VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

VPIphotonics™

Optical Networking

System3

Developed in cooperation with
Prof. Virgilio Gonzalez and his group at
University of Texas at El Paso

Authors:
J. Clardy (†2005), A. Musa, V. Gonzalez

Module Prerequisites

- Introduction to Fiber-Optic Communications I & II

Module Objectives

- Optical switching and Routing
- Key Network Elements
  - OXC, Wavelength conversion, OADMs, etc.
- Key Features,
  - Theory, issues, problems, system analysis, design and optimization
- Case studies

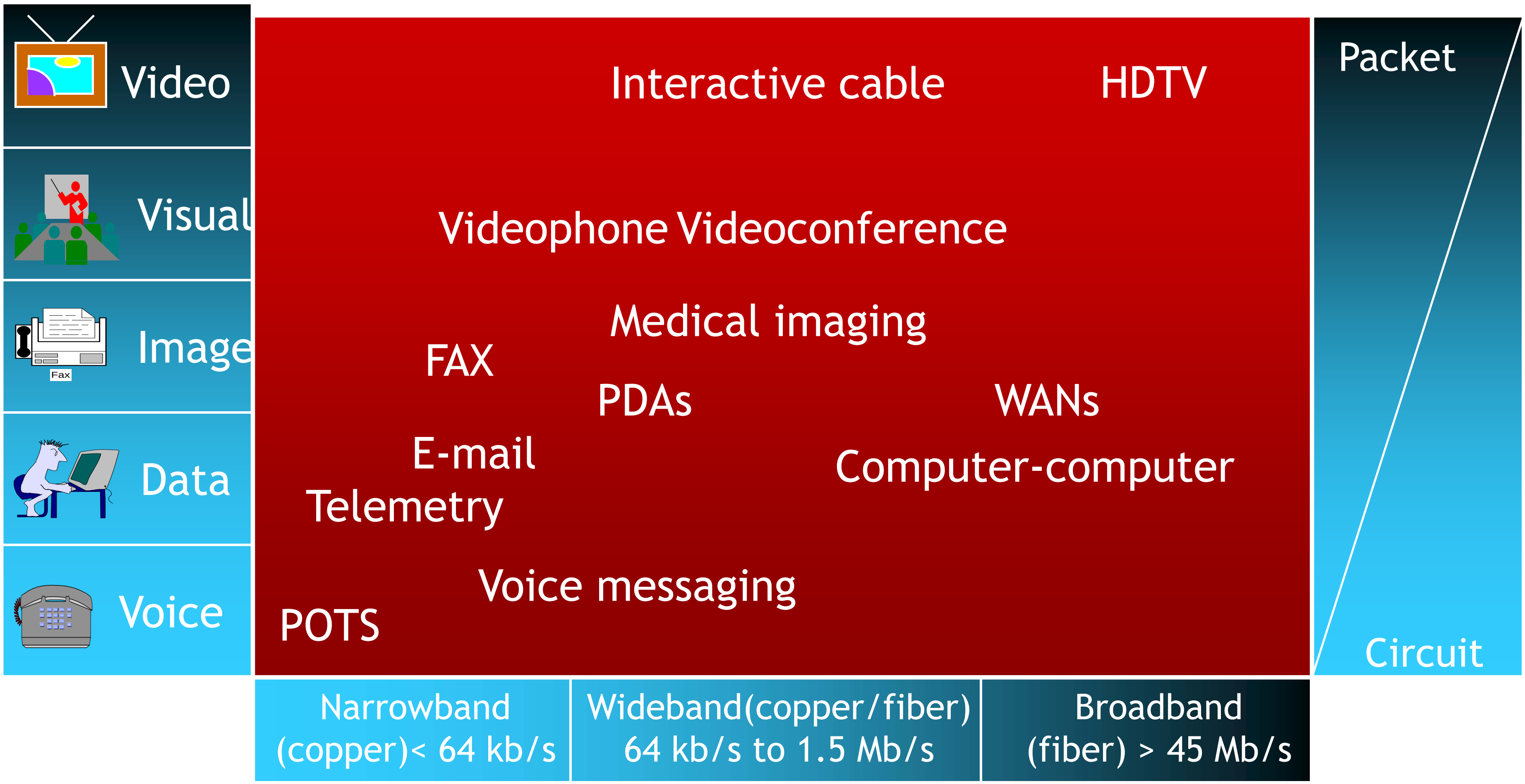
Outline

- Introduction
- Telecommunications Model
- Optical Networking Technologies
- Protection Mechanisms

Introduction - Evolution

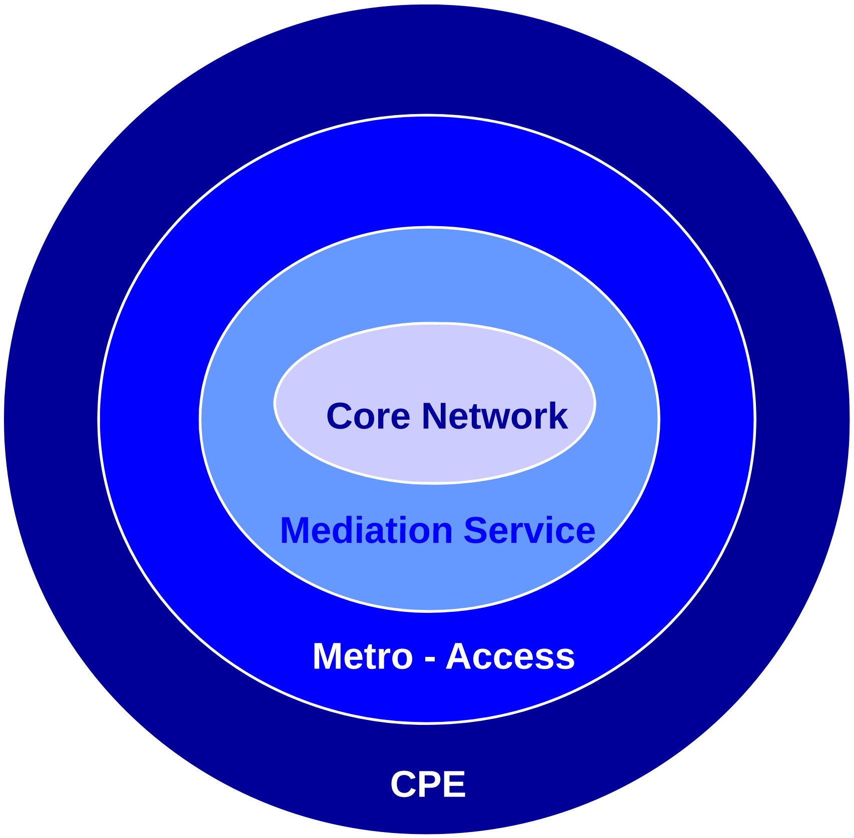
- In early networks, only electronic transmission media was available, such as twisted pair cable, coaxial cable and radio links.
- Most communication networks evolved to support a specific application alone.
  - For example the telephone network only supported telephone service, and the telegraph network only supported telegraph service.
- Optical networks appeared first just to increase capacity of existing telephone network in selected links. Later the demand of data communications, such as the Internet, pushed further the need for bandwidth.
- Capacity and flexibility drive the need for a transparent optical network that is independent of the services supported above.

