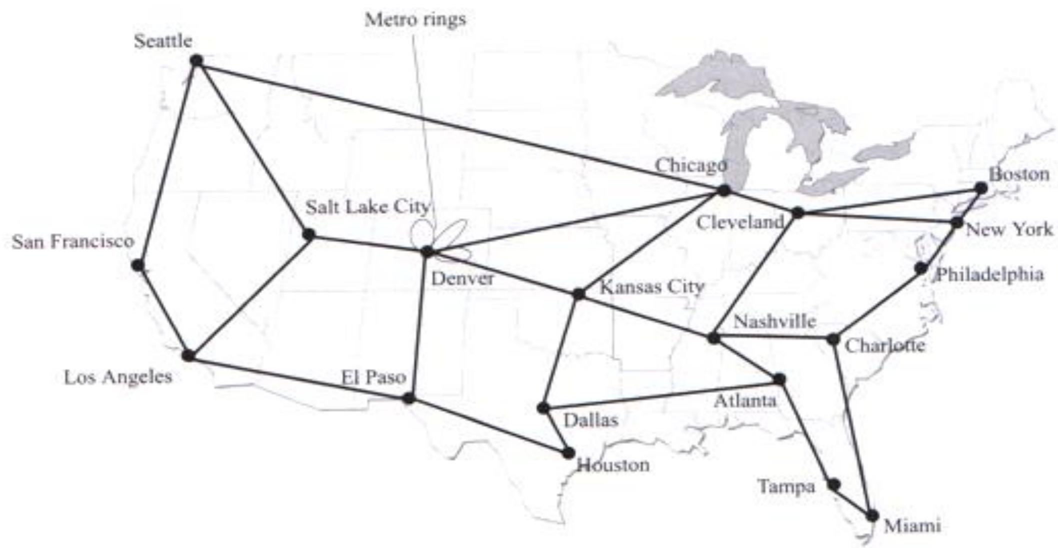
IP transport network (2)

- Alternative framing techniques
  - Ethernet, Gigabit Ethernet
  - These are more and more used since the use of Ethernet expands at the metro level
- IP layer does not guarantees QoS and protection
- **Architecture not appropriate to voice and data traffic**
  - Important business for incumbent carriers
  - IP over optical only used for best-effort traffic, it not not a universal solution
- At backbone level it is more efficient to switch big data amounts rather that individual packets
  - Statistical mux not so useful, traffic already aggregated
  - Traffic is essentially connection oriented
    - While the IP layer is connectionless!
  - MPLS designed to solve these problems
    - MPLS implemented in core router
- In the future: evolution of IP and optical layer to guarantee QoS and protection, IP over optical universal solution

New transport networks (1)

- Up to today many different architectures are installed
- Examples
  - Operator 1: ATM network over Sonet over WDM
    - IP traffic at low bitrate trasported over ATM
    - IP traffic at high bitrate (OC-48c) transported by optical layer
    - Voice and private lines on Sonet network
  - Operator 2: provider of IP services only
    - Architecture IP over WDM
  - Operator 3: ATM network implemented on optical layer
    - Provider of virtual circuits and packet services
- Variety of services hence different architectures
- Migration from architecture in slide 10 to that of the next figure

New transport networks (2)



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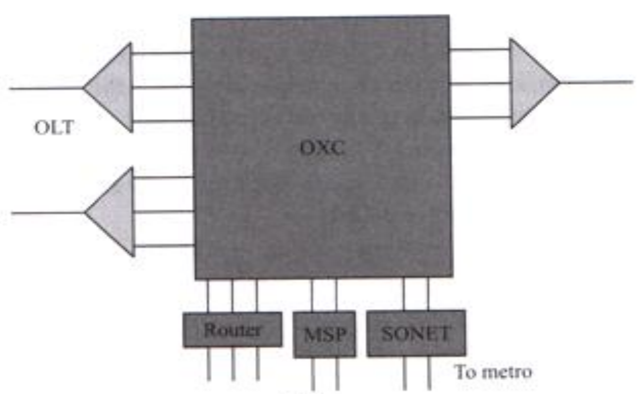

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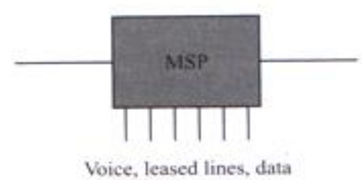


