Optical Communication Networks

Client of the optical layer

Client of the optical layer (1)

- Client of optical layer
  - Sonet/SDH
  - ATM
  - IP
  - MPLS
  - Storage-Area Networks
  - Gigabit Ethernet
  - RPR

Client of the optical layer (2)

- Networks that use optical fiber as transmission medium
  - The optical layer provides lightpaths to clients
    - Equivalent to physical point-to-point links
  - Client layers process data in electrical format, by aggregating fluxes at low bit rate
    - Fixed or statistical multiplexing
  - Main client layers for backbone:
    - Sonet/SDH, IP, ATM
      - IP/ATM over Sonet, or IP/ATM over optical
  - Main client layers for MAN and SAN
    - Gigabit Ethernet, RPR, Fibre Channel

Client of the optical layer

- Client of optical layer
  - Sonet/SDH
  - ATM
  - IP
  - MPLS
  - Storage-Area Networks
  - Gigabit Ethernet
  - RPR

Sonet/SDH vs. PDH (1)

- **Sonet (Synchronous Optical Network)**
  - Standard for multiplexing and high bit rate data trasmissions in US network infrastructures
- **SDH (Synchronous Digital Hierarchy)**
  - Analogous standard adopted in Europe, Japan and for submarine links
- Before Sonet and SDH…
  - PDH (Plesiochronous Digital Hierarchy), 1960
    - In the USA, digital asynchronous hierarchy
    - Objective: multiplexing of voice signals
    - Characteristics of voice signals
      - Bandwidth: 4 kHz
      - Sampling: 8 kHz (Shannon)
      - Quantisation: 8 bits per sample
      - Total bitrate: 64 kbit/s (PCM)
      - Widely adopted standard

Sonet/SDH vs. PDH (2)

- **PCM 64 kbit/s as basic signal**
- Higher bitrate fluxes are multiples of 64 kbit/s
- Different standards in USA, Europe, Japan
- USA
  - PCM 64 kbit/s: signal **DS0** (Digital Signal 0)
  - Signals DS1 (1.544 Mbps), DS3 (44.736 Mbps)…
  - Associated transmission channels are called **T1**, T3…
- Europe
  - Basic unit signal DS0
  - Formats are defined as **E0**, E1, E2, E3, E4

Table 6.1 Transmission rates for asynchronous and plesiochronous signals, adapted from [SS96].

Level	North America	Europe	Japan
0	0.064 Mb/s	0.064 Mb/s	0.064 Mb/s
1	1.544 Mb/s	2.048 Mb/s	1.544 Mb/s
2	6.312 Mb/s	8.448 Mb/s	6.312 Mb/s
3	44.736 Mb/s	34.368 Mb/s	32.064 Mb/s
4	139.264 Mb/s	139.264 Mb/s	97.728 Mb/s

Sonet/SDH vs. PDH (3)

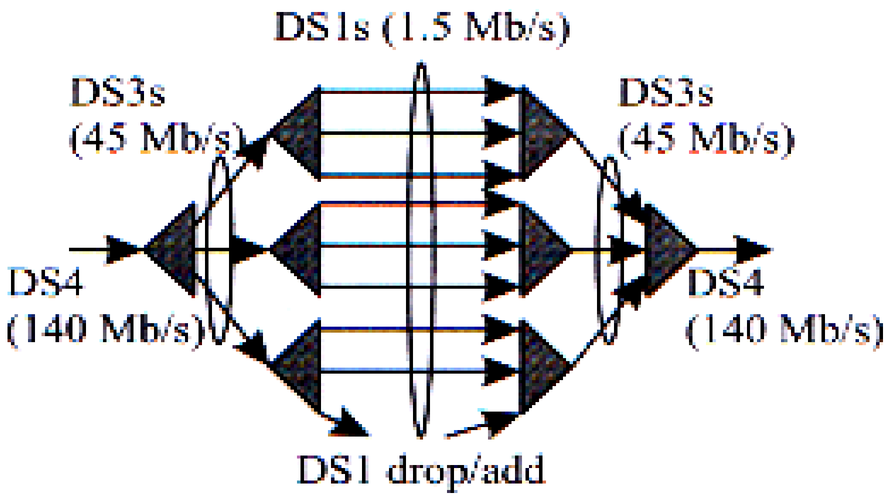
- Previously defined bitrates are still widely used by network operators for renting links to clients
- However PDH had big problems…
  - 1980 – 1990: carriers look for new standards
  - Standard Sonet/SDH
    - Solves many of PDH problems
- Advantages of Sonet/SDH with respect to PDH
  - **1) Simplification of multiplexing process**
    - **Plesiochronous signals (PDH)**: signals characterised by a nominal rate that varies between well-defined limits
    - Asynchronous multiplexing: each terminal has its own clock
    - There is a unique specified nominal clock but…
    - There are significant differences in real values
    - E.g. DS3 signals, clock variations of 20 ppm (realistic value)→ bitrate differences of 1.8 kbit/s!

Sonet/SDH vs. PDH (4)

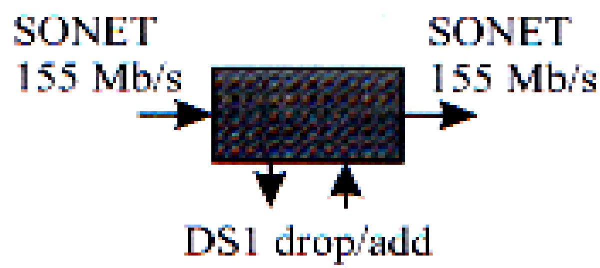
- Necessity of *bit stuffing*
  - When multiplexing low bitrare fluxes, extra bits are added to take into account of misaligned clocks
  - Defined bitrates are not multiples of DS0, but slightly higher
  - E.g., DS1 = 1.544 Mbps, but 24 x 64 kbit/s = 1.5 Mbps
- Difficulties in extracting low bitrate fluxes from high bitrate flux
  - Necessity to fully demultiplex the flux
  - Use of multiplexer/demultiplexer stacks
  - Weak reliability, costly, much electronics required
- **Sonet/SDH è synchronous**
  - All clocks are synchronised to a master clock
    - Bitrates are multiples of DS0, bit stuffing not necessary
  - Reduction of mux/demux cost
  - A low bitrate flux can be extracted at once from Sonet/SDH flux!
  - The design of Sonet ADM is very simple

Sonet/SDH vs. PDH (5)

- E.g. Extraction of DS1 signal from DS4 signal
  - (a) Demultiplexing in PDH case
  - (b) Demultiplexing in Sonet/SDH case



(a)



(b)

Sonet/SDH vs. PDH (6)

- **2) Management**
  - Simplified network management
  - Monitoring of performances
  - Identification of the type of traffic and connection
  - Identification of faults
  - A channel is dedicated to the transmission of informations for network management
  - All above is a property of Sonet/SDH, PDH is not suitable
- **3) Interoperability**
  - PDH did not define a standard transmission format
  - Difficult to connect devices from different makers
    - Different coding, optical interfaces
  - Sonet/SDH define standard optical interfaces
    - Interoperability among devices from different makers
- **4) Network reliability**
  - Sonet/SDH: provide topologies, protocols and protection techniques for highly reliable networks (restoration in **60 ms**)
  - PDH: restoration times from seconds to minutes

Sonet/SDH – Multiplexing (1)

- Complex multiplexing system
  - Implementation with VLSI integrated circuits
- Sonet and SDH are similar, but terminology is different
  - Let us explain Sonet, and point out differences in SDH
- **Sonet**: basic bitrate **51.84 Mbps**
  - Synchronous Transport Signal level-1 (**STS-1**)
  - **STS-N**: signal with N times higher bitrate
    - Interleaving of N STS-1 bytes, frame by frame

Table 6.2 Transmission rates for SONET/SDH, adapted from [SS96].

SONET Signal	SDH Signal	Bit Rate (Mb/s)
STS-1		51.84
STS-3	STM-1	155.52
STS-12	STM-4	622.08
STS-24		1244.16
STS-48	STM-16	2488.32
STS-192	STM-64	9953.28
STS-768	STM-256	39, 814.32

Sonet/SDH – Multiplexing (2)

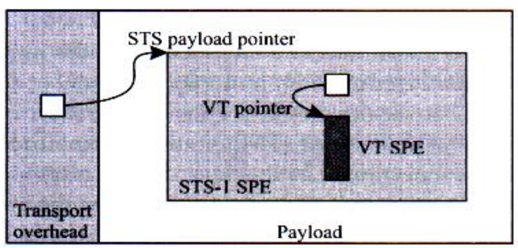
- Clocks of all signals are synchronised
  - Bit stuffing not necessary
  - Low bitrate fluxes can be extracted without total demux
- STS is an electrical signal
  - Such signal often exists in Sonet devices only
  - Optical interface with other devices
    - Transmitted optical signal is STS with scrambling
      - To eliminate long sequences of 1's and 0's
    - The receiver applies descrambling and demodulates
- To the **STS-N** electrical signal, it corresponds the **OC-N** optical interface (Optical Carrier-N)
  - E.g., to STS-3 corresponds OC-3, to STS-12 OC-12…
- **SDH**: basic bitrate **155 Mbps**
  - Synchronous Transport Module-1 (**STM-1**)
    - The same term is used both for electrical and optical signals

Sonet/SDH – Multiplexing (3)

- **Sonet**
  - Bitrate chosen for the transmission of most common asynchronous signals (DS1 and DS3)
- **SDH**
  - Bitrate chosen for the transmission of most common PDH signals (E1, E3, E4)
- Strutture of Sonet frame
  - **Transport Overhead**
  - **Payload**
    - Content of Synchronous Payload Envelope (**SPE**)
    - SPE contains the **Path Overhead** bytes, inserted at the source and extracted at destination only
    - E.g. *path trace* bytes, identify the SPE and are used to verify the connection

Sonet/SDH – Multiplexing (4)

- Use of pointers to indicate the payload within the frame
- SPE does not have a fixed starting point in the frame
  - All clocks derived from a single source
  - Small transient frequency variations are possible
    - Small phase differences between the input and output signals
    - Solution: one allows the payload to shift back and forward in the frame
    - No bit stuffing or buffering, but electronics to manage the pointers
  - Pointer in the Transport Overhead (Line Overhead) indicates the starting byte in the SPE

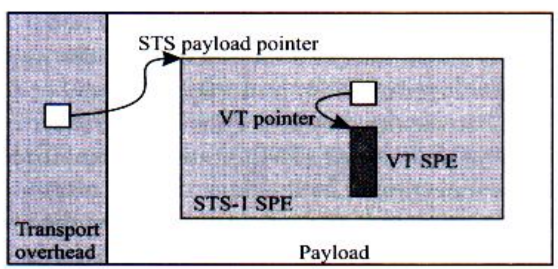


Sonet/SDH – Virtual tributaries (1)

- Necessary to map in frame STS-1 **non Sonet fluxes** at lower bitrate (e.g. DS1)
  - Use of virtual tributaries (**VT**)
  - Each VT designed with sufficient bandwidth to transmit a different payload
  - **Sonet**, 4 VT of different dimensions
    - **VT1.5**: 1.5 Mbps, DS1 signals
    - **VT2**: 2 Mbps, E1 signals
    - **VT3**: 3 Mbps, DS1C signals
    - **VT6**: 6 Mbps, DS2 signals
  - VT composed by
    - **VT SPE**: VT Synchronous Payload Envelope
    - **VT Path Overhead** and **VT pointer**

Sonet/SDH – Virtual tributaries (2)

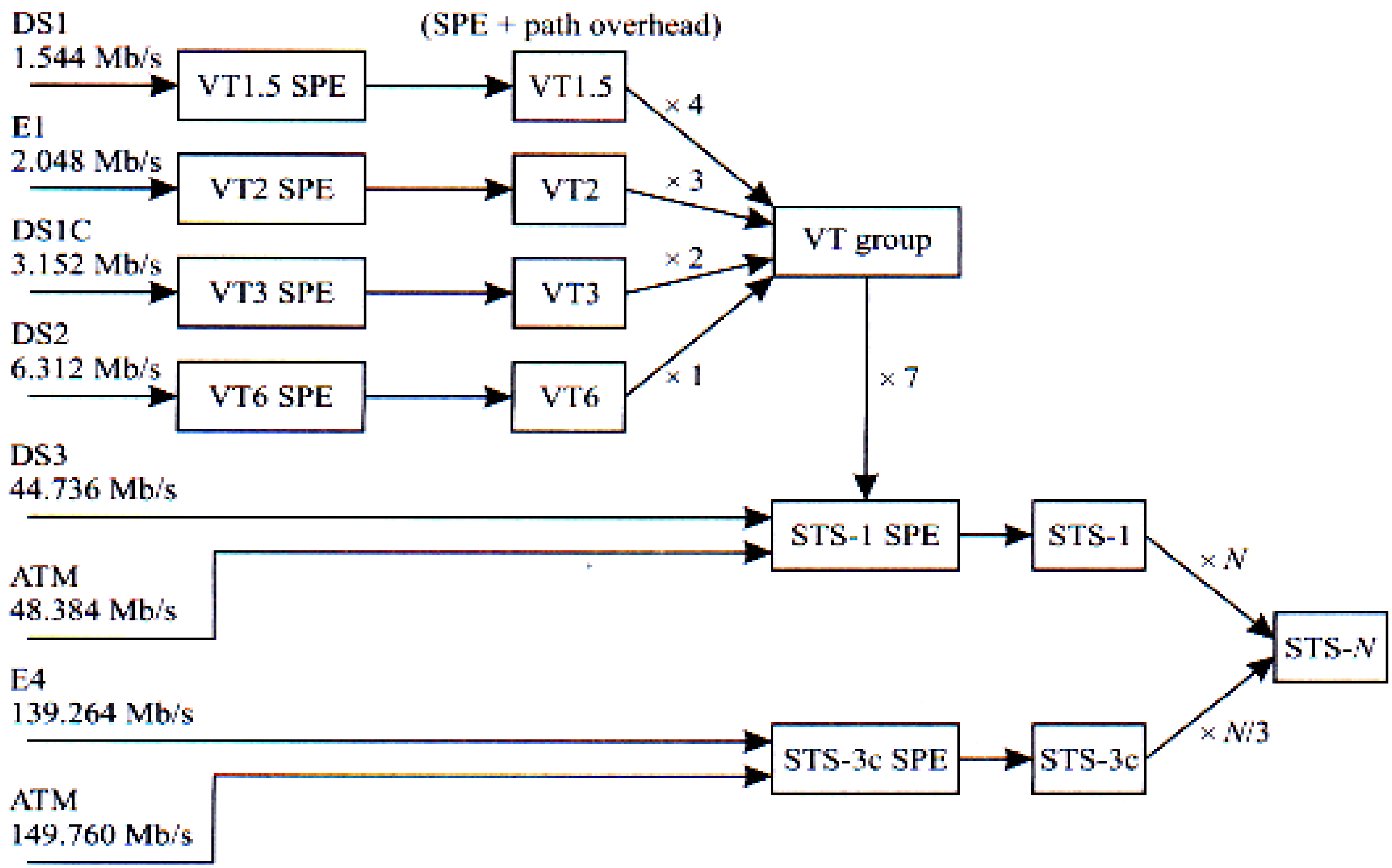
- **VT group**
  - Aggregation of VT in groups, 4 possibilities
    - 4 x VT1.5
    - 3 x VT2
    - 2 x VT3
    - 1 x VT6
- **Sonet STS-1 SPE**
  - Interleaving of 7 VT groups and Path Overhead byte
- VT SPE may fluctuate inside the STS-1 SPE
  - VT pointer (2 bytes) indicates the beginning of VT SPE