Service Requirements



Network Technology Conceptual Architecture

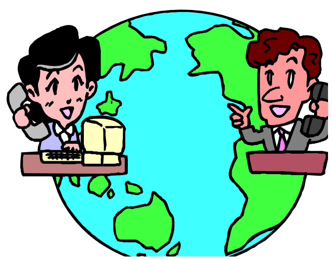
- Network structured in 4 levels
- The Core Network is common for all services and mediation devices, its function is to provide:
  - Transmission Capacity
  - Restoration
  - Flexibility
- Services are provided mostly by mediation devices such as:
  - Telephone switch for voice services
  - Routers for Internet
  - Packet Switches for Frame Relay
- Metro - Access should provide integrated access to various mediation devices (services).
- Optical Technology is mostly used by the Core and Metro - Access
- CPE (Customer Premise Equipment) is the interface between user applications and the network, belongs to the user but could be managed by the Service Provider.



Telecommunication Services

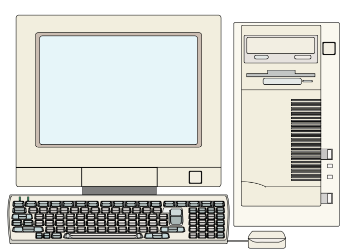
- The “*Service*” is what the user perceives and is related to the specific applications.
- The “*Network”* provides the technological infrastructure to support the services.
- Classic Model
  - In the classic model, the user applications are tied to a class of service (voice, data, transport)
  - Each class of service is supported by a specific network technology.
  - The network technology is also tied to the customer access medium
- Integrated Model
  - In the future the services will have an universal user interface supported by an universal class of network
  - The user applications will be constructed through standardized interfaces to the universal user interface allowing flexible service construction and user customization
  - The network access connectivity will have two major types, Wireless and Cabling
  - Wireless access offers fast deployment but has restricted capacity
  - Cabling through copper may reach small end users, and fiber optics will offer the highest bandwidths to the larger ones.
  - Optical networks will provide transparent high capacity links to all applications.