(c)

New transport networks (3)

- Meshed backbone (interconnected rings) composed by OLT, OADM and OXC (OLT, ADM and DCS)
  - Network is fed by metro rings
- Support of different data types
  - Sonet, ATM, IP
- High bitrate fluxes directly connected to optical layer (Sonet)
- Low bitrate fluxes multiplexed and transported by one of the service layers as seen before (Sonet)
- Sonet/SDH is optimal support for voice and private lines
- High bitrate multiplexing at optical level (Sonet)
- QoS guarantee directly at IP level (Sonet)
- Protection at IP level and/or optical (Sonet)
- MPLS for direct connections between IP routers (Sonet)

New transport networks (4)

- Access to network through a new type of device
  - **Multi Service Platform (MSP)**
    - Combination of fixed and statistical multiplexing
    - Provider of circuit-switched or packet services to network users
    - Basic idea: a single access “box” is used instead of installing different overlapping networks for each service
    - **Metro networks composed of MSP rings**
- Different MSP types, with different functionalities
  - Simple Sonet ADM with voice traffic ports, private lines and data interfaces (ex. Ethernet)
    - Circuit switching, maps Ethernet into Sonet
  - Packet (cell) switching core, fixed TDM and statistical multiplexing
    - Statistical data aggregation, Sonet mapping
  - MSP without TDM, use of packet network
    - QoS of ATM or IP for “circuit-switched-like” services

New transport networks (5)

- Tipically MSP in metro ring networks
  - Classic configuration for metro networks
  - Also most economic configuration for metro networks
  - New users are added without installing new fibers
  - Protection mechanisms based on Sonet
    - Sonet is optimal for ring management
- Evolved MSP with WDM interfaces and OADM capacity
  - WDM in metro networks is not so convenient as in long-haul
- Sonet/SDH with MSP may compete with **PON** and **RPR** for low-medium bitrate access networks
  - Choice based on…
    - Cost
    - Flexibility

Reti di trasporto

- Transport networks
  - Evolution of TLC networks
  - Design of transmission layer
  - Unidirectional and bidirectional WDM systems
  - Long-haul networks
  - Submarine networks
  - Metro networks
  - All optical networks

Design of transmission layer (1)

- Carrier considerations in the choice of transmission layer
- Historical trend
  - Continuous growth of network bandwidth
  - Decrease of cost of transmitted bit
- When installing new networks, carriers expect
  - Capacity multiplied at least by four
  - Cost of equipment multiplied by 2 – 2.5
- 3 methods to increase network bandwidth
  - **SDM (Space Division Multiplexing)**
    - Use other fibers already installed, install new cables (or use multimode fibers)
  - **TDM (Time Division Multiplexing)**
    - Increase channel bitrate
  - **WDM (Wavelength Division Multiplexing)**
    - Increase number of channels in each fiber

Design of transmission layer (2)

- SDM, TDM and WDM are complementary techniques
  - All of the 3 are necessary in networks
  - In general, a proper combination should be selected
- SDM is long term investment
- TDM and WDM quickly increase capacity of installed fiber infrastructure
- Electrical TDM
  - Grooming of low bitrate fluxes, where optics is not convenient
- Optical WDM
  - Amplification of transmission capacity
- Objective
  - Determine right combination of SDM, TDM and WDM for a given network
  - Ex. For a given total capacity of 80 Gbps
    - Choice among 32 x 2.5 Gbps or 8 x 10 Gbps network

Design of transmission layer (3)

- When using new fibers, when TDM and when WDM?
- Many factors influence the choice
  - Consider if it is a new network, or it is upgrade of existing infrastructure
  - Availability and cost of already installed additional fibers
  - Type of available fibers
  - Cost of using new fiber with respect to using TDM and WDM
  - Relative cost of TDM and WDM equipment

SDM (1)

- Simple method for system upgrade
- Applicability depends on the following factors
  - Are there available additional fibers in the cable?
  - If yes, then the path length should be considered
  - For short fiber paths(up to tens of km), with no regenerators and amplifiers, SDM is a valid choice
  - Whenever regenerators and/or EDFA are necessary, cost is high
    - Each fiber requires a separate set of regenerators
    - Necessary to compare expenses for new infrastructure and transmission cost reductions
  - If there are no unused fibers, it is necessary to lay new cables
    - New fibers in old conducts: low cost
    - Laying of new conducts: cost is high even for short links in metro networks
      - One tries to install cables with hundreds of fibers