Sonet/SDH – Virtual tributaries (3)

- Necessity to map **high bitrate non-Sonet fluxes** in STS-1 SPE for Sonet transport
  - Fluxes from IP router or ATM switch transported with Sonet
- **STS-Nc** (*c* means "concatenated")
  - Signal *locked payload*, that is it cannot be demultiplexed in low bitrate fluxes
- E.g., ATM 150 Mbps signal transmitted on Sonet
  - Use STS-3c signal
- Mapping defined for many classes of signals
  - ATM, IP, FDDI…
- **SDH**: same reasoning, different terminology
  - **VC** (virtual containers) instead of VT
  - VC-11 (DS1), VC-12 (E1), VC-2 (E2), VC-3 (E3 e DS3), VC-4 (E4)
  - VC-11, VC-12 and VC-2 multiplexed in VC-3 e VC-4
  - VC-3 e VC-4 multiplexed to form STM-1

Sonet/SDH – Multiplexing scheme

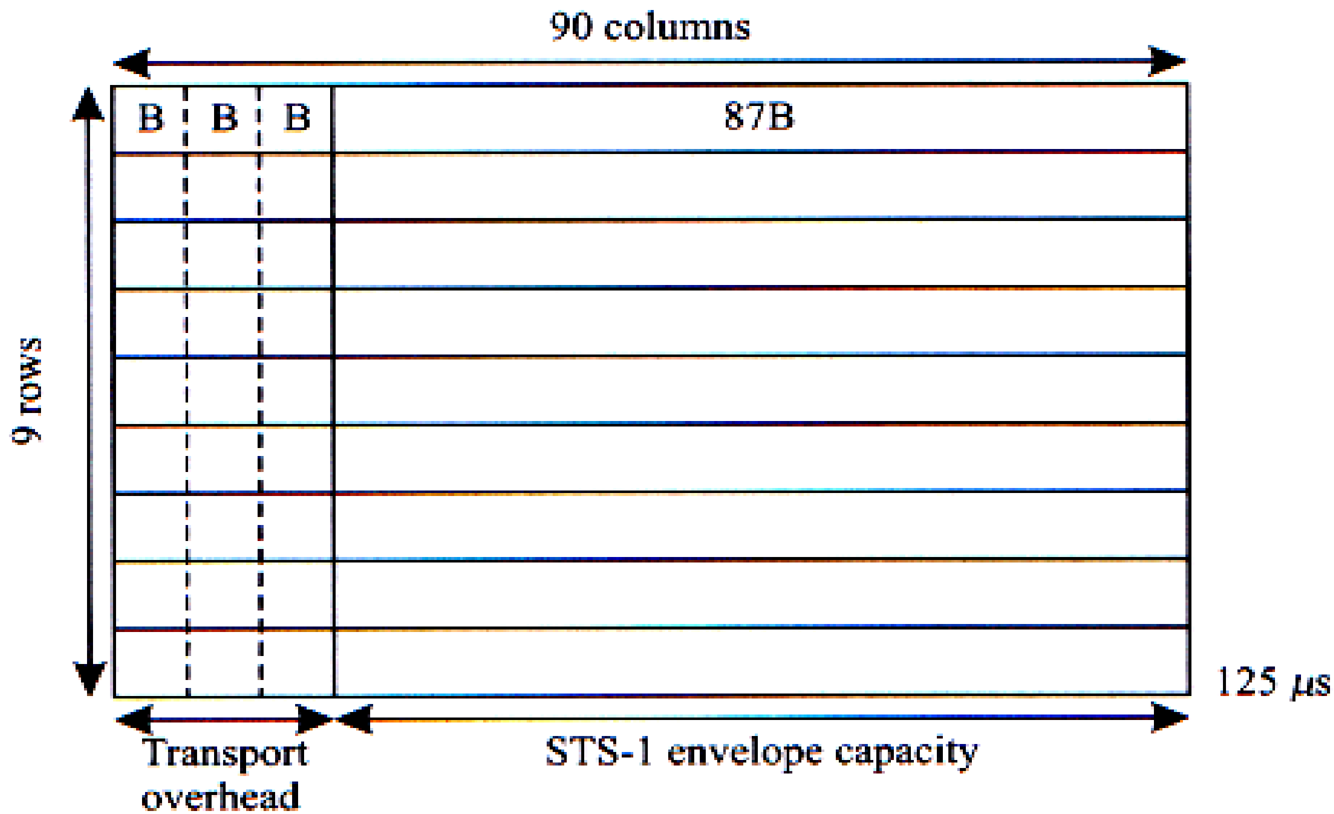


Sonet/SDH –STS-1 Frame (1)

- **STS-1 Frame**
  - Duration 125 μs (8000 frames/s)
    - In analogy with 8 kHz of PCM signal
    - Indipendent of Sonet signal bitrate
  - 9 rows by 90 columns, each cell is 1 byte
    - Overall 810 bytes, payload + overhead
    - **(9 x 90 x 8) bit/frame x 8000 frames/s = 51.84 Mbps**
  - Bytes are transmitted row after row, from left to right, the MSB (most significant bit) is transmitted first
  - First 3 columns for the Transport Overhead
    - Overhead Section Overhead Line
  - Other columns for STS-1 SPE
    - The first column contains the Path Overhead

Sonet/SDH –STS-1 Frame (2)

- Structure of the STS-1 frame

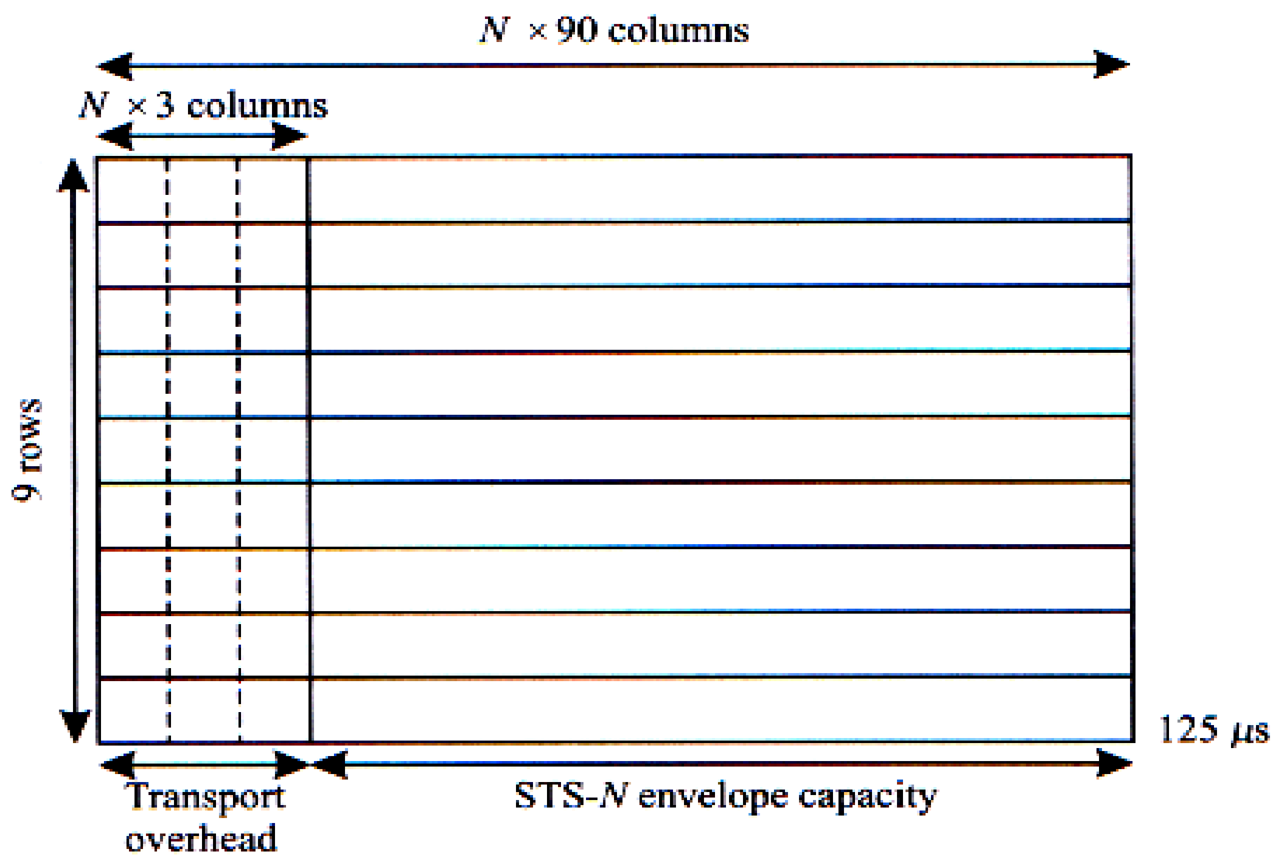


Sonet/SDH –STS-N Frame (3)

- **STS-N Frame**
  - Interleaving of the N STS-1 frame bytes
  - Transport Overhead in first 3N columns
  - N sets of overhead bytes, 1 for each STS-1
    - Alignment with the frame
  - Payload in remaining 87N columns
    - Frame alignment not necessary
- **STS-Nc Frame**
  - Similar to STS-N, but the payload in the 87N columns cannot be demultiplexed by Sonet
  - STS payload pointer indicates the concatenated frame
  - 1 set of overhead bytes only
    - Payload remains unchanged from sender to receiver

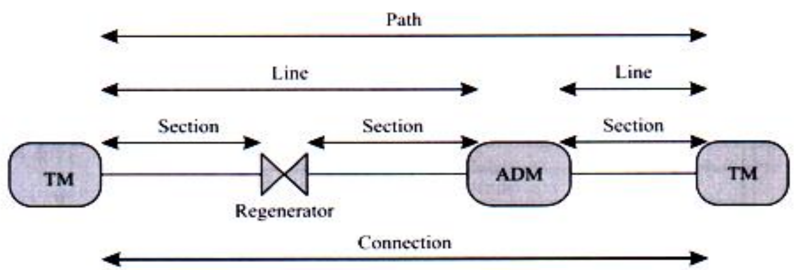
Sonet/SDH – STS-N Frame (4)

- Structure of STS-N frame



Sonet/SDH – Layers (1)

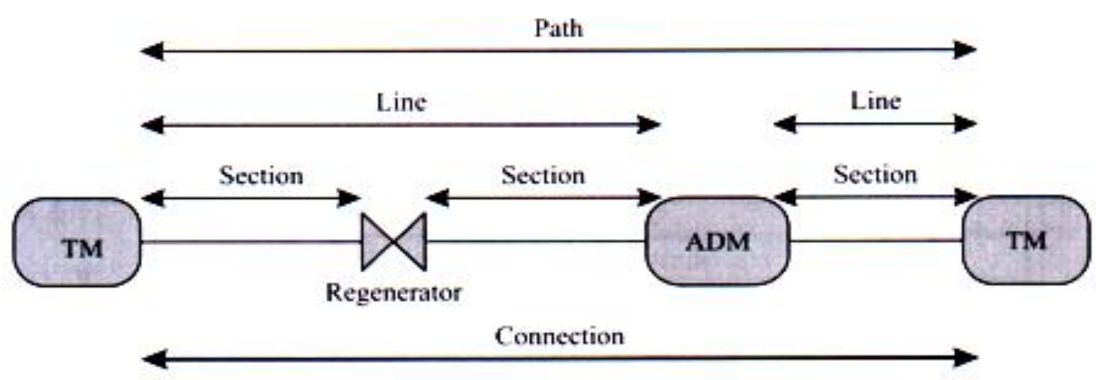
- Sonet layer divided in 4 sublayers
  - **Path layer**
  - **Line layer**
  - **Section layer**
  - **Physical layer**



- Each layer, except for the physical one, adds overhead
- Overhead bytes added when introducing the layer and removed when the layer is finished
  - Meaning of this overhead is explained later on
- Sonet (SDH)
  - Path layer: end-to-end connection between nodes, only visible at link extremities
    - Path overhead inserted by sender, extracted by receiver

Sonet/SDH – Layers (2)

- Line layer (multiplex section layer): multiplexes a certain number of connections at path level on a single link between 2 nodes
  - Line overhead is processed at each intermediate node with TM (Terminal Mux) or ADM (Add-Drop Mux)
  - Responsable of protection switching (faults)
- Section layer (regenerator-section layer): corresponds to each span between regenerators
- Physical layer: trasmission of bits on fiber