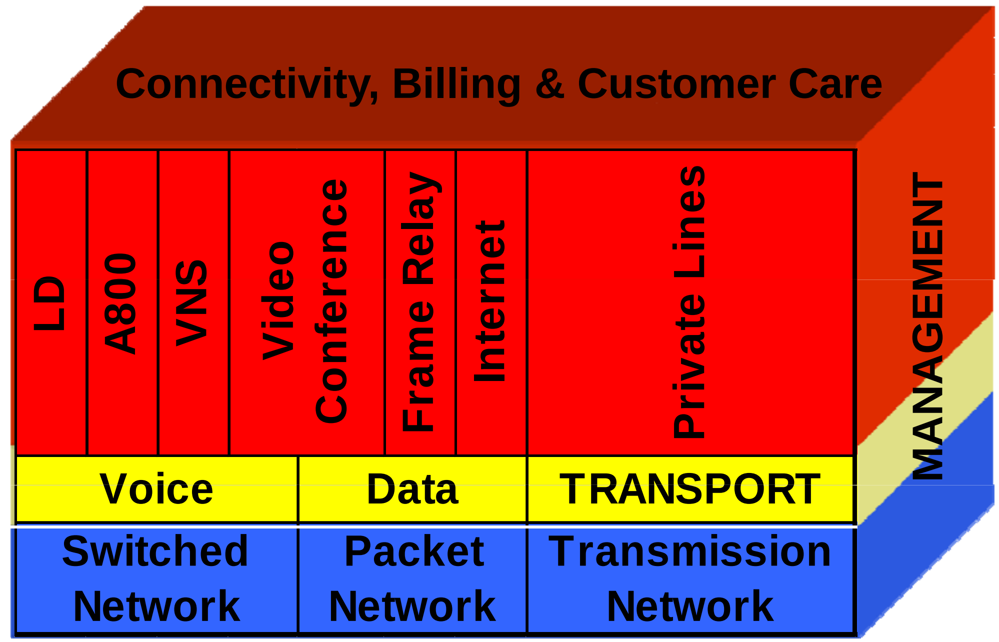
Classic Model



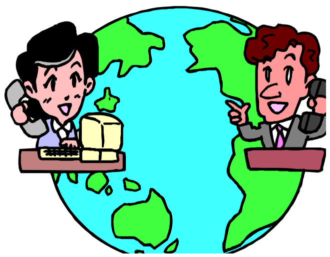
SERVICE PLANE

TECHNOLOGY PLANE



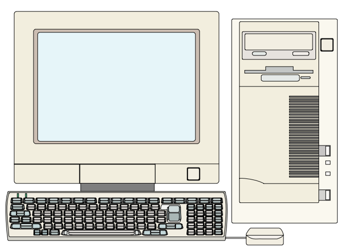


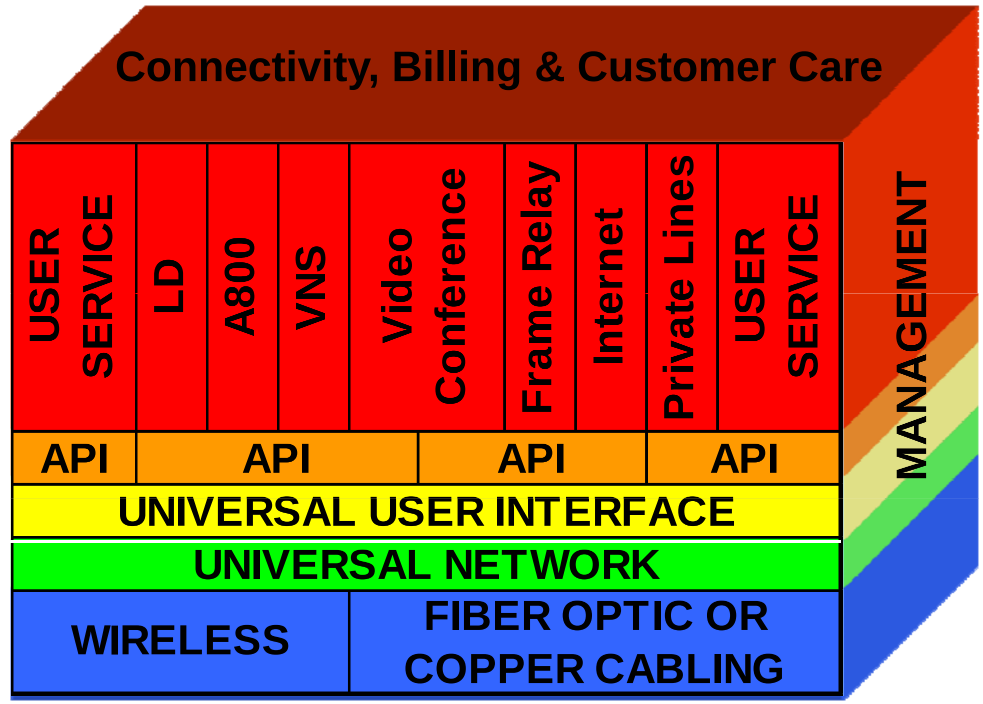
Integrated Model



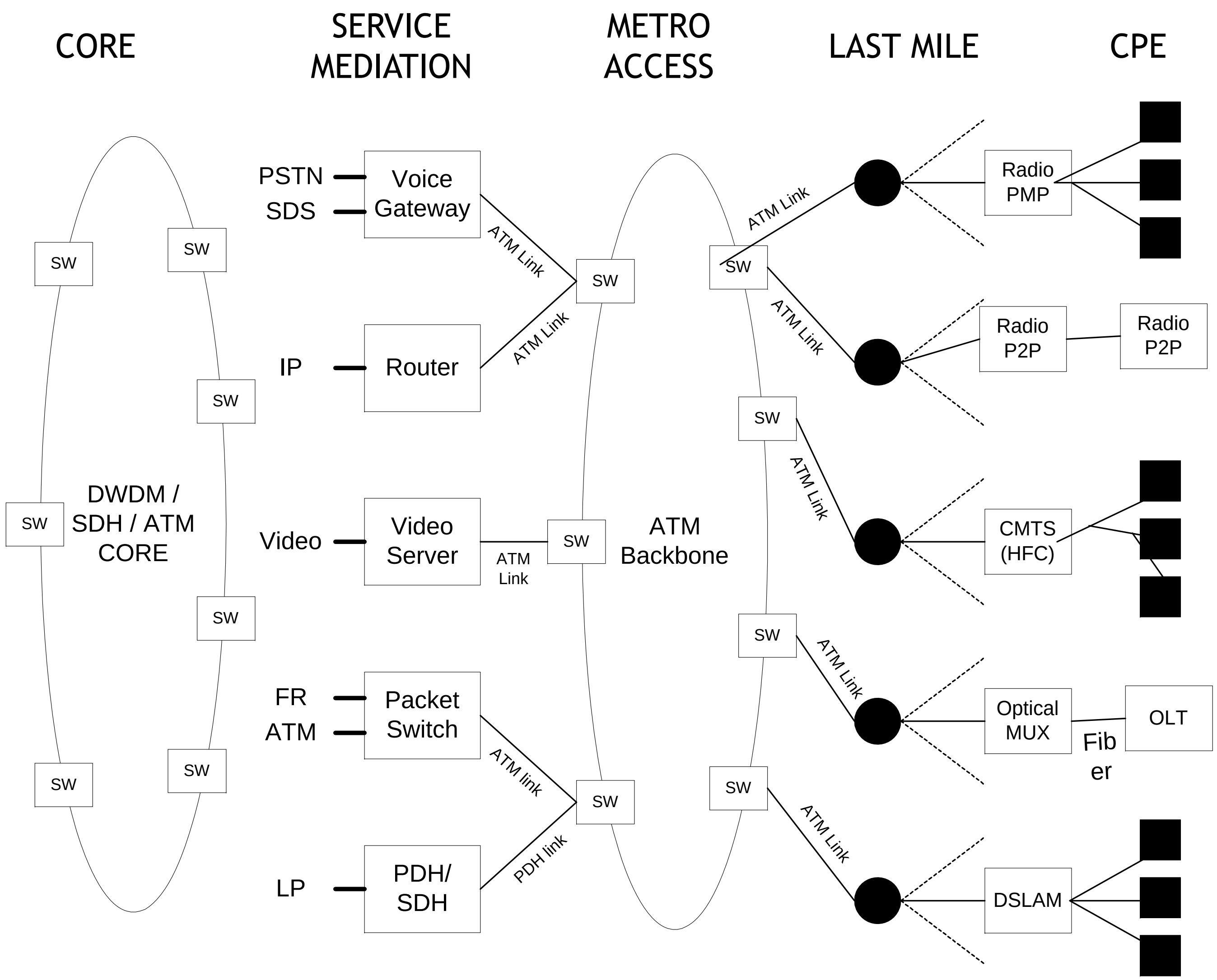
SERVICE PLANE

TECHNOLOGY PLANE