SDM (2)

- Time necessary for laying new optical cables
  - Months, if not years
  - Necessary to obtain permits from municipalities
    - Difficult to obtain permits in dense metro areas, where there is heavy impact of installation work on road traffic
- Necessary time for TDM or WDM upgrade
  - Days, max weeks
  - Quick answer to requests for new services
- Upgrade to be planned in advance with respect to its necessity
  - When the last fiber in the cable is lit
  - Planning of new cable installations
  - Alternatively
    - TDM + WDM system on last available fibers
    - Traffic routed from low capacity fibers to new system
    - This allows to make some fibers free in the cable

TDM (1)

- Grooming of low bitrate fluxes
- Optimal bitrate of each channel is planned
  - Bit rate depends on the type of available fiber
- Long-haul link: typical bitrates 2.5 or 10 Gbps
- Metro inter-office link: typically 2.5 Gbps
- Metro access links: lower bitrates
- Electrical TDM at 40 Gbps, towards 80 Gbps
- For bitrates higher than 80 Gbps: optical TDM
- High bitrate-> transmission affected by penalties from
  - Dispersion, PMD, nonlinear effects
- **Dispersion effects**
  - SMF, dispersion limit: 60 km at 10 Gbps or 1000 km at 2.5 Gbps
  - This is ideal case, in pratice SPM adds extra penalty
  - 3R regeneration or dispersion compensation necessary

TDM (2)

- For 10 Gbps transmissions, dispersion compensation is used
  - Inexpensive for WDM systems
- **Effects of PMD**
  - PMD-induced transmission limit at 10 Gbps is 16 times less than max distance at 2.5 Gbps
  - In old fibers, PMD as high as 2 ps/√km
    - PP = 1 dB, PMD limit: 25 km at 10 Gbps
    - Optical regeneration or PMD compensation is necessary
    - In practice, situation even worse because of PMD induced by other components
  - PMD is not a limiting factor in new fiber links
    - PMD values as low as 0.1 ps/√km
- **Nonlinear effects**
  - Limitation on max power per channel→ larger numer of EDFA is necessary → increase of costs
  - At 10 Gbps the power per channel must be less than 5 dBm
- Current long-haul TDM + WDM systems operate at 10 Gbps
  - Next generation of systems at 40 Gbps or 100 Gbps

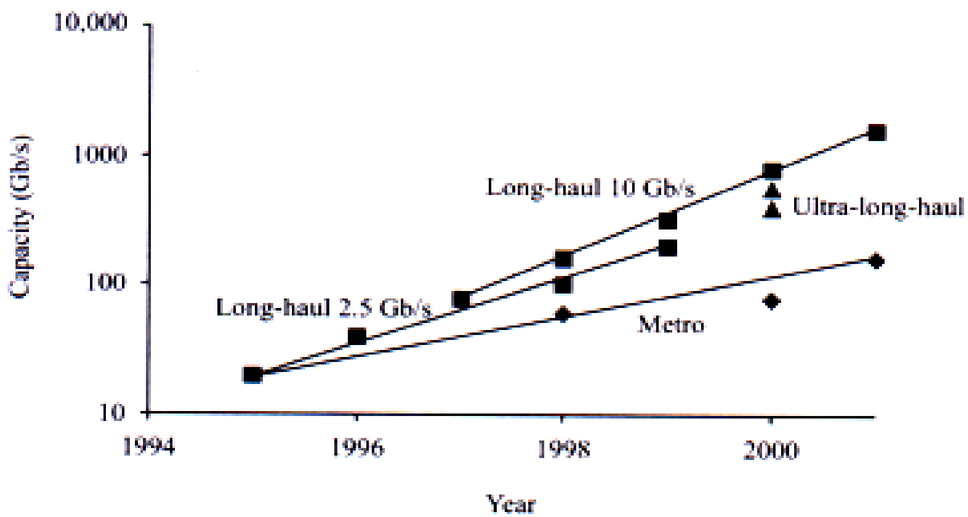
WDM (1)