Sonet/SDH – Overhead

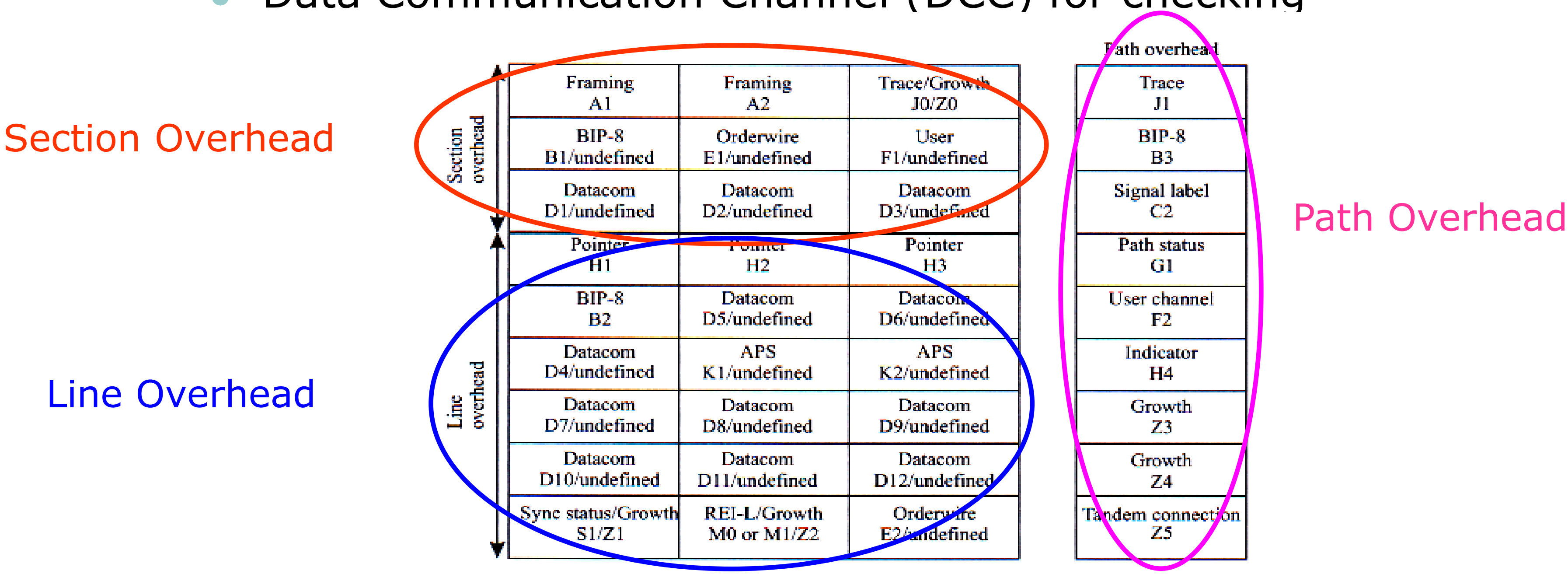
- Provide advanced management functions
  - Particularly useful for carriers
- Enable understanding of connection functioning rather than exact localization and format
- Section and Line Overhead are important for the optical layer
  - Many bytes are controlled by the optical layer
  - Other bytes are still undefined…
  - Suitable for transporting the optical layer overhead
- In Sonet/SDH we have 3 types of overhead
  - **Section Overhead**
  - **Line Overhead**
  - **Path Overhead**

Sonet/SDH – Section Overhead (1)

- **Framing (A1/A2)**
  - Used by network elements to allocate the frame, in each STS-1 inside a STS-N
- **Section Trace (J0)/Section Growth (Z0)**
  - J0 in the first STS-1 inside a STS-N, identification byte to monitor the connection between nodes
  - Z0 in the remaining STS-1, not yet used
- **Section BIP-8 (B1)**
  - In the first STS-1 inside a STS-N
  - BER monitoring between adjacent nodes
- **Orderwire (E1)**
  - In first STS-1 inside a STS-N
  - Voice channel of mantainance personnel

Sonet/SDH – Section Overhead (2)

- **Section User Channel (F1)**
  - In first STS-1 inside a STS-N
  - Insertion of user specific informations
- **Section Data Communication Channel (D1-D3)**
  - In first STS-1 inside a STS-N
  - Data Communication Channel (DCC) for checking

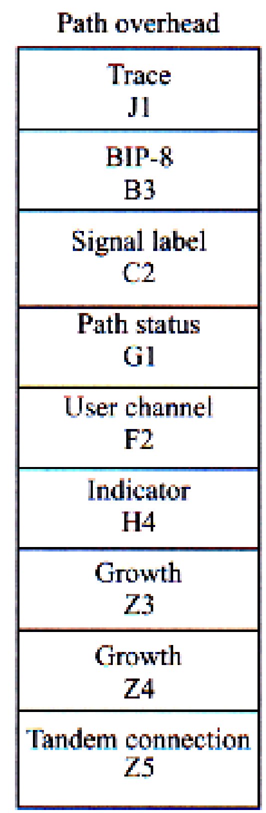


Sonet/SDH – Line Overhead

- **STS Payload Pointer (H1, H2)**
  - 2 bytes pointer, pointing to STS SPE
  - Bytes offset between pointer and first SPE byte
- **Line BIP-8 (B2)**
  - Parity check for each STS-1 inside a STS-N, used by TM and ADM only
  - Regenerators act on B1, and not on B2
- **APS channel (K1, K2)**
  - Signaling channel for APS (Automatic Protection Switching)
  - In general used for maintainance
- **Line Data Communication Channel (D4-D12)**
  - In first STS-1 inside a STS-N
  - Line DCC for maintanance and control

Sonet/SDH – Path Overhead

- **STS Path Trace (J1)**
  - Path identifier for connection monitoring
- **STS Path BIP-8 (B3)**
  - Path level BER control (end-to-end)
- **STS Path Signal Label (C2)**
  - Indicates the SPE content
  - Unique Label for each type of signal mapped in STS
- **Path Status (G1)**
  - The receiver uses if to inform the sender of path performances
  - The receiver inserts the current number of errors



Sonet/SDH – Physical Layer (1)

- Many **standard interfaces** are defined for Sonet/SDH
  - Change depending on bitrate and distance
- ITU standard for SDH is most used (see tables)
- Classification of **SDH** (Sonet) connections
  - **Intra-office I** (short reach)
    - Distances less than 2 km
  - **Inter-office Short-haul S** (intermediate reach)
    - 15 km at 1310 nm and 40 km at 1550 nm
  - **Inter-office Long-haul (L)** (long reach)
    - 40 km at 1310 nm and 80 km at 1550 nm
  - **Inter-office Very-long-haul (V)**
    - 60 km at 1310 nm and 120 km at 1550 nm
  - **Inter-office Ultra-long-haul (U)**
    - About 160 km

Sonet/SDH – Physical Layer (2)

- **Fiber types**
  - G.652 SMF standard fiber
  - G.653 Dispersion Shifted fiber (DSF)
  - G.655 Non Zero Dispersion Shifted Fiber (NZDSF)
- **Source types**
  - LED at 1310 nm
  - MLM Fabry Perot laser at 1310 nm
  - SLM DFB laser at 1550 nm: **high bitrate and distance**
- Physical layer uses scrambling technique to avoid long sequences of 1 and 0
- The standard specifies
  - Maximum loss level (fiber, joints, connectors…)
    - High in intra-office connections
  - Maximum admissible chromatic dispersion

Sonet/SDH – Physical Layer (3)

- Loss specifications translate on distance limitations
  - Intra-office connections: 3.5 dB/km
    - High because of many interconnections
  - Short-haul connections: 0.8 dB/km
  - Long-distance connections: 0.5 dB/km at 1310 nm and 0.3 dB/km at 1550 nm
- Similar situation for dispersion
- The standard includes use of preamplification and high-power amplification …
  - In-line amplification is not included
  - In-line amplification often requires proprietary solutions, hence there is no standard
- With in-line amplification, WDM systems are possible with distance among regenerators between 400 and 600 km

Sonet/SDH – Physical Layer (4)

- Standard physical interfaces for SDH
  - ITU G.957, ITU G.691

- Standard codes
  - Letter (I, S, L, V, U)
    - Type of connection
  - Number (1, 4, 16, 64)
    - Bitrate
  - Number (1, 2, 3, 5)
    - Fiber and wavelength
      - 1: G.652 at 1310 nm
      - 2: G.652 at 1550 nm
      - 3: G.653 at 1550 nm
      - 5: G.655 at 1550 nm
- For ex. V-16.3
  - Very-long-haul, STM-16
  - DSF at 1550 nm

Bit Rate	Code	Wavelength (nm)	Fiber	Loss (dB)	Transmitter	Dispersion (ps/nm)
STM-1	I-1	1310	G.652	0-7	LED/MLM	18/25
	S-1.1	1310	G.652	0-12	MLM	96
	S-1.2	1550	G.652	0-12	MLM/SLM	296/NA
	L-1.1	1310	G.652	10-28	MLM/SLM	246/NA
	L-1.2	1550	G.652	10-28	SLM	NA
	L-1.3	1550	G.653	10-28	MLM/SLM	296/NA
STM-4	I-4	1310	G.652	0-7	LED/MLM	14/13
	S-4.1	1310	G.652	0-12	MLM	74
	S-4.2	1310	G.652	0-12	SLM	NA
	L-4.1	1310	G.652	10-24	MLM/SLM	109/NA
	L-4.2	1550	G.652	10-24	SLM	ffs
	L-4.3	1550	G.653	10-24	SLM	NA
	V-4.1	1310	G.652	22-33	SLM	200
	V-4.2	1550	G.652	22-33	SLM	2400
	V-4.3	1550	G.653	22-33	SLM	400
	U-4.2	1550	G.652	33-44	SLM	3200
	U-4.3	1550	G.653	33-44	SLM	530
STM-16	I-16	1310	G.652	0-7	MLM	12
	S-16.1	1310	G.652	0-12	SLM	NA
	S-16.2	1550	G.652	0-12	SLM	ffs
	L-16.1	1310	G.652	10-24	SLM	NA
	L-16.2	1550	G.652	10-24	SLM	1600
	L-16.3	1550	G.653	10-24	SLM	ffs
	V-16.2	1550	G.652	22-33	SLM	2400
	V-16.3	1550	G.653	22-33	SLM	400
	U-4.2	1550	G.652	33-44	SLM	3200
	U-4.3	1550	G.653	33-44	SLM	530

Sonet/SDH – Physical Layer (5)

- Continuation…
  - The two *D* values correspond to the two different sources
  - ffs: specification to be defined later
  - NA: not applicable limitation (loss limited link)

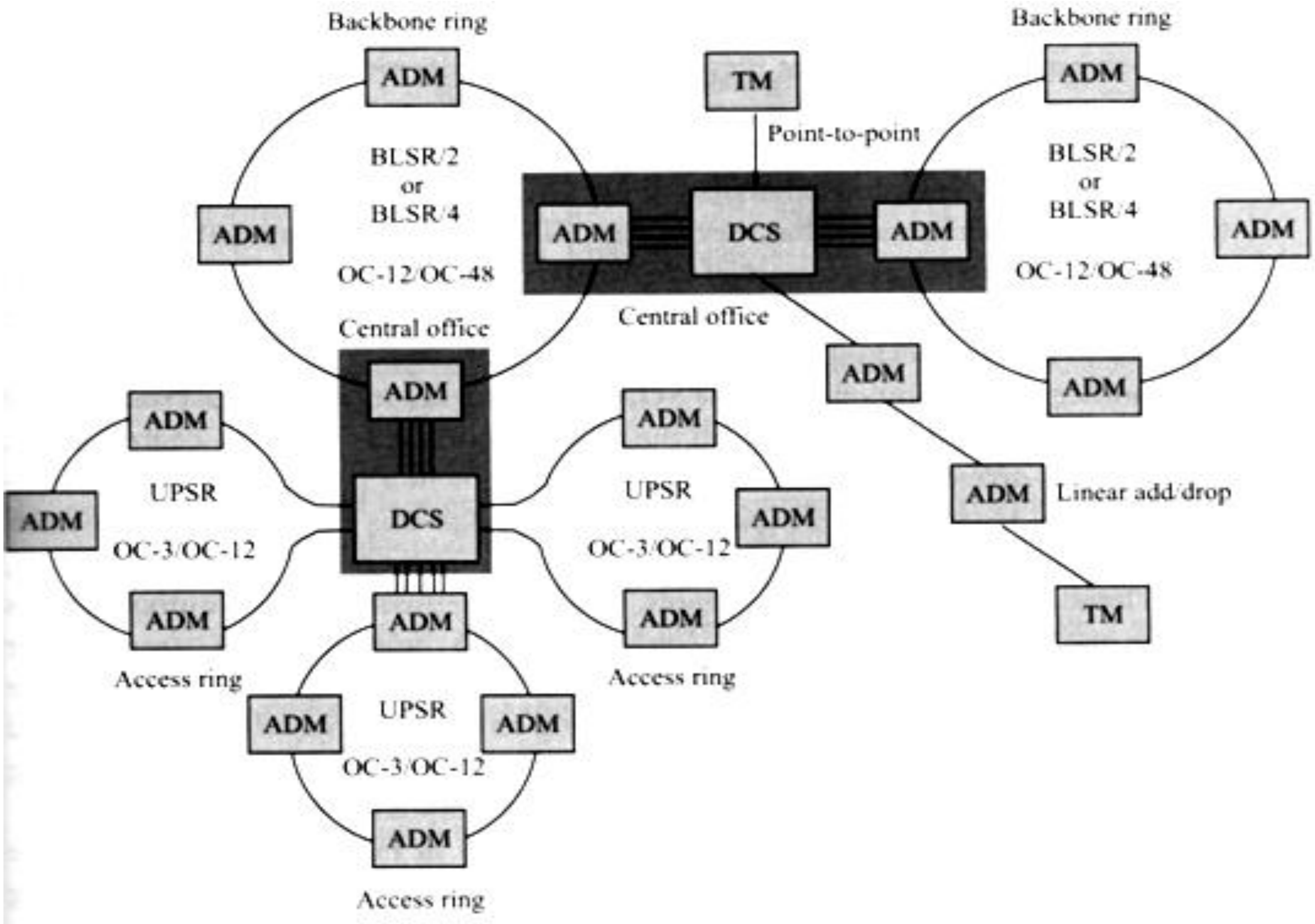
Table 6.3 Different physical interfaces for SDH *(continued)*.