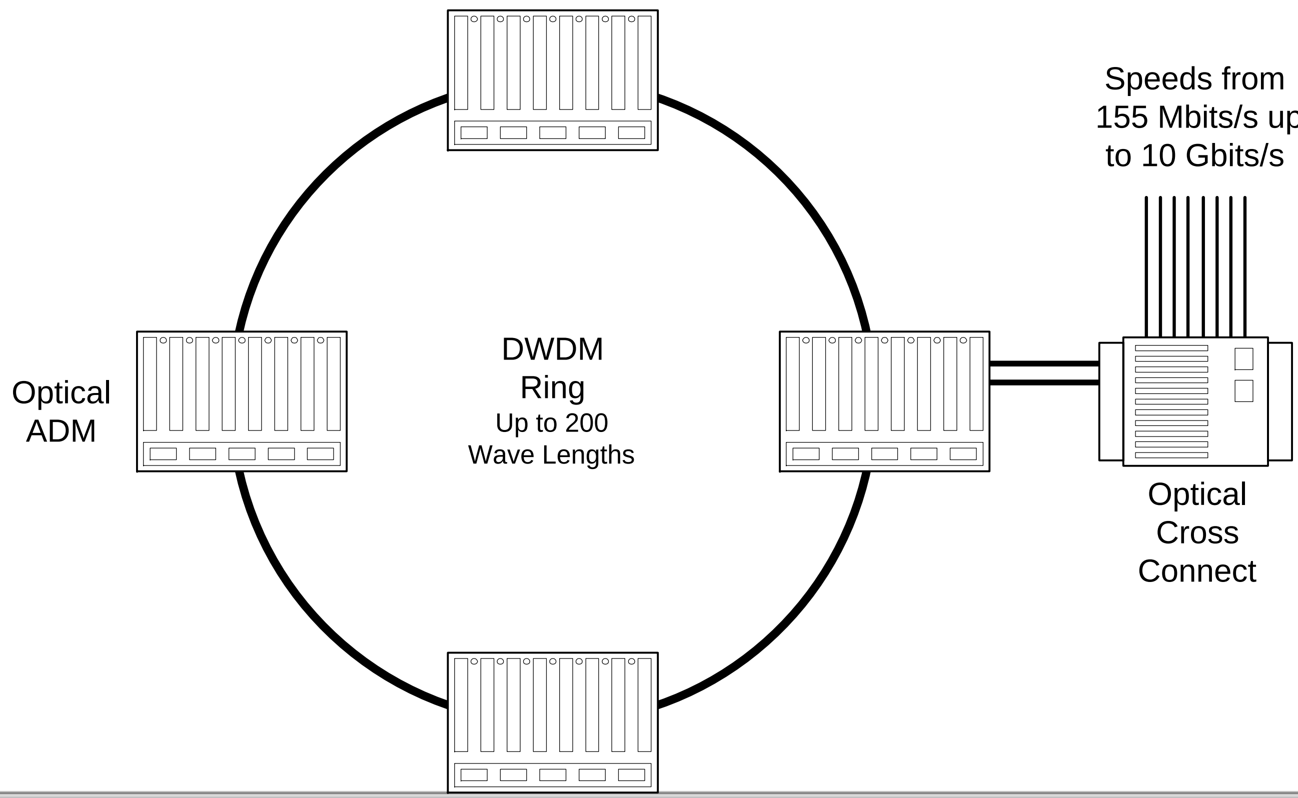
Example of Network Structure Model



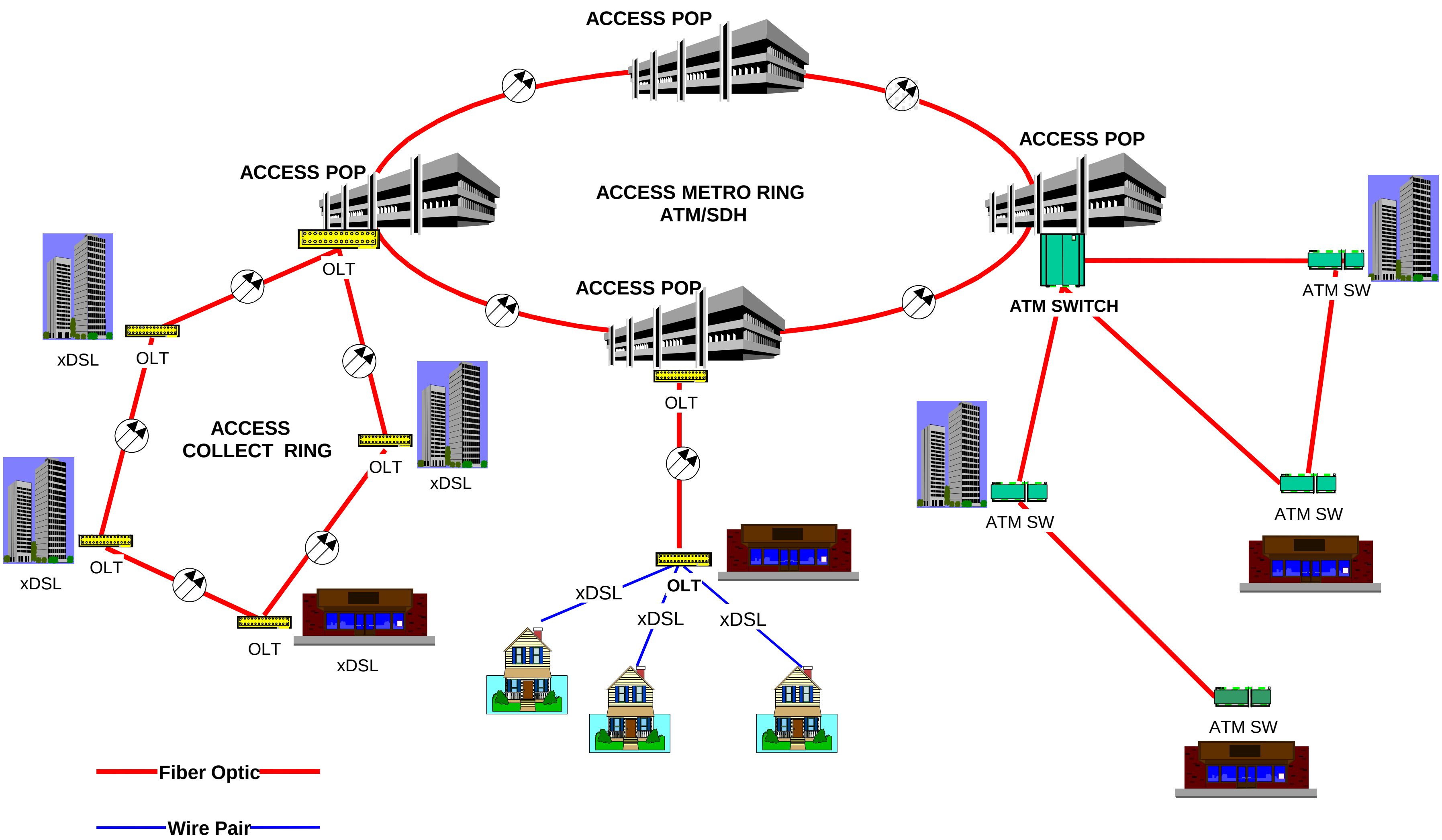
Services	
Without IAD	With IAD
FR IP PL ATM	Voice ATM ISDN FR IP PL
PL FR ATM	Voice ATM IP ISDN PL FR
CATV IP Voice PL & FR with TDM (CBR)	
PL FR ATM	Voice ATM IP ISDN PL FR
FR Voice IP	PL Voice ISDN IP CATV FR ATM