- Optimal choice: use a relatively low bitrate (e.g. 10 Gbps) and transmit several wavelengths
- Low bitrate means that the system is less penalised by dispersion, PMD, SPM…
- WDM not suitable for use of DSF
  - FWM effects are very large at 1550 nm
- WDM systems are transparent to:
  - bitrate and data format
  - This is key advantage for many applications
- WDM systems are very flexible
  - Permit optimal management of passthrough traffic at nodes
    - This traffic generally prevails over added/dropped traffic
  - Use of OADM instead of terminating all traffic at the node

WDM (2)

- Unstoppable growth of WDM systems capacity
  - Channel number is larger than 100
  - Channel spacing from 100 to 50 down to 25 GHz
  - Use of L band (1565 – 1625 nm)
  - EDFA spacing between 80 and 120 km
  - Long-haul systems
    - 100 channels at 10 Gbps, regenerators placed every 400 – 600 km
  - Ultra-long-haul systems
    - Reduced capacity, regenerators every 4000 km
  - Metro systems
    - Regenerators every 50 – 75 km

WDM (3)



Long-haul	
Year	**Capacity**
1995	8 × 2.5 Gb/s
1996	16 × 2.5 Gb/s
1997	8 × 10 Gb/s
1998	40 × 2.5 Gb/s
1998	16 × 10 Gb/s
1999	80 × 2.5 Gb/s
1999	32 × 10 Gb/s
2000	80 × 10 Gb/s
2001	160 × 10 Gb/s

Ultra-long-haul	
Year	**Capacity**
2000	160 × 2.5 Gb/s 56 × 10 Gb/s

Metro	
Year	**Capacity**
1995	20 × 1 Gb/s
1998	24 × 2.5 Gb/s
2000	32 × 2.5 Gb/s
2001	64 × 2.5 Gb/s

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Long-haul networks (1)

- Length of long-haul links
  - North America: several hundreds- a few thousands of km
  - Europe: a few hundreds of km
- WDM is fundamental for long-haul system cost savings
  - WDM extensively used by long-haul carriers
  - Use of EDFAs permits to save regenerators
  - Rapid response to bandwidth request by market is possible
- Choice of proper combination between TDM and WDM
  - Depends on already installed fibers and services provided
- Examples (USA)
  - AT&T and Sprint: installed fibers are SMF
    - WDM is optimal choice with this type of fibers
    - Links at 2.5 Gbps (OC-48) instead of 10 Gbps (OC-192)
    - Old fibers, problems with PMD and SPM

Long-haul networks (2)

  - Providers of medium bitrate services (DS3), heavy investment for the purchase of mux/demux Sonet devices
- Worldcom: installed fibers are SMF and DSF
  - Use of high bitrates (10 Gbps) on DSF
  - WDM systems on SMF
  - Newly installed links use NZDSF
    - Upgrade possible via either TDM or WDM
- In long haul market there are many new providers
  - Qwest, Level 3 Communications
  - New fiber links are installed
    - Use of NZDSF or LEAF
    - Generally in cables there is extra space left for future upgrades
  - Providers of bulk OC-12/48/192 bandwidth to customers
  - For this business it is meaningful to install WDM OC-192 systems

Long-haul networks (3)

- Choice among system in C band only or in C + L bands
  - Band L requires separate, ad hoc designed EDFAs
    - More expensive as they require higher pump powers
  - WDM systems in C band are mostly installed
  - Diffusion of WDM system in L band is slow
    - It is cheaper to install a new system in C band on different fibers than adding the L band!
    - This particularly true for new carriers who have excess fiber
  - Carriers with installed systems using DSF are very interested in using L band for WDM
    - DSF is unsuitable for WDM in C band...
      - When dispersion is near zero, heavy penalties from FWM
    - However dispersion is nonzero in L band for DSF!