Bit Rate	Code	Wavelength (nm)	Fiber	Loss (dB)	Transmitter	Dispersion (ps/nm)
STM-64	I-64.1r	1310	G.652	0-4	MLM	3.8
	I-64.1	1310	G.652	0-4	SLM	6.6
	I-64.2r	1550	G.652	0-7	SLM	40
	I-64.2	1550	G.652	0-7	SLM	500
	I-64.3	1550	G.653	0-7	SLM	80
	I-64.5	1550	G.655	0-7	SLM	ffs
	S-64.1	1550	G.652	6-11	SLM	70
	S-64.2	1550	G.652	3/7-11	SLM	800
	S-64.3	1550	G.653	3/7-11	SLM	130
	S-64.5	1550	G.655	3/7-11	SLM	130
	L-64.1	1310	G.652	17-22	SLM	130
	L-64.2	1550	G.652	11/16-22	SLM	1600
	L-64.3	1550	G.653	16-22	SLM	260
	L-64.3	1550	G.653	0-7	SLM	ffs
	V-64.2	1550	G.652	22-33	SLM	2400
	V-64.3	1550	G.653	22-33	SLM	400

Sonet/SDH – Infrastructure (1)

- 3 types of configurations for Sonet networks
  - **Point-to-point**
    - Used in early installed links, still useful for some applications
    - Nodes are called Terminal Mux (**TM**), or Line Terminating Equipment (**LTE**)
  - **Linear with ADM**
    - Add/Drop of low bitrate fluxes
      - Multiplexer add/drop (**ADM**)
      - Ex. OC-48 ADM, add/drop OC-12 and OC-3 fluxes
      - ADM inserted between TM create linear configuration
  - **Ring**
    - Used more and more frequently: high reliability
    - Simple, alternate link in case of failure

Sonet/SDH – Infrastructure (2)



Sonet/SDH – Ring networks

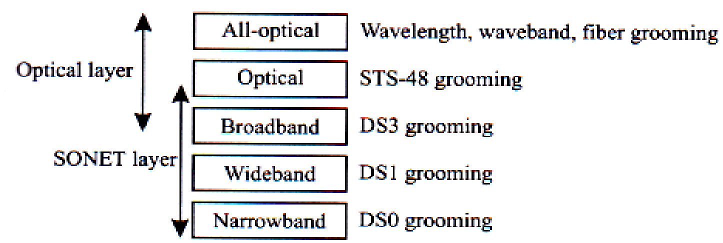
- Sonet ADM devices configurable as …
  - Ring ADM, linear ADM, TM
- Sonet rings composed by ADM
  - Multiplexing, demultiplexing, fault protection
- **Backbone rings**
  - OC-12/OC-48/OC-192 (now we move towards 40 Gbps)
  - Rings overlay, each at different wavelength
  - **BLSR** architecture (Bidirectional Line-Switched Ring)
    - 2 fibers (BLSR/2) or 4 fibers (BLSR/4) per ring
    - Connections between multiple central offices (CO)
- **Access rings**
  - OC-3/OC-12
  - **UPSR** (Unidirectional Path-Switched Ring) architecture
    - 1 fiber per ring
    - In CO are connections between users and hub node

Sonet/SDH – DCS (1)

- **DCS (Digital CrossConnect)**
  - Basic component of Sonet network
    - Manages all transmission resources
  - DCS substitutes manual patch panels in CO
    - Hundreds/thousands of ports
    - Thousands of DS1/DS3 fluxes cannot be handled manually
  - Automatic interconnection under software control, plus mux/demux and performance control
  - Management of PDH, Sonet and SDH fluxes
  - **Traffic Grooming**
    - Traffic aggregation of similar type, QoS, destination
    - Including mux/demux of low bitrate fluxes

Sonet/SDH – DCS (2)

- Types of DCS
  - Classified on the basis of grooming granularity
    - **Narrowband DCS**
      - Grooming at the level of DS0 flux
    - **Wideband DCS**
      - Grooming at the level of DS1 flux
    - **Broadband DCS**
      - Grooming at the level of DS3 (STS-1) flux
    - **Optical DCS (OXC)**
      - Grooming at the level of STS-48 flux, wavelength…
      - Fully optical DCS
  - Interfaces from grooming bitrate up to higher bitrates
    - Ex. broadband DCS interfaces from DS3 to OC-48



Clients of the optical layer

- Clients of optical layer
  - Sonet/SDH
  - ATM
  - IP
  - MPLS
  - Storage-Area Networks
  - Gigabit Ethernet
  - RPR

ATM (1)

- **ATM (Asynchronous Transfer Mode)**
  - Objective: integration between voice and data
    - Traditionally, voice and data networks were separate
  - ATM networks in LAN, MAN, WAN
  - Packets (*cells*) with fixed dimension of 53 bytes
    - 48 bytes of payload and 5 of overhead
    - **Compromise between voice and data requirements**
      - Voice prefers small packets
        - Little delivery delay
      - Data prefer big packets
        - Less overhead
  - Statistical cell multiplexing
    - Efficient use of bandwidth
  - Possibility to guarantee QoS
    - Minimum bandwidth, maximum delay…

ATM (2)

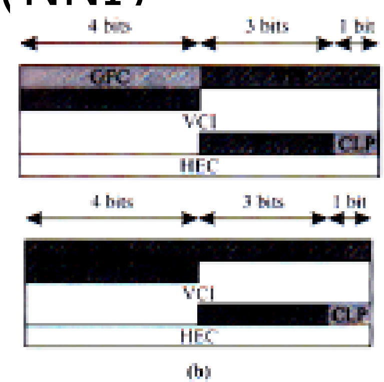
- Key point of ATM: guarantee of QoS
  - Use of **virtual circuits** (VC)
  - Knowledge of peak and average bandwidth for each VC
  - Admission control for new connections
  - Use of switching also in LAN
    - This differentiates ATM from Ethernet, token ring and FDDI
      - Easier to guarantee QoS in ATM LAN
- **Fixed cell dimension**
  - Simple and inexpensive high speed switches
- Standard physical layers for ATM
  - 25.6 Mbps on copper
  - 622.08 Mbps on monomode fiber
- Some standard optical interfaces…
  - 100 Mbps, with same parameters as FDDI
  - 155.52 Mbps with LED on MMF at 1310 nm

ATM (3)

- **Private user-network interfaces**
  - Interfaces for interconnections between ATM users and switches of private businesses
  - Ex. The two interfaces described in the previous slide
- **Public user-network interfaces**
  - Interfaces for interconnection between ATM users and switches for public networks
  - Use of PDH or Sonet/SDH as lower layer
    - DS3, STS-3c, STS-12c, STS-48c
- ATM terminology
  - Its lower layer is the physical layer (ex. Sonet)
    - Interface ATM/Sonet: interface with physical level
- ISO/OSI layer model
  - Sonet is data-link level of ATM

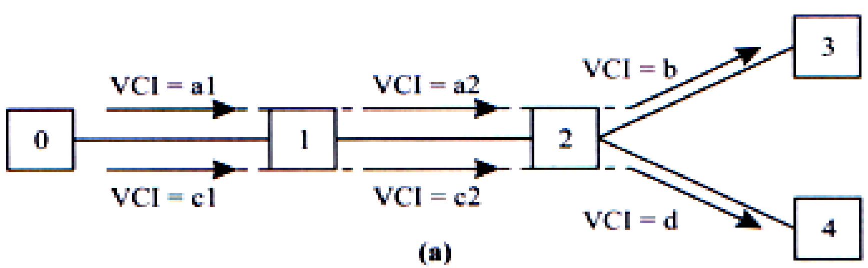
ATM Functionalities

- **UNI** (User-to-Network Interface)
  - Data transmitted from user to ATM network through a UNI
- **NNI** (Network-to-Network Interface)
  - Data transmitted between ATM switches through a NNI
- Header (5 bytes) is different in UNI and NNI
  - **GFC** (Generic Flow Control): 4 (0) bit UNI (NNI)
  - **VPI** (Virtual Path Identifier): 8 (12) bit UNI (NNI)
  - **VCI** (Virtual Circuit Identifier): 16 bit
  - **PT** (Payload Type): 3 bit
  - **CLP** (Cell Loss Priority): 1 bit
  - **HEC** (Header Error Control): 8 bit
    - CRC on 5 header bytes



ATM Connections

- Concept of end-to-end **connection**
  - ATM service is connection-oriented
  - Different from IP, which is connectionless
  - ATM connection: **virtual channel (VC)**
    - With VCI identifier
      - It is unique for each link through which the connection goes through, but it may vary from link to link
      - Ex. The upper connection has VCI *a1*, *a2* e *b* on 0-3 link
    - VCI determined at connection setup…
      - Released when connection is terminated
    - Each switch handles a VCI table
      - 3 columns: input VCI, exit VCI, output link



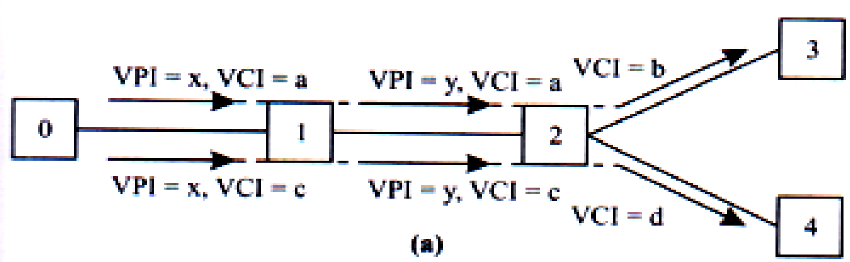
(a)

Incoming VCI	Outgoing link	Outgoing VCI
a1	1 to 2	a2
c1	1 to 2	c2

(b)

Virtual Paths (1)

- Millions of VC share same link
  - VCI tables with more than 65.000 elements are not manageable
  - Aggregation of VCs by routing
    - Thousands of VC with partially overlapping paths
    - Use of virtual paths (VP), with VPI identifiers
    - Ex. Two VCs share the 0 – 1 – 2 path
    - Common VPI assigned for each link
      - Ex. *x* between 0 and 1, *y* between 1 and 2
    - Virtual path composed of 2 links
      - 0 starting node, 2 destination node
    - In the two links, routing using VPI



(a)

Incoming VPI	Outgoing link	Outgoing VPI
x	1 to 2	y

(b)

Virtual Paths (2)

- Advantages of two-levels routing
  - Simplification of cell routing
  - Development of low cost ATM switches
  - Creation of logical links between nodes
    - Virtual path between nodes is treated by VCs as logical link
    - Ex. VP between 0 and 2 nodes is a logical link for the VCs
  - When using VCI only…
    - 24 bit VCI for UNI, 28 bit for NNI
    - Routing is complex and costly

Adaptation layers

- Applications on ATM generate…
  - Continuous data fluxes (video, voice)
  - Large dimension packets of variable size (IP)
- ATM uses fixed size cells (53 bytes)
  - Necessity to map user data into cells
  - Task of **AAL** (ATM Adaptation Layers)
    - Segmentation and reassembly (SAR)
    - AAL segments user data in ATM cells…
    - Reassembles them at destination
- ITU I.363
  - AAL standard: AAL-1, AAL-2, AAL-3/4, AAL-5
    - AAL-3 and AAL-4 are degenerate

AAL-1

- **Constant bitrate data trasport**
  - Voice, video
  - Time continuous data flux
- Segmentation in 47 payload bytes AAL, 1 header byte AAL
  - Header contains a sequence number
  - Sequence number is protected by CRC (cyclic redundancy check)
- Passing to ATM level
  - ATM adds its 5 bytes header
- The 47 payload bytes are not protected
  - Adequate for voice/video transmission

AAL-5

- **Trasport of variable size packets**
  - Bytes with up to $2^{16} = 65536$ length
  - Trasport of IP packets on ATM
- AAL-5 segments IP packets in ATM cells without adding overhead in each cell
  - Use of PT field in the ATM header to indicate the last cell that forms the packet
  - In the last cell, last 2 bytes are AAL header
    - Length of IP packet and CRC of packet
- In all cells less one…
  - AAL payload coincides with the ATM one
  - Reduced overhead with respect to AAL-1
  - CRC code on payload

Quality of Service QoS (1)

- ATM QoS
  - Limitation on lost cells, delay and jitter
  - **Traffic shaping**
    - Contract with user on traffic characteristics
      - Min and max cell rate, dimension of bursts that can be transfered through a UNI
      - Cells that do not respect the contract are eliminated
      - Otherwise their CLP (cell loss priority) is set
        - These are eliminated first in case of congestion
    - Accurate control of connection traffic
      - In exchange, ATM guarantees high QoS
  - **Admission control**
    - Based on traffic shaping parameters
      - New connections are accepted only if they are compatible with QoS of already existing connections

Quality of Service QoS (2)

- **Service classes**
  - Chosen on the basis of traffic parameters and of the QoS
  - Each connection belongs to a class
  - Examples
    - **CBR** (Constant Bit Rate)
      - The connection specifies the peak cell rate and guarantees against cell loss, delay and jitter
      - AAL-1
    - **UBR** (Unspecified Bit Rate)
      - The connection specifies the peak cell rate, but without guarantee of QoS
      - AAL-5
- Complex queue management techniques
  - Guarantee of QoS for connections of different classes

Flux control– Routing (1)

- **Flux control**
  - Control of user traffic not based on contract, but on network congestion
  - Data traffic applications are not CBR controllable
    - Ex. FTP
  - Control through GFC bytes in UNI header
    - They signal if transmission should be enabled or blocked
- **Routing**
  - Routing protocols enable to build VCI e VPI tables at each switch
  - Protocols are standardized by ATM forum
    - **PNNI (Private Network-to-Network Interface)**
    - B-ICI (Broadband Inter Carrier Interface)

PNNI Protocol

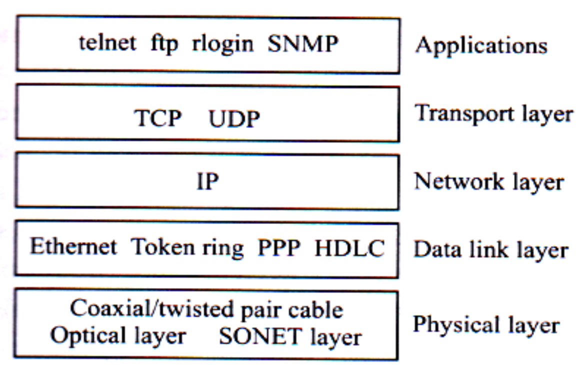
- Task
  - Determine a path through the network from sender to receiver
  - Necessary to provide the requested QoS
  - State of the link
    - Available bandwidth, lost cells, maximum delay …
    - Administrative cost, or weight
  - Each switch performs flooding with the state of all output link with which it is connected to
    - Each switch knows the state of all nodes
  - When a new connection is requested
    - Input switch compute path that guarantees QoS with minimum cost
    - Path switches are informed of the new connection and of requested QoS