Core Network

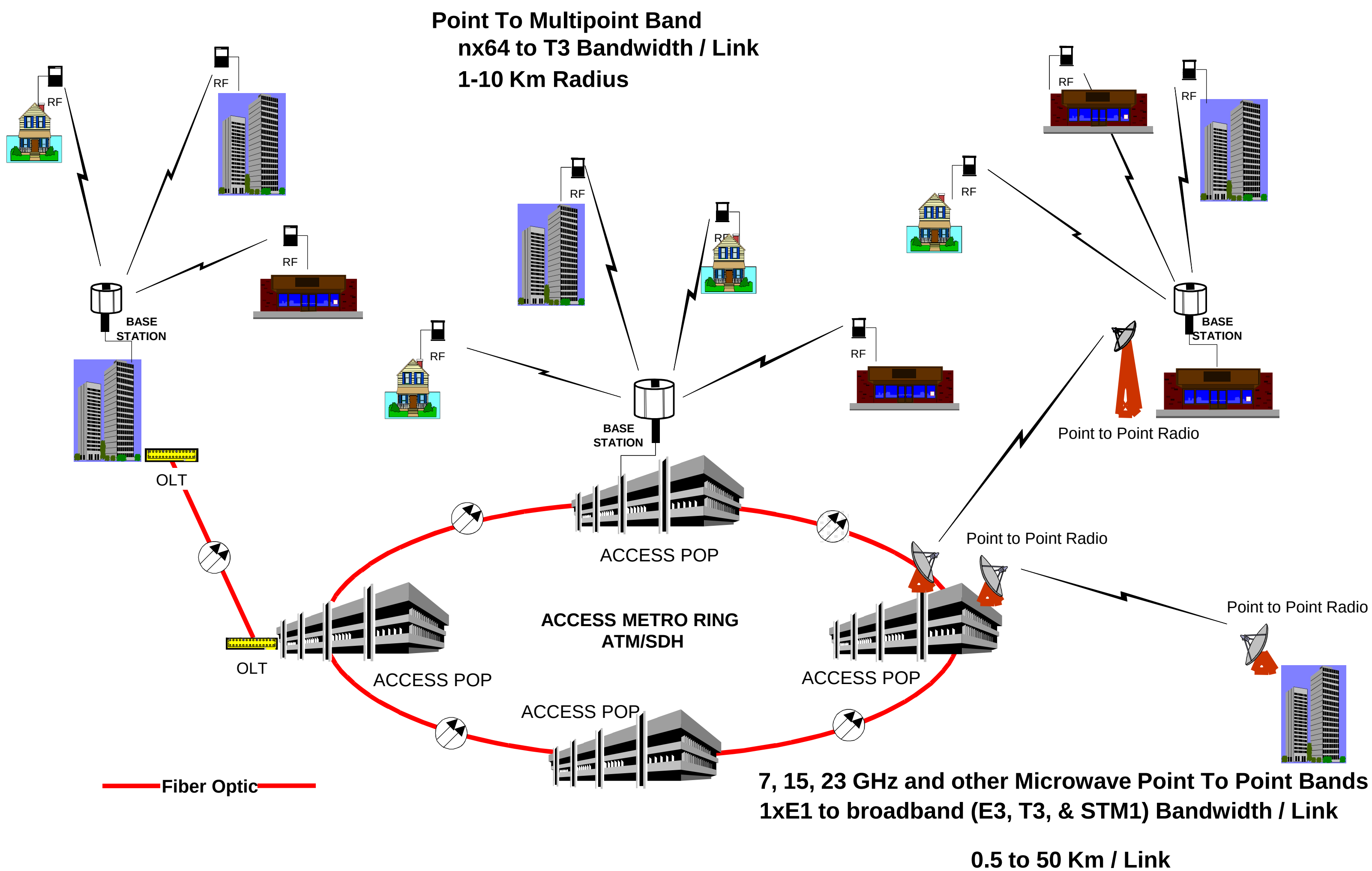
- It provides high capacity optical links (or lightpaths).
- Complete optical core network (WDM and Optical Cross-Connects)
- Intelligence and restoration capabilities could be provided directly by the optical core.
- Capable of supporting high speed ports from SONET, ATM, IP or other services.
- Capable of delivering up to a full wavelength per service.



Wireline Metropolitan Access



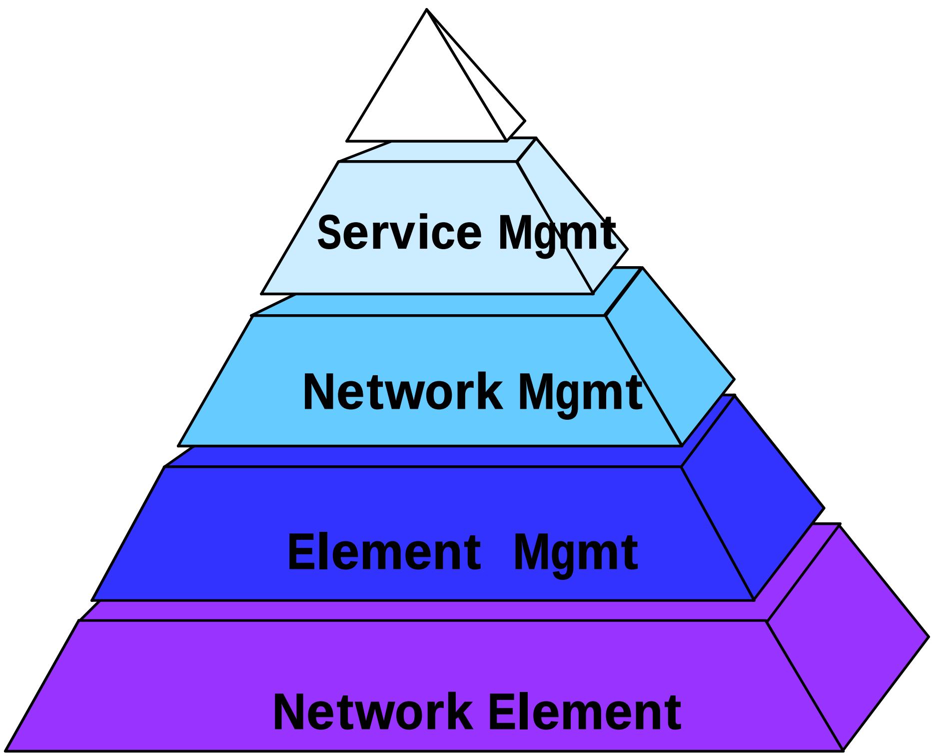
Wireless Metropolitan Access, Point-to-Point and Point-to-Multipoint



Management Layered Approach (TNM)

The Telecommunications Network Management (TNM) model provides a layered framework to design the applications to control network and services

- Business Management
  - Manage overall business, e.g., achieving ROI, market share, employee satisfaction
- Service Management
  - Manage services offered to customers, e.g., meeting SLA's, quality, costs.
- Network and Systems Management
  - Manage the networks and systems that deliver services, e.g., capacity, diversity, congestion.
- Element Management
  - Manage elements comprising the networks and systems e.g., switches, routers
- Network Element
  - Switches, transmission elements, routers, etc.



Optical Networking Technologies

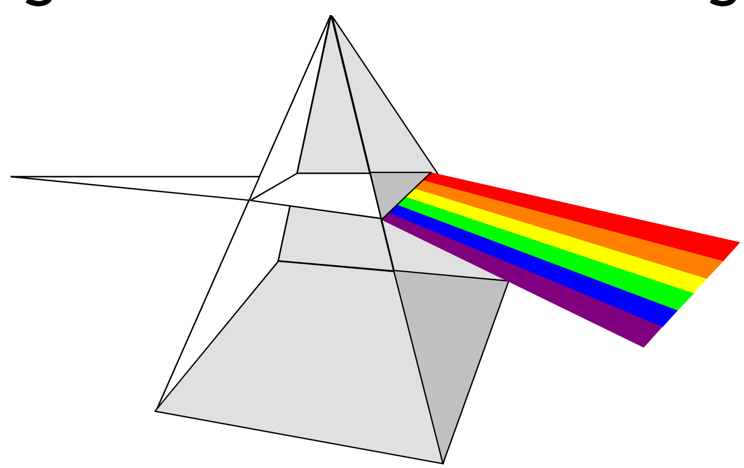
- Multiplexing
- Circuits vs. Packets
- ISDN, ATM, IP and MPLS
- OEO vs. OOO devices
- Switching
- Wavelength conversion

Multiplexing

- Multiplexing allows several signals to be sent together using a common medium. The de-multiplexing process separates them at the receiver site.
- The multiplexing methods are:
  - Space: This method consists in a simple bundling of several links in a single path. For example old telephony cables formed of many twisted pairs. This is costly and undesirable.
  - Frequency (FDM or WDM): Similar to radio stations, this method allocates each channel to different spectrum bands.
  - Time (TDM): This allocates “turns” to each channel.
  - Code (CDM): Newer method using advanced signal processing techniques. Commonly used in cellular telephone transmission.
- Common Optical multiplexers mostly employ the frequency method allocating different channels into different wavelengths. However there are many research efforts to exploit the other methods.