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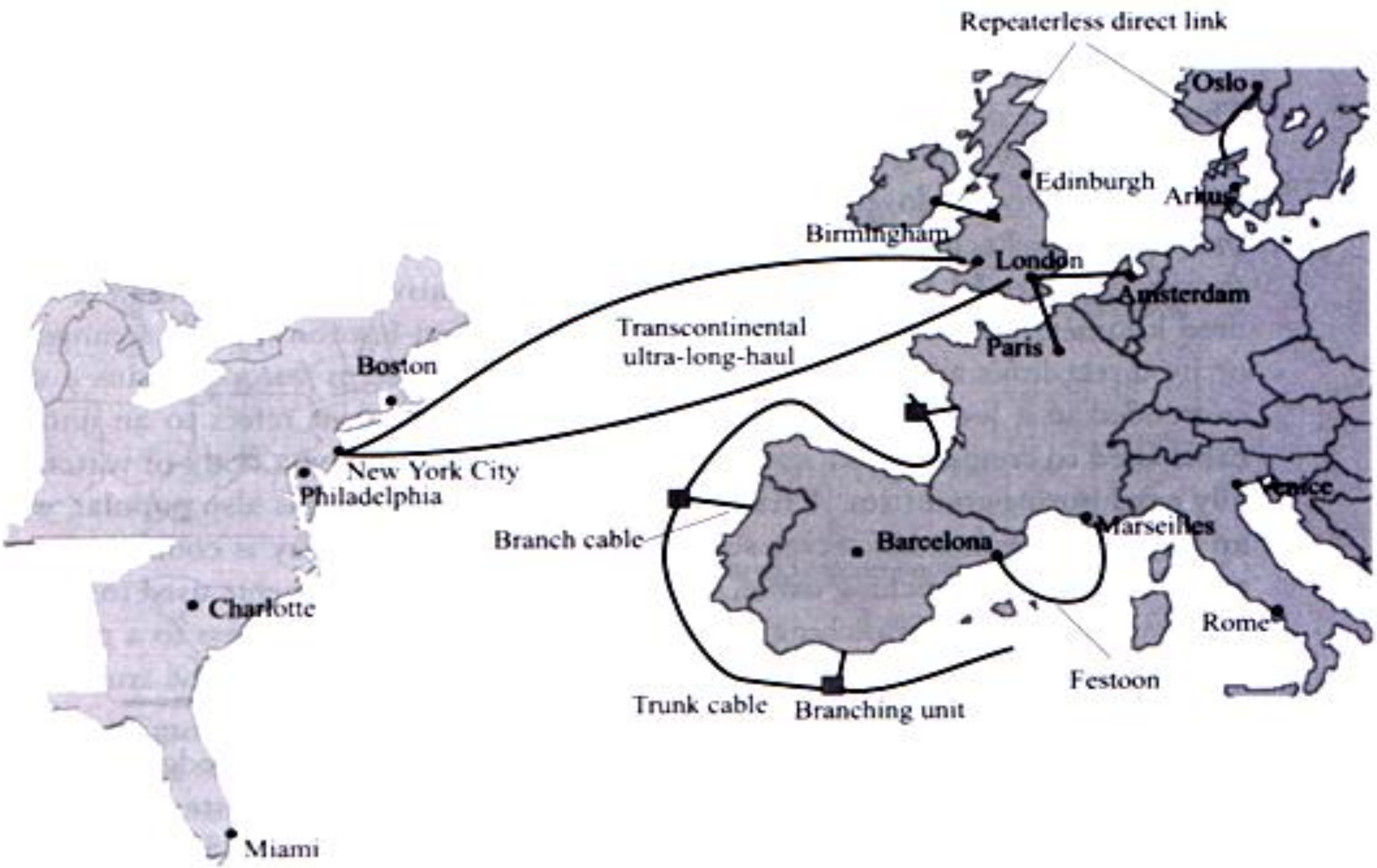
Submarine networks (1)

- Cost issues similar to terrestrial systems
- Different types of installed submarine systems
  - **Intercontinental link**
    - Thousands of km length across the atlantic or pacific ocean
  - **Direct link**
    - Relatively short link(hundreds of km)
  - **Festoon**
    - Direct link with string shape susmended among two 2 nodes
    - Submarine cable connecting two points not separated by water (typically two countries with common border)
  - **Trunk-and-Branch**
    - A main trunk connects more counties
    - Each nation connected via branching cable
    - Branching obtained with passive optical components
    - If a branch unit breaks down, connection lost for that nation only, the trunk cable still operates

Submarine networks (2)



Submarine networks (3)