Client of optical layer

- Client of optical layer
  - Sonet/SDH
  - ATM
  - IP
  - MPLS
  - Storage-Area Networks
  - Gigabit Ethernet
  - RPR

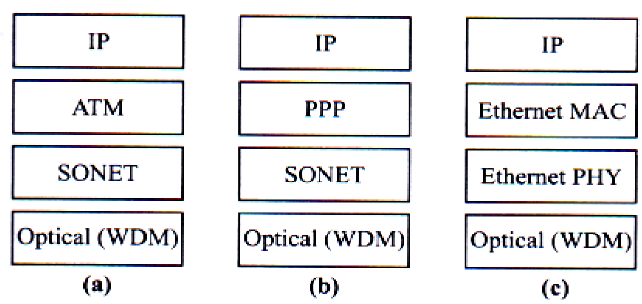
IP (1)

- **IP (Internet Protocol)**
  - The most widely used technology for WAN networks today
  - Internet protocol for Internet and Intranet
    - Connectionless service
  - May work on many different data-link levels
    - Ethernet, token ring, PPP, HDLC
    - This is one of the reasons for the success of IP
  - Transport protocols
    - **TCP** (Transmission Control Protocol)
      - Connection oriented
      - FTP, Telnet, HTTP…
    - **UDP** (User Datagram Protocol)
      - Connectionless
      - Trasport of simple messages
      - Streaming, NFS, SNMP



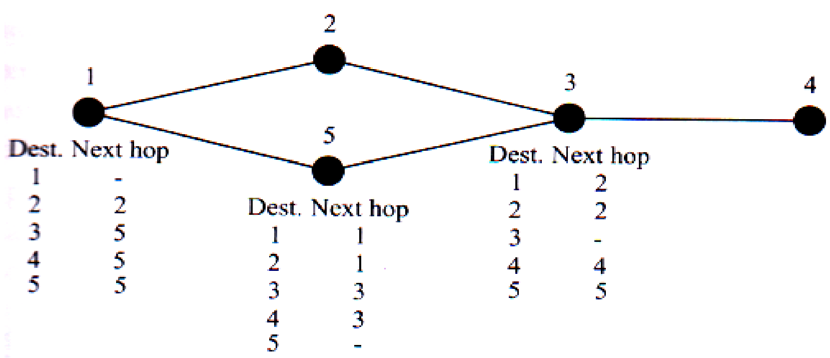
IP (2)

- **IP over WDM**
  - Mapping of IP on the optical layer
    - **IP over ATM over Sonet** (a)
      - IP packets mapped in ATM cells, coded in Sonet frame and transmitted on a WDM channel
    - **Packet over Sonet, POS** (b)
      - IP packets mapped in PPP frame, coded in Sonet frame and transmitted on WDM channel
    - **IP over Gigabit Ethernet** (c)
      - 10 GE as MAC, IP packets coded in 10 GE frame and transmitted on WDM channel



Routing (1)

- IP packets have variable length
  - Maximum dimension is 65535 bytes
- IP router is key element of internet networks
- Routing mechanism
  - Each router has a routing table
    - One or more entries for each destination router
    - Indicates the adjacent node to to pass the packet
    - The router searches in the packet header the destination address, hence it routes based on the table
  - Management of routing tables in crucial for the network
    - **Routing protocols**



Routing (2)

- **Intra-domain** routing protocols
  - Ex. **OSPF** (Open Shortest Path First) protocol
  - Each router samples the state of adjacent nodes
  - If a state variation is found
    - Flooding of the link state to all network nodes
    - Modification of all routing tables based on the new informations
    - All nodes know the current topology
  - The flooding must be “smart”
    - Old link state may arrive after a new one
      - Sequence number assigned to each link state
      - Link states with older sequence numbers are discarded
      - Link states are periodically generated
        - Since some of them could be lost

Routing (3)

- Link state packets provide to each router a global overview of the network
  - Hence the router computes the optimum path between itself and other routers, and stores the next node for each destination
    - Dijkstra algorithm
  - It is impossibile that each router keeps the topology of the entire Internet
    - Division of Internet in Autonomous Systems (**AS**)
    - Intra-domain protocol (ex. OSPF) within the AS
    - Inter-domain protocol for routing between AS
      - Ex. **BGP** (Border Gateway Protocol) protocol

Quality of Service QoS

- IP offers **"best effort"** service
  - Packets undergo different paths, different delays, non-sequential delivery, in case of congestions packets are eliminated
  - Strong demand for QoS in IP networks
  - **Diff-Serv** (Differentiated Services)
    - Packets grouped in classes, indicated in the header
    - Different classes, different treatment by routers
      - Packets **EF** (Expedited Forwarding)
        - Separate queue, rapid delivery
      - Assured Forwarding (**AF**)
        - Indicates priority of discarding of packet
    - Diff-Serv faces the QoS problem, but it cannot provide end-to-end guarantees
      - Ex. One cannot say a priori if there is enough bandwidth for a new real-time traffic flux

Client of the optical layer

- Client of optical layer
  - Sonet/SDH
  - ATM
  - IP
  - MPLS
  - Storage-Area Networks
  - Gigabit Ethernet
  - RPR

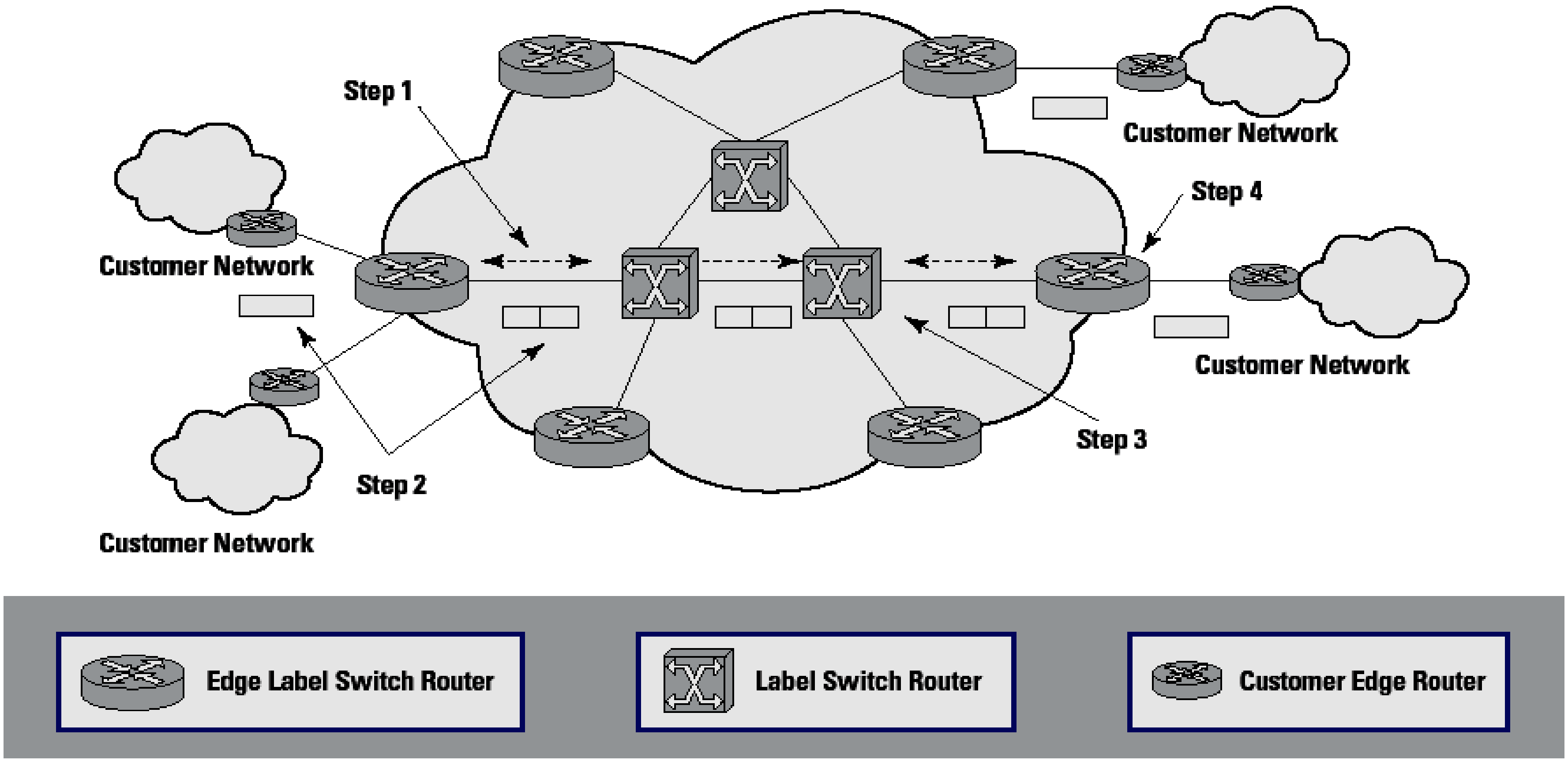
MPLS

- **MPLS (Multi-Protocol Label Switching)**
  - Strong demand of end-to-end QoS in IP networks
  - Delivery of different services differentiated by class
    - Differentiation among different traffic types
  - **MPLS is layer between IP and data-link level (level 2.5)**
  - MPLS networks based on label switching concept
    - Labels indicate path and attributes of services
    - At network input, processing of packets
      - Selection and use of proper label
    - Internal routers read the label, apply the requested services in a proper way and route
      - Routing based on label content
    - Analysis and classification of packets at input only
    - Network output: label is eliminated and delivery to destination

MPLS – Label switching (1)

- Path of a packet along the network
  - **Step 1**: classic construction of routing labels
    - OSPF algorithm, also MPLS routers take part to it
    - **LDP** protocol (Label Distribution Protocol)
      - Uses routing tables to determine labels among adjacent nodes
      - Creation of pre-configured **LSP** (Label Switching Paths)
  - **Step 2**: a packet arrives at network input
    - Edge Label Switching Router (**LSR**)
    - LSR determines service of level 3 (QoS)
    - LSR applies a label and routes the packet
  - **Step 3**: at each node, LSR reads the label, substitutes it with a new one (from the table) and routes it
  - **Step 4:** at the output, Edge LSR eliminates the label and routes to destination

MPLS – Label switching (2)



MPLS – Advantages (1)

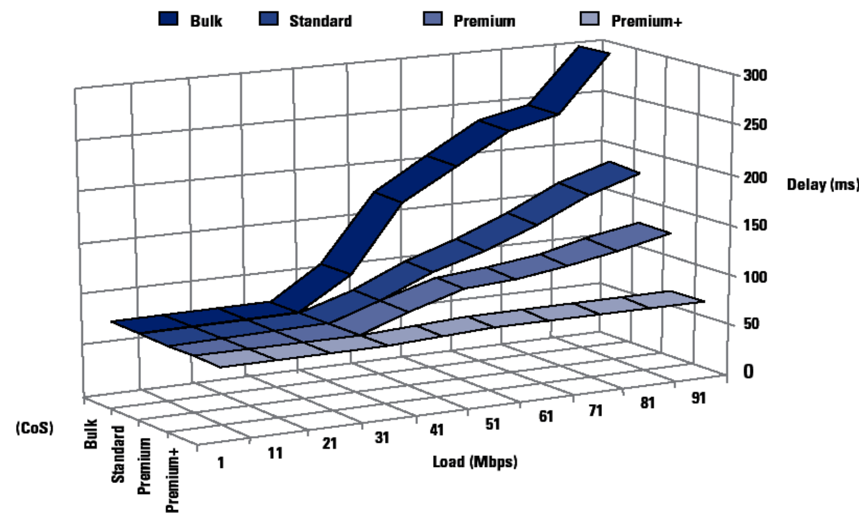
- Paradigms of MPLS network
  - **Separate creation of LSP and routing**
    - Creation of LSP as network control functionality
    - Hardware optimized for routing
    - Both functionalities fully hardware implemented
    - Label switching much simpler than IP routing
      - Higher number of packets per second can be processed
  - **Concept of path in IP network**
    - IP routes without knowing the end-to-end connection
    - MPLS permits to specify paths for packets
      - Bandwidth optimization, congestion prevention, QoS…
  - **Concept of end-to-end QoS in IP network**
    - Possibility to reserve bandwidth for a LSP
    - LSP are distinguished on the basis of traffic type

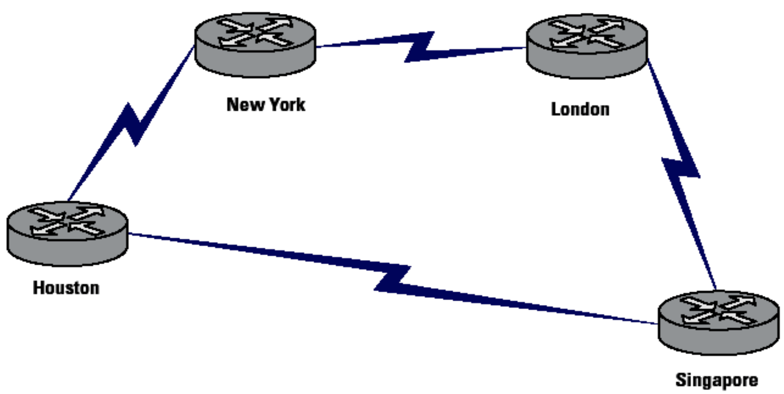
MPLS – Advantages (2)

- **Greater reliability in case of a fault**
  - Definition of 2 LSP among the same nodes
  - Fast switching in case of a fault
  - IP routing is very inefficient and slow in such cases
- **Creation of Virtual Private Networks (VPN)**
  - MPLS-based IP VPN
    - Connectionless IP networks able to provide security and QoS through service classes
    - Easy and efficient method to reduce costs to extend a LAN from intranet to extranet
    - Traffic classification and routing according to the type
      - Voce, video, e-mail…
    - Each VPN traffic is transported by a set of LSP
    - A single infrastructure supports many VPN, so it is easy to add or erase a VPN
    - Architecture for next generation IP services