Wavelength Division Multiplexing

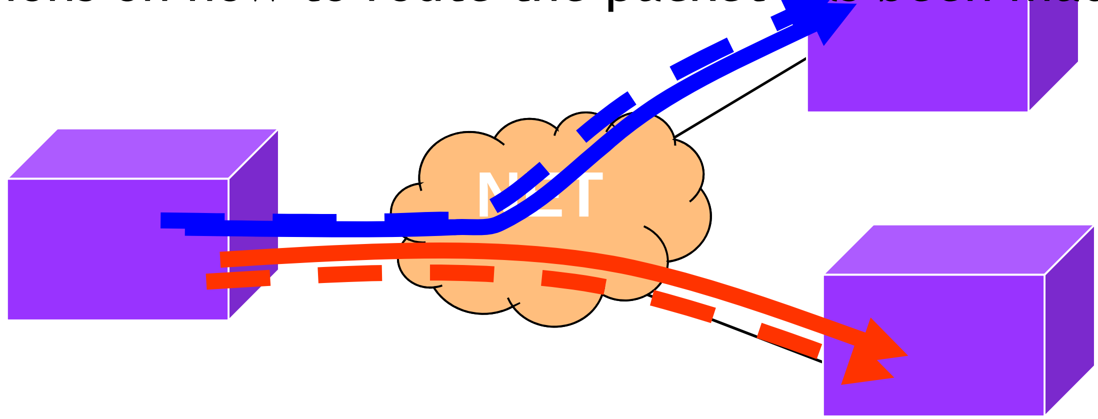
- Type of FDM but at optical frequencies where each “color” is used for a different channel
- Operates in ~200nm bands at the 1300nm and 1550nm regions
- Bands are typically restricted by amplifier devices to ~25nm (1540-1565nm for EDFA)
- The International Telecommunications Union (ITU) defined a standard channel spacing of 100 GHz or 50 GHz grids around 193.1 THz.



VPIphotonics™

Circuits and Packets

- Circuit switching is a method to establish a path across the network reserving exclusively a “resource” for the whole duration of the transmission. The resource can be a cable, a frequency carrier, a time slot or a code.
- In a packet network each information unit has a “header” that contains all the necessary information required to properly deliver it to the destination. Each intermediate node must decide how to handle each packet.
- A “virtual circuit” uses packets for the transmission. However the decisions on how to route the packet has been made beforehand.



ISDN, ATM, IP and MPLS

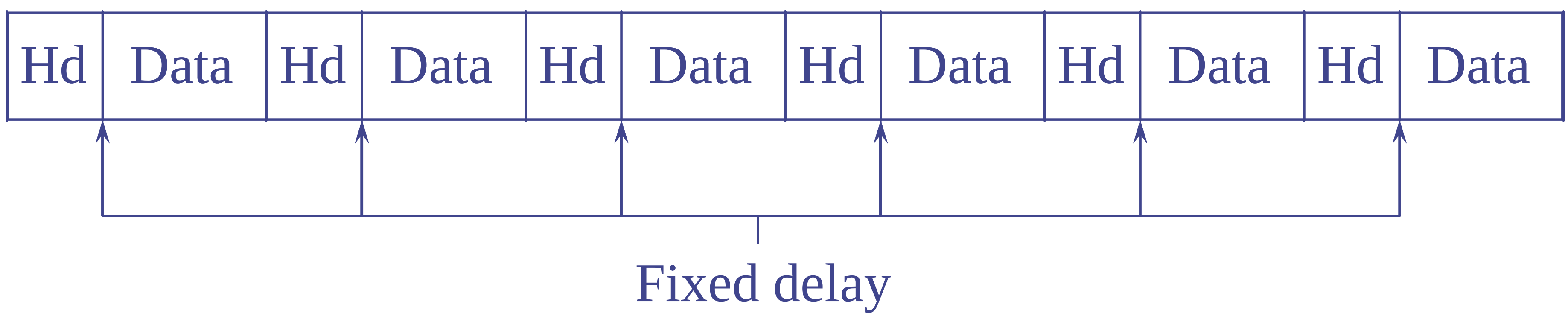
- The telephone industry tried to provide multimedia services in the late 80’s using ISDN. This was an extension of the traditional telephone switched network to support other applications.
- The Asynchronous Transfer Mode (ATM) or Broadband ISDN (B-ISDN) tried to increase the capacity and flexibility to support all existing communication services. This is a packet switched technology that offers quality of service using fixed size packets or *cells*.
- The Internet Protocol was developed for computer communications, but its characteristics and applications quickly dominated all other network protocols. The disadvantages are related to the higher delays and lower quality due to the routing process.
- A Multi-Protocol Label Switched (MPLS) network tries to mix the flexibility of routed networks with the robustness of a switched virtual circuit. For an IP stream it creates a virtual circuit and then assigns a “label” to the packets to expedite their processing.

Packet vs. CELL Frames

PACKET STREAM

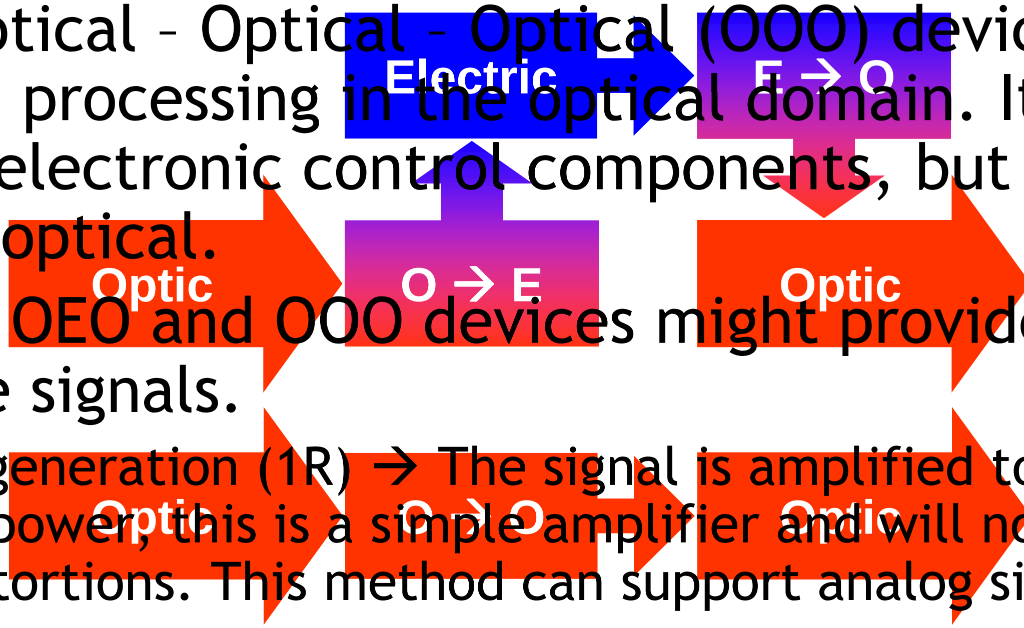
Hd	Data	Hd	Data	Hd	Data	Hd	Data	Hd	Dt	Hd	Data