- WDM widely used in all of previous configurations
  - WDM permits optimal management of shared capacity among different users
- Submarine systems operate with state of the art technology → high costs
- Long reaches, many transmission limitations
  - Dispersion, PMD, nonlinear effects…
- Use of optical dispersion compensation
  - Alternation of fibers with opposite signs of dispersion
  - Large local dispersion, low average dispersion
- Direct links must have low costs
  - One tries not to uses EDFAs→ high transmitted power
- Evolution of trunk-and-branch systems
  - **Use of OADM in branch points**
- Submarine systems designed for high reliability
  - For example, EDFAs with redundant (extra) pumps are used
  - In general, optical components more reliable than electronic ones
  - High maintenance costs
- **Often installation of new system is cheaper than upgrade of existing system**

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Metro networks (1)

- Metro network is divided in two parts
  - **Metro access network**: from CO to customer
    - Traffic aggregation from individual users
    - Typically in ring configuration
      - Diameter from a few to tens of km
    - Traffic concentrates from users to CO
  - **Metro interoffice network**: connection between COs
    - Network with distributed traffic
    - A few tens of km between adjacent nodes
- Short links, WDM not strictly necessary
  - Alternatively, use multiple fibers and/orTDM
  - Just a few OC-192 (10 Gbps) installed systems
    - Delivery of low bitrate services (DS1, DS3) expensive, but the situation improves as new devices are introduced
  - Different reasons push towards WDM anyways

Metro networks (2)

- Metro provider deliver many different services
  - Private lines, ATM, IP, frame relay, GE, ESCON…
  - In many cases the networks are super-imposed, one for each service, all based on the same infrastructure
  - Transparent WDM is better than Sonet in this case
- Traffic distribution varies rapidly in metro networks
  - Fast and efficient network re-configuration
  - WDM networks permit flexible bandwidth delivery

- There is strong push towards WDM metro from SAN applications
  - Connection between big business datacenters
    - Link distances: a few tens of km
    - Transactions mirroring, backup…
    - Massive bandwidth request
      - Ex.: hundreds of Fibre Channel channels at 1 Gbps
    - Datacenter in metro areas with many installed fibers
    - Use of many different protocols and bitrates
    - **Transparent WDM networks are ideal for SAN transport**

Metro networks (3)

- Passthrough traffic prevails in metro networks
  - Installation of metro WDM rings with OADM…
  - Better than high bitrate TDM rings
- In spite of short links, EDFAs are often necessary
  - Old fibers, with many connectors and joints
    - High losses, e.g., 10 dB for a 10 km link
  - High losses introduced by OADMs
    - A few dB of loss for each OADM
  - Long protection paths are sometimes necessary
- Metro WDM networks in expansion for business use
  - Many carriers have already installed WDM metro networks
  - Others are still evaluating benefits of solution with respect to other available choices
- In general: WDM of ever-increasing use in metro networks, but not as much as in long-haul networks

Transport networks

- Transport networks
  - Evolution of TLC networks
  - Design of transmission layer
  - Unidirectional and bidirectional WDM systems
  - Long-haul networks
  - Submarine networks
  - Metro networks
  - All optical networks

All-optical networks (1)

- Evolution of optical layer in terms of capacity as well as functionality
- **Opaque networks**: point-to-point WDM systems, all output functionalities at link output at electrical level
  - O-E, O-E-O conversions are costly, they should be kept at minimum particularly at high bitrates
- First step: ultra-long-haul systems
  - Large distance before 3R regeneration is performed
- Second step: manage node traffic as much as possible at optical level
  - Use of OADM and OXC at nodes, optical passthrough
  - Manage channel bands and not individual channels
  - Savings in terms of costs, power, space
- Towards all-optical networks (**transparent networks**)

All-optical networks (2)

- Next evolution: "agile" optical network
  - Fast setup of lightpaths on demand if necessary, real time service delivery
  - Use of re-configurable optical OXCs and OADMs
  - Complex design of physical level
    - Management of power, of dispersion compensation
    - These problems are partially solved for ultra-long-haul links
- Drawbacks of all-optical networks
  - Wavelength conversion, regeneration and grooming at electrical level only
    - A "practical" node combines OXC and electrical switching
      - If possible, one should perform optical switching, and perform electrical functions only if they are impossible at optical level
  - Interoperability among devices of different makers
    - Often necessary to use electrical transponders
    - **All optical network is proprietary solution**
    - **"Realistic" network: all optical sub-networks connected by transponders at their borders**