MPLS - Applications

- **Classes of service (CoS)**
  - Delivery of ad-hoc QoS for each CoS
  - Ex. Guarantee of maximum delivery delay for a given CoS
    - Streaming video





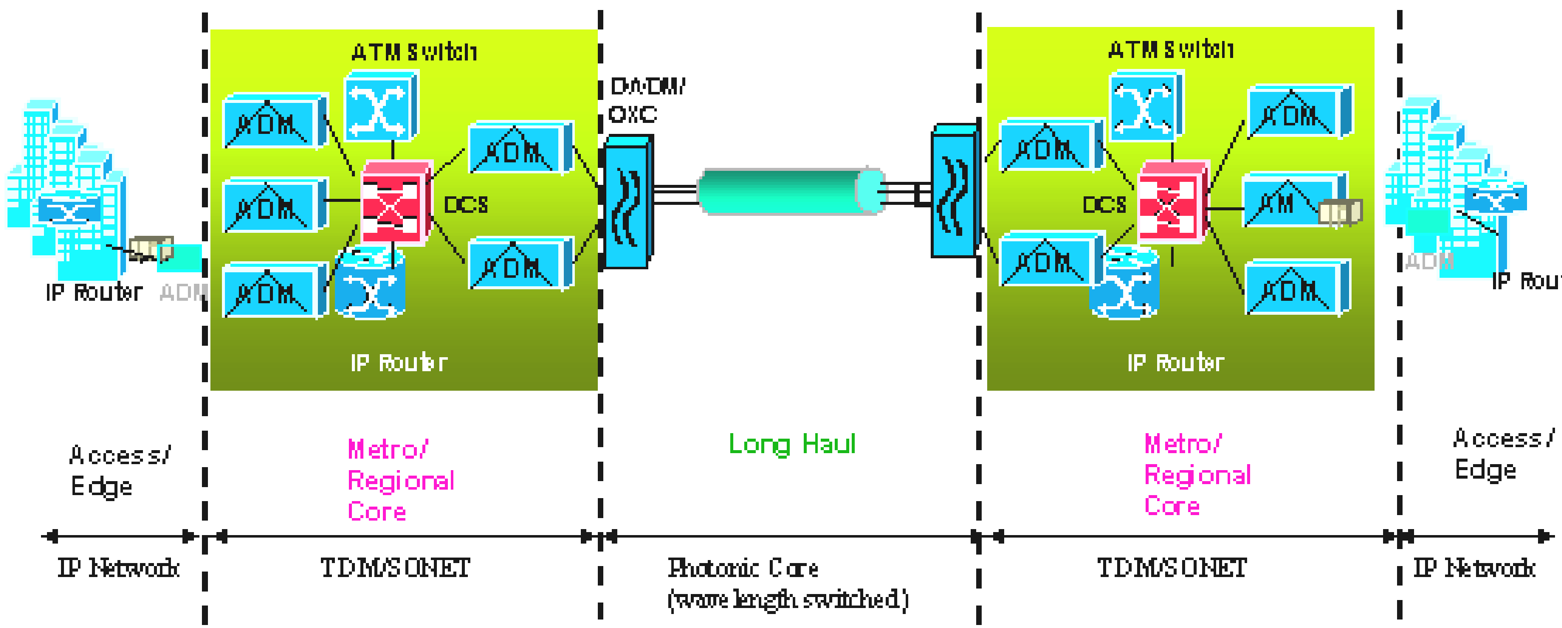
- **Traffic engineering**
  - Path control to avoid network congestion
  - Sending of data from Houston – Singapore
  - OSPF chooses the direct link
    - A traffic jam may ultimately result
  - MPLS may use a secondary link
    - Bandwidth usage is optimized

GMPLS – hints (1)

- **Generalized MPLS**
  - Extension of MPLS to packet, TDM, wavelength, fiber switching
  - Use of labels at all levels
  - Problems with optical networks and TDM
    - Devices are not designed to extract and process labels
    - Discrete bandwidth allocation only
    - Huge quantities of data and resources to manage
    - Configuration of DCS, OXC is time-consuming
    - Fault management (ex. 50 ms with Sonet)

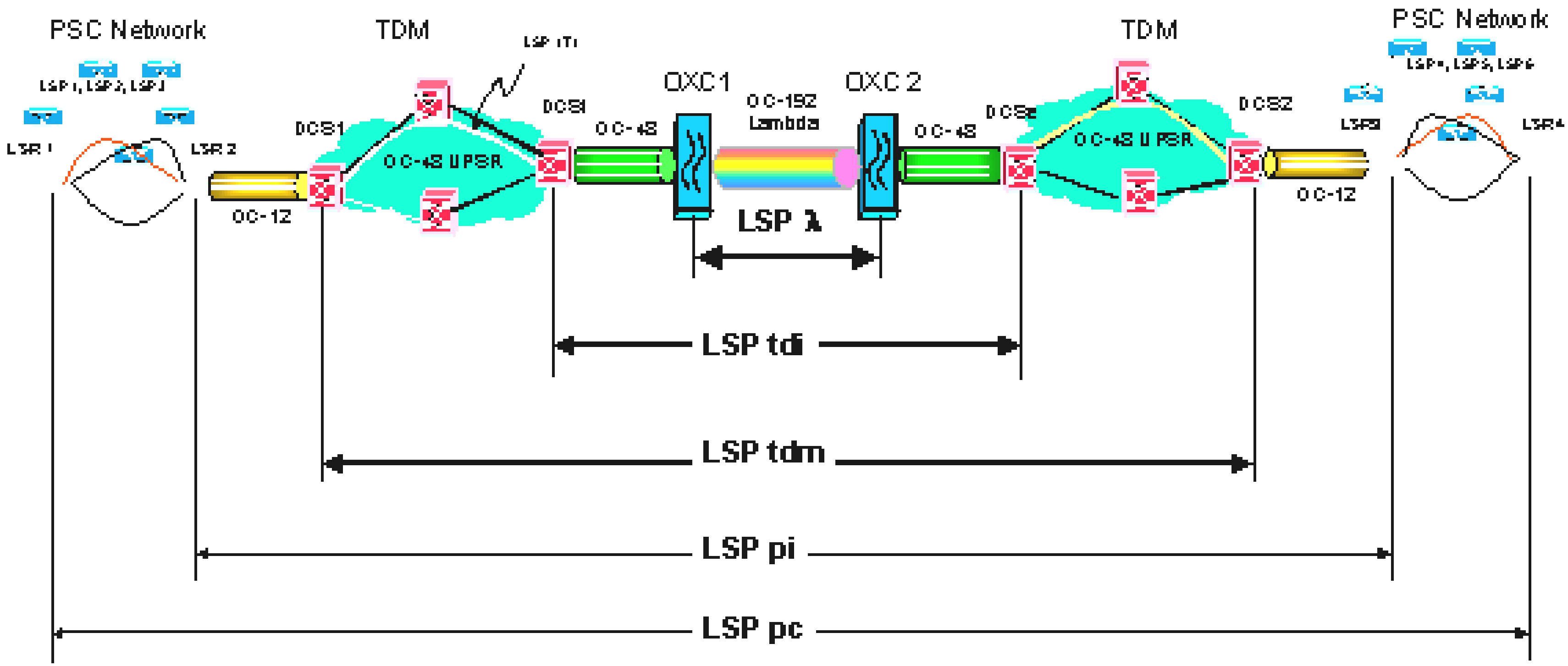
GMPLS – hints (2)

- Example
  - IP routers connected to Sonet metro networks
  - Metro networks connected via DWDM



GMPLS – cenni (3)

- **Generalised label**
  - It refers to packet, time-slot, wavelength or fiber

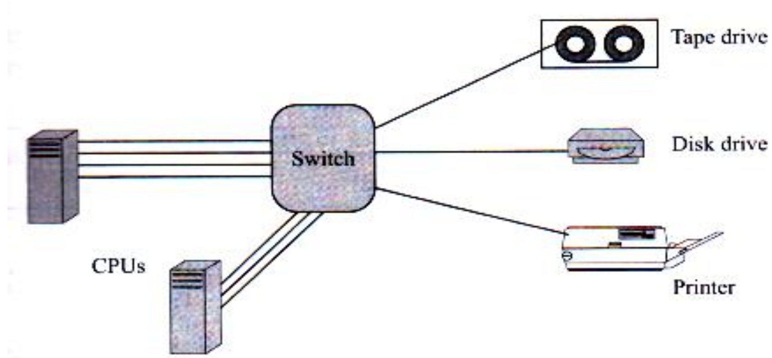


Client of optical layer

- Client of optical layer
  - Sonet/SDH
  - ATM
  - IP
  - MPLS
  - Storage-Area Networks
  - Gigabit Ethernet
  - RPR

Storage-Area Networks (1)

- **SAN (Storage Area Networks)**
  - Networks for connections between computers and other devices
    - Useful for business with big datacenters
  - The key element is an **electronic switch**
    - Connections among devices are reconfigurable
    - **Circuit switching** connections
  - In the past, SAN limited to a building or campus
  - Now SAN extends to metro level, or even long haul
    - Reliability against disasters (backup)
    - Delocalization of datacenters (cost reduction)



Storage-Area Networks (2)

- Bitrates typically between 200 Mbps and 1 Gbps on fiber
- Not very high bitrate, the keypoint for the optical layer is the number of connections
  - From hundreds to thousands of links between datacenters
- Main SAN technologies
  - **ESCON (Enterprise Serial Connection)**
  - **Fibre Channel**
  - **HIPPI (High Performance Parallel Interface)**
- Use of line coding for fiber transmission
  - Data rate (Mbytes/s) vs. transmission rate (Mbaud/s)

Network	Data Rate (MBytes/s)	Transmission Rate (Mbaud)	Physical Interface
ESCON	17	200	LED/MMF
			MLM/SMF
HIPPI	100		parallel copper
HIPPI (serialized)	100	1200	MLM/SMF
Fibre Channel	100	1063	MLM/SMF or copper
	50	531	MLM/SMF or copper
	25	266	MLM/SMF or copper
	12.5	133	MLM/SMF or copper
	200	2126	MLM/SMF
	400	4252	MLM/SMF

ESCON

- Developed by IBM at the end of the ‘80
- Substitutes the ineffective, slow copper connections
- Widely used to connect mainframes
- Data rate 17 Mbytes/s
  - Overhead and line coding (8, 10), 200 Mbaud/s
- Physical level
  - MMF fiber at 1310 nm with LED sources for L < 3 km
  - SMF fiber at 1310 nm with MLM sources for L < 20 km
- **Data-link level: stop-and-wait**
  - Sending of data, then wait for ACK before new block
  - Reduction of throughput as length grows
  - Heavy liniting factor with ESCON
    - Specifications on maximum interconnection distances

Fibre Channel

- Standard developed at the end of the ’90
- Same applications as ESCON, with I/O ports on peripherals and computer, electrical switching
- Widely used until now
- The standard includes a large veriety of bitrates
  - Starting from the “full speed” version at 100 Mbytes/s
  - Version at ¼ speed (25 Mbytes/s)
  - Version at 400 Mbytes/s
- Line coding (8, 10) as in ESCON
- Use of both copper and fiber interfaces

  Copper up to 100 Mbytes/s, fiber beyond

HIPPI

- Widely used for supercomputer links
- Parallel electical interface at 100 Mbytes/s
- Clock skew limits maximum distance to 25 m
- Beyond 25 m HIPPI is made serial and transmitted over fiber
  - Serial HIPPI, optical interfaces up to 1.2 Gbaud
- Other versions
  - Serial interface at 200 Mbytes/s with 2 fibers
  - 12 fiber interface, each at 100 Mbytes/s
- HIPPI competitor of Fibre Channel and ESCON
- HIPPI network composed by host and peripherals connected to HIPPI switches by optical fibers

Client of optical layer

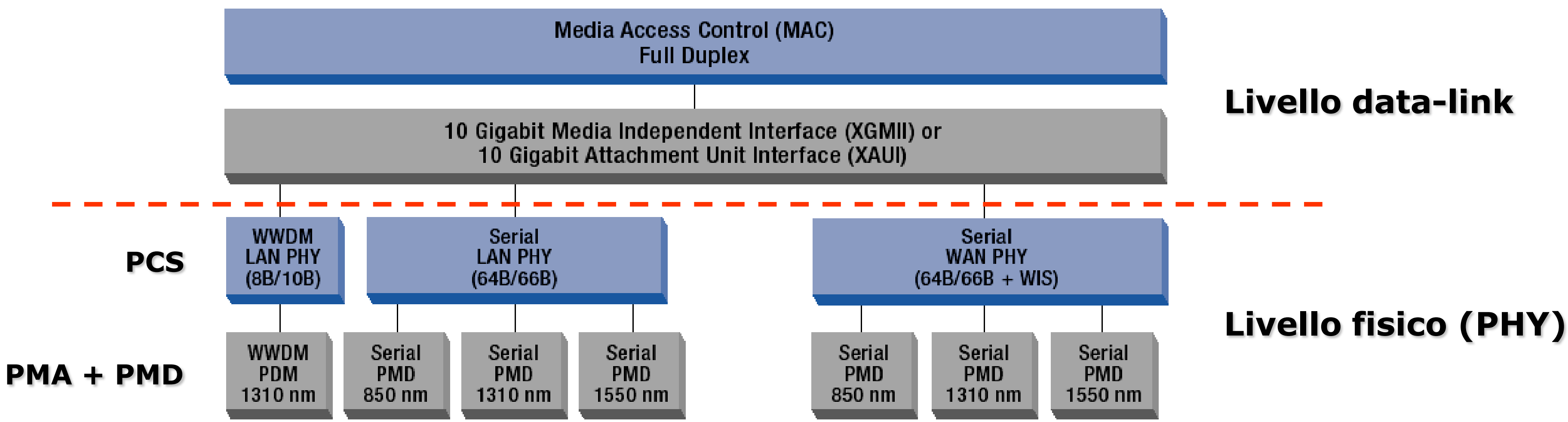
- Client of optical layer
  - Sonet/SDH
  - ATM
  - IP
  - MPLS
  - Storage-Area Networks
  - Gigabit Ethernet
  - RPR