CELL STREAM



OEO vs. OOO networks

- An Optical – Electrical – Optical (OEO) device requires to convert the incoming optical signal into the electric domain. Then process the information electronically and convert it again to optic.
- An Optical – Optical – Optical (OOO) device does all the signal processing in the optical domain. It might still have electronic control components, but the signal stays optical.
- Some OEO and OOO devices might provide regeneration of the signals.
  - Regeneration (1R) → The signal is amplified to compensate loss of power, this is a simple amplifier and will not correct distortions. This method can support analog signals as well.
  - Regeneration and Reshape (2R) → In addition to 1R the signal is shaped as a digital symbol by a thresholding device.
  - Regeneration, Reshape and Re-time (3R) → In addition to 2R the signal clocking is adjusted for jitter errors.



SONET/ SDH

- Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) are methods standardized by the telephone industry, in the late 80's and early 90's, to synchronize and multiplex high speed TDM channels.
- The synchronization is based on the use of very precise frequency sources (atomic clocks) and maintain all the signals aligned. The reference signal can be local or derived from the tributary links.
- The basic frame structure for the OC-1 is made of 90 columns by 9 rows. It includes a large "header" section of 3 columns including multiple administrative functions and the use of "pointers".
- Higher order channels are obtained by simple interleaving of the lower order channels OC1→ x3 → OC3 → x4 → OC12 → x4 → OC48
- SONET is used mostly in US/Canada, and the SDH International version is almost equivalent. STM1≈OC3; STM4≈OC12; STM16≈OC48; etc.
- The solution to support tributaries not well synchronized consists of allowing them to "float" inside the payload area and use the pointers to distinguish them.

VPIphotonics™

SONET OC1 Frame

90 Columns

3 Col. Transport Overhead

9 Rows

Framing	Framing	Trace	Path Status
BIP-8	Orderwire	User	User Channel
Datacom	Datacom	Datacom	Indicator
Pointer	Pointer	Pointer	Growth
BIP-8	Datacom	Datacom	Growth
Datacom	APS	APS	Tandem
Datacom	Datacom	Datacom	Trace
Datacom	Datacom	Datacom	BIP-8
Sync Status	REI-L	Orderwire	Signal Label
Framing	Framing	Trace	Path Status
BIP-8	Orderwire	User	User Channel
Datacom	Datacom	Datacom	Indicator
Pointer	Pointer	Pointer	Growth
BIP-8	Datacom	Datacom	Growth
Datacom	APS	APS	Tandem
Datacom	Datacom	Datacom	Trace
Datacom	Datacom	Datacom	BIP-8
Sync Status	REI-L	Orderwire	Signal Label

Path Overhead

Optical Switch Fabrics

- The optical switch fabric is the mesh of paths and “decision” elements needed to connect an input port to the desired exit port.
- There are many ways to interconnect the intermediate switching elements to realize the larger switch. Common methods include Crossbar, Clos, Spanke, Benes and Spanke-Benes.
- The performance considerations include the number of switching elements, loss uniformity and blocking characteristics
  - A large switch is made of smaller switching elements. The number of such components is determined by the arrangement of connections needed.
  - The loss uniformity is related to the difference in length of the possible paths depending on the switch structure.
  - The desired switch structures should always provide the connection between unoccupied entry and exit ports. Some configurations can do this all the time, others need complex controllers to rearrange the connections and accommodate new links. Blocking inside a switch occurs when there is no possible path between an input and an output port.

Switching element technology

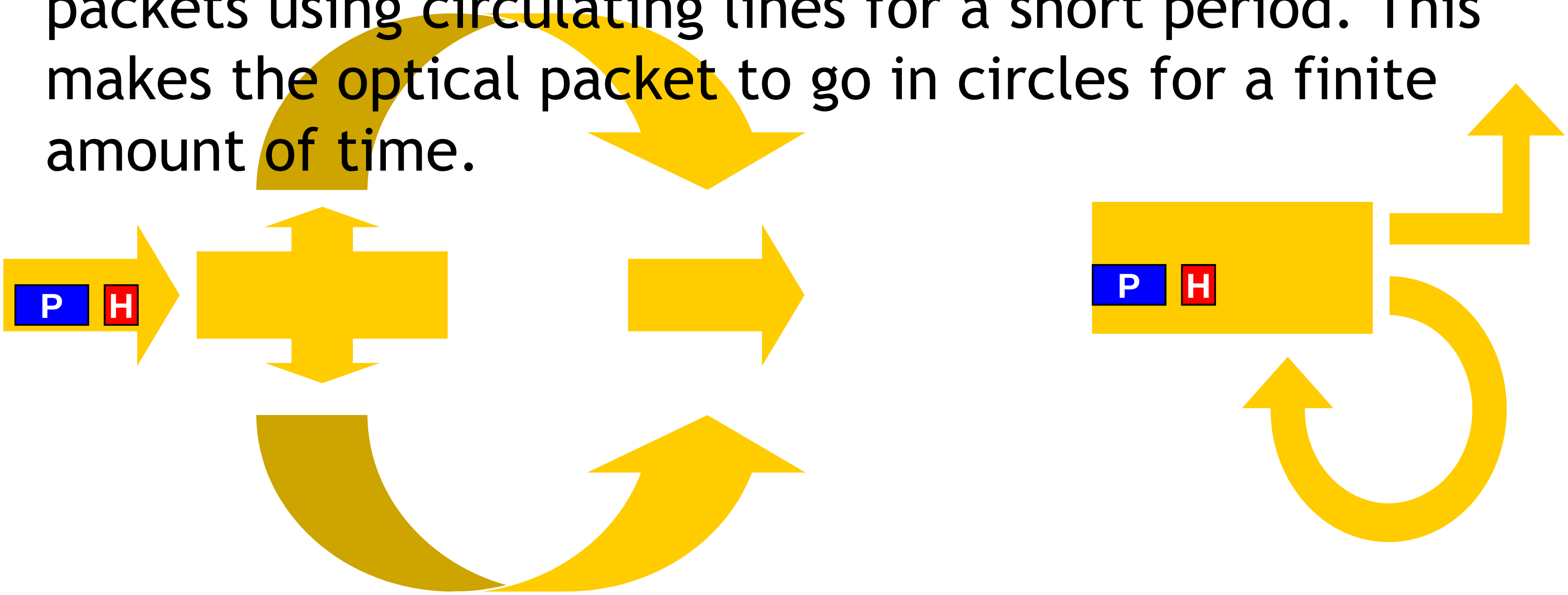
- An optical switch element redirects an incoming optical signal to a selected exit port. This is a building block for large switch fabrics.
- The most common type of switch element is a 2x2. This means two input ports and two exit ports. Therefore a binary decision will be to connect the ports straight or do a crossover.
- The lack of "optical memories" requires that an incoming signal will always be connected to an outgoing port. Thus the existing methods to do the light redirection are:
  - Mechanical, using large mirrors. They are bulky and have small number of ports.
  - MEMS (Micro Electro Mechanical System) use microscopic mirrors created on silicon substrates. The size allows large number of components, and simpler maintenance.
  - 2x2 Mach-Zehnder Interferometer configuration (MZI). In these approaches one of the arms is subject to a stimuli to change the delay thus switching the exit port. The delayed line can be modified by mechanical, thermo-optic or electric means.
    - Mechanical stretching or bending. Slow but inexpensive.
    - Thermo-optic material that changes refraction index in a small region
    - Electro-optic material ($LiNbO_3$)This is the fastest switch but the more expensive.
  - Liquid crystal. Uses similar principle to LCDs changing the polarization of the light. It is combined with polarization filters to select the appropriate output.
  - Bubble-based Waveguide. Uses the same principle of Ink-jet printers creating micro bubbles that reflect or allow the passing of light through a waveguide.
  - Semiconductor Optical Amplifiers (SOA) that can be turned ON or OFF. They could either block the signal or let it pass after amplifying.