10 Gigabit Ethernet (1)

- Almost all Internet traffic originates and is delivered to Ethernet networks
  - Low cost, reliable, simple to install
- The evolution of Ethernet (born 40 years ago) goes towards the requirements of modern packed networks
- Standard 10 Gigabit Ethernet
  - Extension of protocols IEEE 802.3 at 10 Gbps bitrate and to applications on WAN links (**IEEE 802.3ae**)
  - Full compatibility with previous versions IEEE 802.3
  - 10 GE maintains the traditional Ethernet architecture…
    - It is a protocol of level 1 and 2
    - Necessity of a MAC (Media Access Control)
    - Format and dimensions of frames
  - The evolution continues in terms of bitrate and distance

10 Gigabit Ethernet (2)

- Only a difference between Ethernet and 10 GE
  - 10 GE is full-duplex technology
  - Protocol CSMA-CD is not necessary
- Architecture of protocol **IEEE 802.3ae**



10 Gigabit Ethernet (3)

- **MAC** connected to physical level (**PHY**) through a medium indipendent interface (**XGMII**)
- Physical lavel divided in 3 sublevels
  - **PMD** (Physical Media Dependent)
    - Provides physical connection to the medium
    - Ex. transceivers are PMDs
  - **PMA** (Physical Medium Attachment)
  - **PCS** (Physical Coding Sublayer)
    - Provides coding (ex. 64B/66B) and multiplexing
- Two different types of PHY
  - **LAN PHY**
  - **WAN PHY**
    - Similar to LAN PHY, but the PCS permits the connection with Sonet STS-192

10 Gigabit Ethernet - PMD

- IEEE 802.3ae defines 4 PMD
  - Serial PMD at 1310 nm, monomode fiber on maximum distance of 10 km
  - Serial PMD at 1550 nm, monomode fiber on maximum distance of 40 km
  - Serial PMD at 850 nm, multimode fiber on maximum distance of 300 m
  - PMD WWDM (Wide-Wave WDM) at 1310 nm, monomode fiber on maximum distance of 10 km or multimode fiber on maximum distance of 300 m

Device	8B/10B PCS	64B/66B PCS	WIS	850 nm Serial	1310 nm WWDM	1310 nm Serial	1550 nm Serial
10GBASE-SR		■		■			
10GBASE-SW		■	■	■			
10GBASE-LX4	■				■		
10GBASE-LR		■				■	
10GBASE-LW		■	■			■	
10GBASE-ER		■					■
10GBASE-ER		■	■				■

10 Gigabit Ethernet - Advantages

- Basic ethernet is most adopted technology for LAN
- Ever growing bandwidth request
- Convergence of voice and data networks on Ethernet
- 10 GE supports bitrates up to **10 Gbps** on distances up to **40 km**
  - Multimode fibers
  - Monomode fibers
    - Distance spans from 5 to 40 km
  - Use of VCSEL sources
  - In general, possible to use low cost optics
  - Natural choice for expansion of existing Ethernet networks
    - Ethernet has easy interoperability with 10 GE
    - Basic knowledge and management are very similar
    - Standard products available from several vendors

10 Gigabit Ethernet – Applications (1)

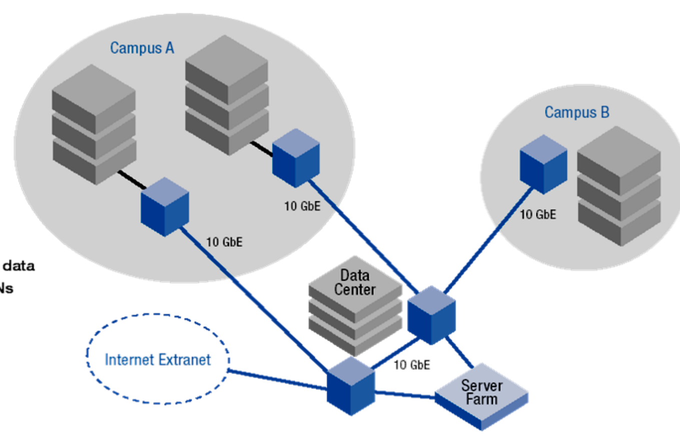
- Packets leave the server through a 10 GE short-haul connection, move on a DWDM network and arrive to a PC connected to a GE port
  - No protocol conversion or re-framing
- **Server connection**
  - Proprietary solutions
    - High cost, difficult management and maintanance
  - Fibre Channel
    - Standard but costly, low interoperability, not well known by personnel
  - 10 Gigabit Ethernet
    - Optimal solution for server interconnection
      - Offers sufficient bandwidth (10 Gbps)
      - Single server sufficient bandwidth to replace many others
      - Low latency time, crucial for clustering

10 Gigabit Ethernet – Applications (2)

- **LAN**
  - Guarantee of greater bandwidth on longer distances
  - Support of multimode and monomode fibers
  - Possible ad hoc choice of server and datacenter location within 40 km
  - Backbone 10 GE short-haul multimode fiber for switch-switch and server-switch connections
    - Low cost, high performances
    - Low link congestion, low latency

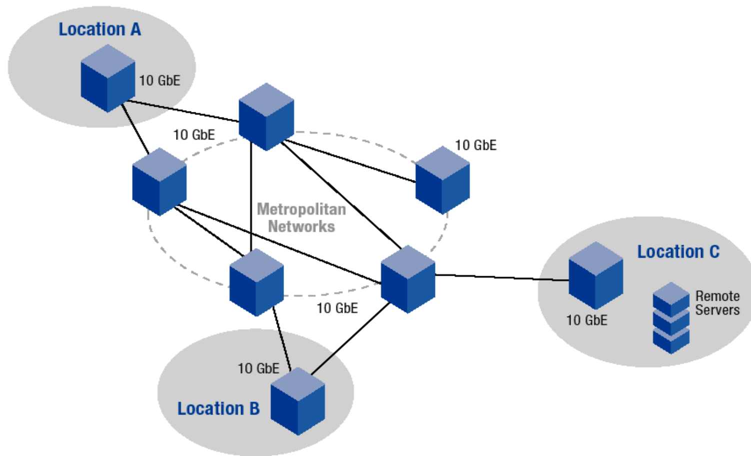
10 GbE in service provider data centers and enterprise LANs

- Switch to switch
- Switch to server
- Data centers
- Between buildings



10 Gigabit Ethernet – Applications (3)

- **MAN/SAN**
  - Excellent solution for backbone of metro networks
  - Use of SMF, link up to 40 km that can reach all customers in a city
- **WAN**
  - Links with high performances between switches/routers connected to Sonet/SDH networks
  - Interfaces WAN PHY
    - LAN connected by Sonet/SDH through DWDM



Client of the optical layer

- Client of the optical layer
  - Sonet/SDH
  - ATM
  - IP
  - MPLS
  - Storage-Area Networks
  - Gigabit Ethernet
  - RPR

RPR (1)

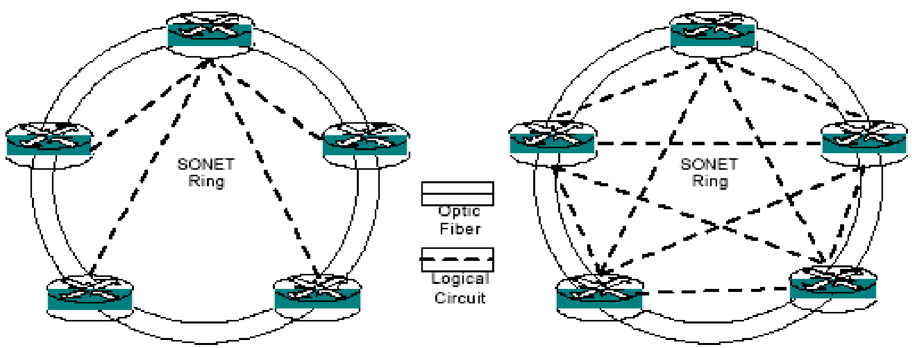
- **RPR (Resilient Packet Ring)**
  - Migration of packet-based networks from LAN to MAN
  - Data traffic ever increasing, difficult to trasport on Sonet/SDH networks which are optimized for voice
  - Solution: packet networks also in metro networks
  - Ethernet handles in optimal way IP packets as well
  - 10 GE has enough speed for metro networks
  - However…
    - Most of installed MAN are ring type
      - High reliability, fast restoration (< 60 ms)
    - Ethernet not adapted to ring networks
      - Missing the MAC for ring management!
    - Ethernet has no protection mechanisms

RPR (2)

- Necessity of **new technology** that…
  - Exploits at best the characteristics of rings
  - Maintaining advantages of packet transport
- **RPR** emerging technology for transport on metro networks
  - Efficient support of rings (as in Sonet)
  - Fast recovery from faults (as in Sonet)
  - Simple, efficient (as Ethernet)
  - Equity in management of resources
  - Management of network congestion problems

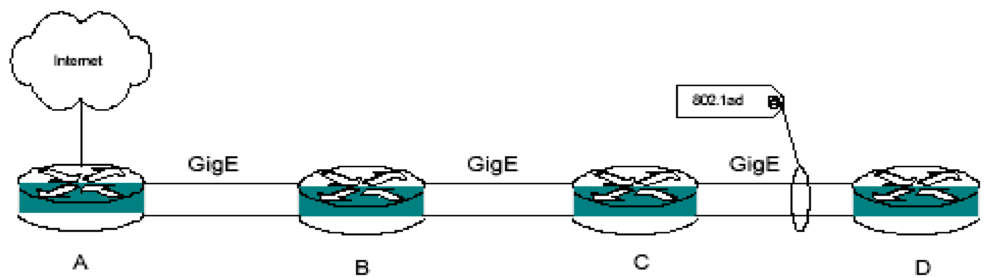
Sonet Metro Ring

- Ring is natural configuration for Sonet/SDH
- Sonet born for point-to-point circuit switching
- Many disadvantages in data transport using Sonet
  - Fixed circuits
    - Bandwidth waste if the circuit not used
  - Waste of bandwidth for logic mesh
    - Difficult and inefficient to create logic mesh
  - Bad management of multicast traffic
    - A circuit and a packet for each destination
  - Waste of bandwidth for protection
    - Tipically 50%



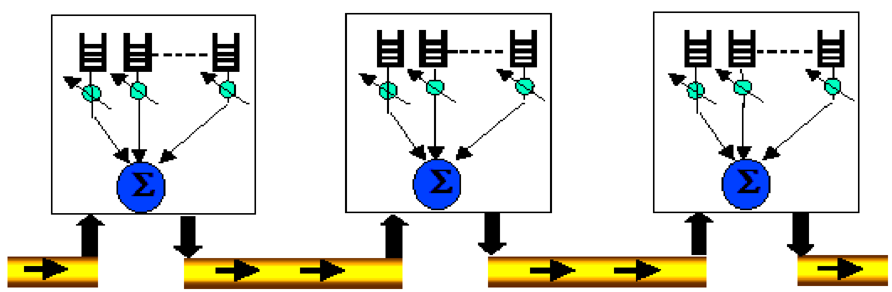
Ethernet Metro Ring

- Ethernet uses the available bandwidth in efficient way
- But it does not use efficiently the ring topology
  - No efficient ring protection system
  - Ethernet protection only active at link level, and very slow
    - 500 ms compared with 50 ms with Sonet
  - Non equal management of the shared medium
    - Equity only present at link level…
    - Which does not translate into global equity
  - Ethernet is on the ring… but it does not know about it!
    - Logical scheme in figure below



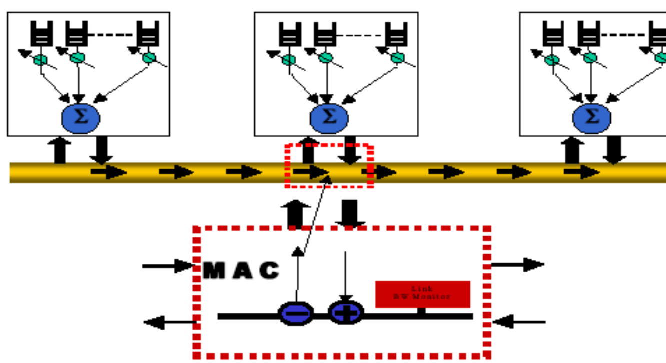
Resilient Packet Ring (1)

- RPR philosophy
  - The problem of managing the shared medium is solved at the MAC level
  - **RPR (IEEE 802.17)**
    - New MAC protocol for metro ring networks
    - Packet ADM architecture (Add/Drop Mux)
  - Comparison between Packet ADM and Ethernet switch
    - Ethernet network composed by point-to-point links
      - Queueing and routing at each node
      - Each node processes the traffic that enters at the line rate
      - Beyond 10 Gbps, this approach is no longer valid



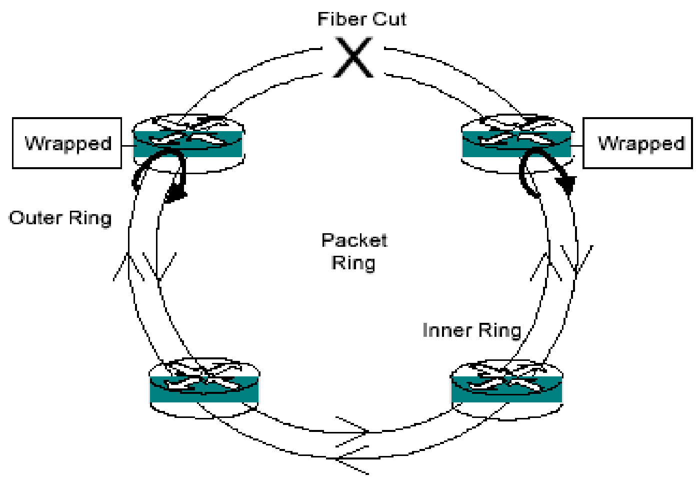
Resilient Packet Ring (2)

- RPR has the notion of **transit traffic**
  - Traffic not delivered to the node passes without queueing
  - The MAC has 3 functions
    - **Add**: insertion of new traffic
    - **Drop**: drop of part of the traffic
    - **Pass**: transit without processing
  - Transit path is part of transmission medium
    - RPR ring is a continuous medium shared among nodes
    - Packet ADM architecture does not process transit traffic
      - High scalability at large bitrates



Resilient Packet Ring – Advantages (1)

- **Versatility at the physical level**
  - RPR defines a single standard for MAC
  - At level 1 you may have Ethernet, Sonet, DWDM…
- **Reliability**
  - Efficient recovery mechanism: "ring wrap"
  - In case of fault, you may reach the destination by going through the ring in the opposite direction

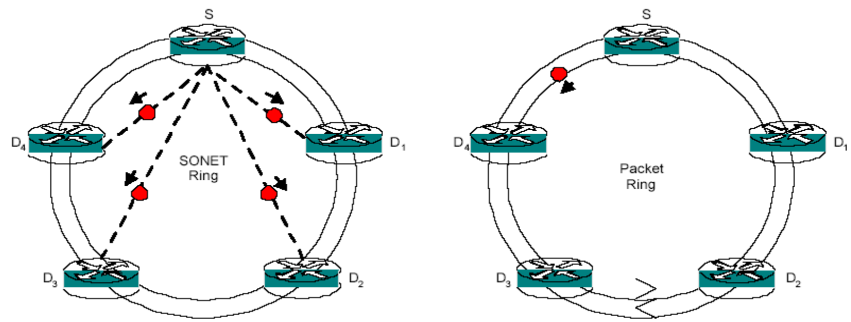


Resilient Packet Ring – Advantages (2)

- **Equitable bandwidth management**
  - A shared ring is very sensitive to excessive usage by some users
  - Necessary to guarantee equitable bandwidth management…
    - At global ring level, and not link by link!
  - This is impossible with Sonet and with Ethernet
    - Sonet user utilises resources, Ethernet non equal usage
  - There is a feedback mechanism in RPR
    - Traffic monitoring (task of MAC)
    - Traffic data delivered to all nodes
    - Sources modify the traffic accordingly
  - Non-equity of Ethernet in bandwidth management gets worse when number of nodes increases!

Resilient Packet Ring – Advantages (3)

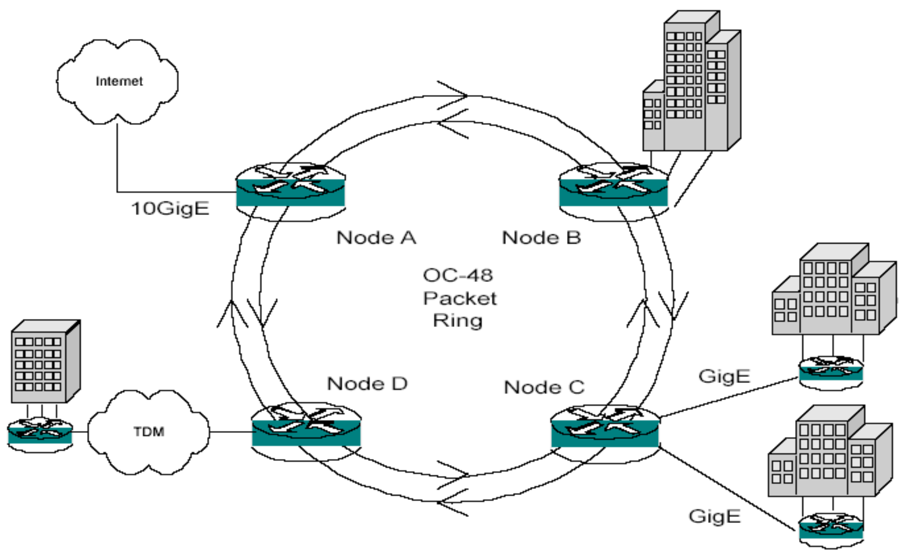
- **Multicast traffic management**
  - Packet ring is ideal configuration
    - Only one copy of a packet circulates in the ring



- **Simplified service delivery**
  - Activation times in Sonet networks are high
    - Ex. DS1, DS3 require weeks
  - Activation is immediate in RPR ring
    - Ring is shared medium, all nodes have global vision of the network

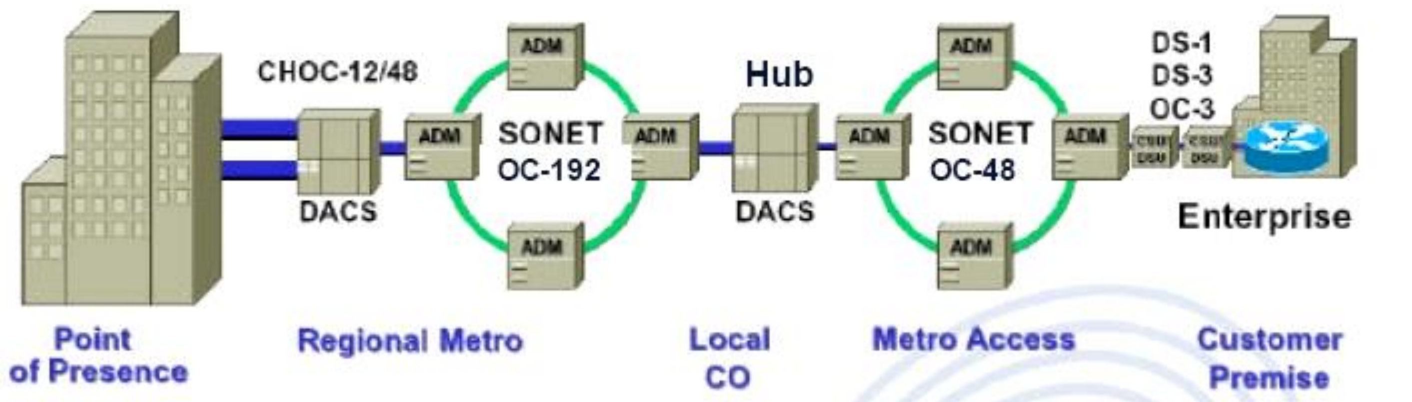
Resilient Packet Ring - Applications

- RPR is useful each time data are transported on fiber ring
  - Ex. Metro Service Provider, DSL access network
  - A single RPR ring connects multiple buildings in the area
    - High reliability (< 50 ms), easy to drop at nodes
    - Bandwidth is equally divided among users

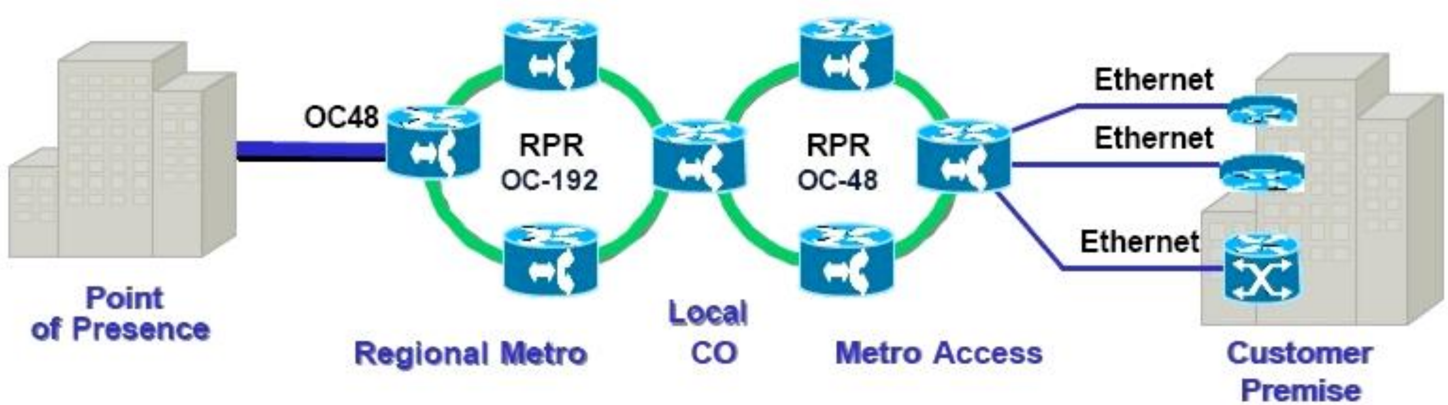


RPR – case study (1)

- **Sonet/SDH (1) vs. RPR (2)**



(1)



(2)

RPR – case study (2)

- **Case 1**
  - 100 users equally distributed among 5 nodes
  - 1.5 Mbps per user

Scenario 1: Initial deployment with 1.5 Mbps service per subscriber		
	TDM only	RPR
Number of nodes (SONET/SDH or RPR ADMs)	5	5
Subscribers per node	20	20
Total subscribers	100	100
Bandwidth per subscriber	1.5Mbps	1.5Mbps
Bandwidth required per node	20x1.5Mbps=30Mbps	20x1.5Mbps=30Mbps
Total bandwidth required	5x30Mbps = 150Mbps	5x30Mbps = 150Mbps
Access ring speed	OC-48 (2.4 Gbps)	OC-48 (2.4 Gbps)
Effective ring bandwidth	2.4Gbps	4.8Gbps
Port count	100 T1 ports	100 10/100 Ethernet ports
Per port cost/month	$1,000	$1,000
Number of access rings required	1	1

RPR – Case study (3)

- **Case 2**
  - Bitrate upgrade for everybody at 5 Mbps

Scenario 2: Increase the BW/user to 5 Mbps with fractional T3 interfaces		
	TDM only	**RPR**
Number of nodes (SONET/SDH or RPR ADMs)	5	5
Subscribers per node	20	20
Total subscribers	100	100
Bandwidth per subscriber	6Mbps (Frac T3)	5Mbps
Bandwidth required per node	20x6Mbps=120Mbps	100Mbps
Total bandwidth required	5x120Mbps = 600Mbps	5x100Mbps = 500Mbps
Access ring speed	OC-48 (2.4 Gbps)	OC-48 (2.4 Gbps)
Effective ring bandwidth	2.4Gbps	4.8Gbps
Port count	100 fractional T3 (6Mbps) ports	100 10/100 Ethernet ports
Per port cost/month	$2,600	$1,000
Number of access rings required	1	1

RPR – Case study (4)

- **Case 3**
  - Strong increase of user bitrate
  - 80 users at 40 Mbps, 10 at 100 Mbps, 10 at 1 Gbps

Scenario 3: Rapid increase in per user bandwidth		
	TDM only	RPR
Number of nodes (SONET/SDH or RPR ADMs)	5	5
Subscribers per node	20	20
Total subscribers	100	100
Each Node composition:		
Number of subscribers receiving 40 Mbps (T3)	16	16
Number of subscribers receiving 100 Mbps (OC3)	2	2
Number of subscribers receiving 1 Gbps (OC48)	2	2
Bandwidth required per node	16x45Mbps+2x155Mbps+ 2x2.4Gbps=5.83Gbps	16x40Mbps+2x100Mbps +2x1Gbps=2.84Gbps
Total bandwidth required	5x5.83Gbps=29.15Gbps	5x2.84Gbps=14.2Gbps
Oversubscription	"1:1"	"1:3"
Access ring speed	OC-48 (2.4 Gbps)	OC-48 (2.4 Gbps)
Effective ring bandwidth	2.4Gbps	4.8Gbps
Port count	80 T3 10 OC3 10 OC48	90 10/100 Ethernet ports 10 1GbE ports
Per port cost/month	T3: $25,000 OC3: $50,000 OC48: $450,000	10/100: $1000 1GbE: $10,000
Number of access rings required	29.15Gbps/2.4Gbps=13	14.2Gbps/(3x4.8Gbps)=1

RPR – Case study (5)

- **Case 4**
  - 10 fold increase of number of users
  - 80% at 40 Mbps, 10% at 10 Mbps, 10% at 1 Gbps

Scenario 4: Increase the number of users by tenfold		
	TDM only	RPR
Number of nodes (SONET/SDH or RPR ADMs)	50	50
Subscribers per node	20	20
Total subscribers	1000	1000
Each Node composition:		
Number of subscribers receiving 40 Mbps (T3)	16	16
Number of subscribers receiving 100 Mbps (OC3)	2	2
Number of subscribers receiving 1 Gbps (OC48)	2	2
Bandwidth required per node	16x45Mbps+2x155Mbps +2x2.4Gbps=5.83Gps	16x40Mbps+2x100Mbps+ 2x1Gbps=2.84Gbps
Total bandwidth required	50x5.83Gbps=291.5Gbps	50x2.84Gbps=142Gbps
Oversubscription	"1:1"	"1:3"
Access ring speed	OC-48 (2.4 Gbps)	OC-48 (2.4 Gbps)
Effective ring bandwidth	2.4Gbps	4.8Gbps
Port count	800 T3 100 OC3 100 OC48	900 10/100 Ethernet ports 100 1GbE ports
Per port cost/month	T3: $25,000 OC3: $50,000 OC48: $450,000	10/100: $1000 1GbE: $10,000
Number of access rings required	291.5Gbps/2.4Gbps=122	142Gbps/4.8Gbps=10

RPR – Case study (6)

- **Case 5**
  - Same services requested as in case 4
  - New generation Sonet systems
    - Use of Ethernet interfaces mapped on Sonet/SDH networks
    - VCAT (Virtual Concatenation)
      - Resolution of TDM granularity problem
      - **Ethernet 100 Mbps** transported in 2 STS-1 (~ 2 x 52 Mbps = **104 Mbps**)
      - **Ethernet 1 Gbps** transported in 21 STS-1 (~ 21 x 52 Mbps = **1.092 Gbps**)

RPR – Case study (7)

Scenario 5: Same as scenario 4 but with VC based SONET/SDH network		
	TDM only	**RPR**
Number of nodes (SONET/SDH or RPR ADMs)	50	50
Subscribers per node	20	20
Total subscribers	1000	1000
Each Node composition:		
Number of subscribers receiving 40 Mbps (T3)	16	16
Number of subscribers receiving 100 Mbps (OC3)	2	2
Number of subscribers receiving 1 Gbps (OC48)	2	2
Bandwidth required per node	16x45Mbps+2x104Mbps +2x1.092Gbps=3.112Gbps	16x40Mbps+2x100Mbps +2x1Gbps=2.84Gbps
Total bandwidth required	50x3.112Gbps=155.6Gbps	50x2.84Gbps=142Gbps
Oversubscription	"1:1"	"1:3"
Access ring speed	OC-48 (2.4 Gbps)	OC-48 (2.4 Gbps)
Effective ring bandwidth	2.4Gbps	4.8Gbps
Port count	900 10/100 Ethernet ports 100 1GbE ports	900 10/100 Ethernet ports 100 1GbE ports
Per port cost/month	10/100: $1000 1GbE: $10,000	10/100: $1000 1GbE: $10,000
Number of access rings required	155.6Gbps/2.4Gbps=65	142Gbps/(3x4.8Gbps)=10