Wavelength Conversion

- This is the process to receive a signal operating at a wavelength $\lambda 1$ and change the output to $\lambda 2$.
- The simpler method is to convert the incoming signal to the electric domain, process it and then convert back to optic in the desired output wavelength.
  - Optoelectronics might combine electronic amplification, reshaping or retiming of the signal before retransmission.
- All-optical approaches don't convert the signal to the electric domain, however they are not mature enough for commercial applications.
  - Optical Gating, uses a SOA with the incoming signal $\lambda 1$ interfering with λp or "probe", λp is the only allowed to exit the device through a filter. This is called cross-gain modulation because the two signals "compete" for the SOA carrier population. An increase in the amplitude of $\lambda 1$ will decrease the output of λp.
  - Interferometric technique, also uses SOAs in a MZI arrangement. It is more sensitive than optical gating but also is more complex.
  - Four Wave Mixing. It employs nonlinear properties of the fiber in which three waves (f1, f2 and f3) interact generating a fourth wave (f4=f1+f2-f3). Therefore we could obtain $\lambda 2=2\,\lambda p-\lambda 1$ and $\lambda 3=2\,\lambda 1-\lambda p$.

Buffering

- The major limitation for optical switching is that we don’t have practical optical memories yet.
- One approach consists on processing the header first to make the appropriate routing decisions while the optical packet is “delayed”
- A proposed method is to trap “fixed size” optical packets using circulating lines for a short period. This makes the optical packet to go in circles for a finite amount of time.



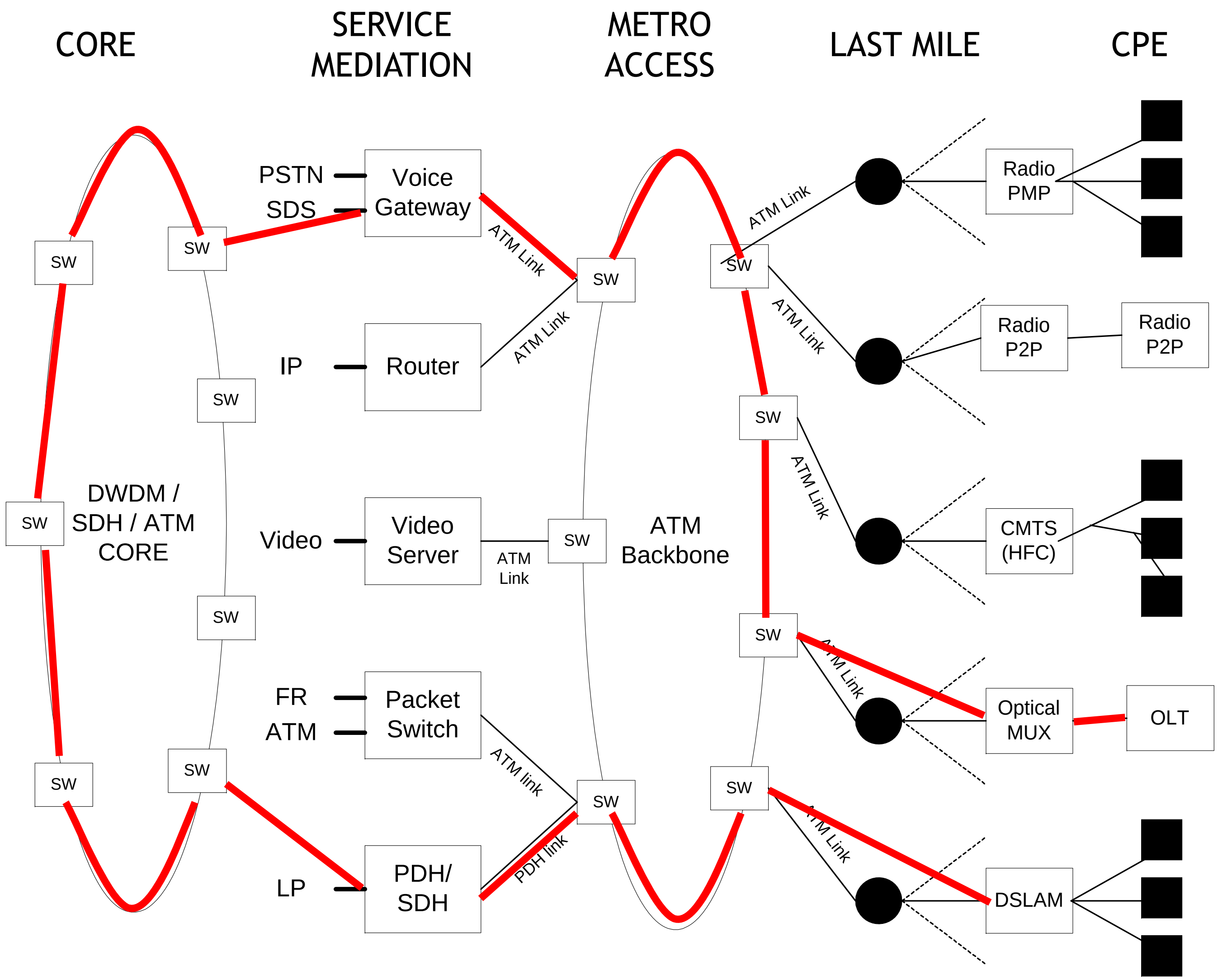
Optical Network Types

- Photonic Point to Point
- Photonic Point to Multipoint
- Optical Cross connect
- Optical Circuit switched
- Optical Bursting
- Optical Packet switching

Photonic Point to Point (SONET, Optical Ethernet, IP, etc)

- The optical path only exists between two devices. The signals must be processed in the electronic domain.
- Multiple channels can be multiplexed using WDM to increase link capacity.

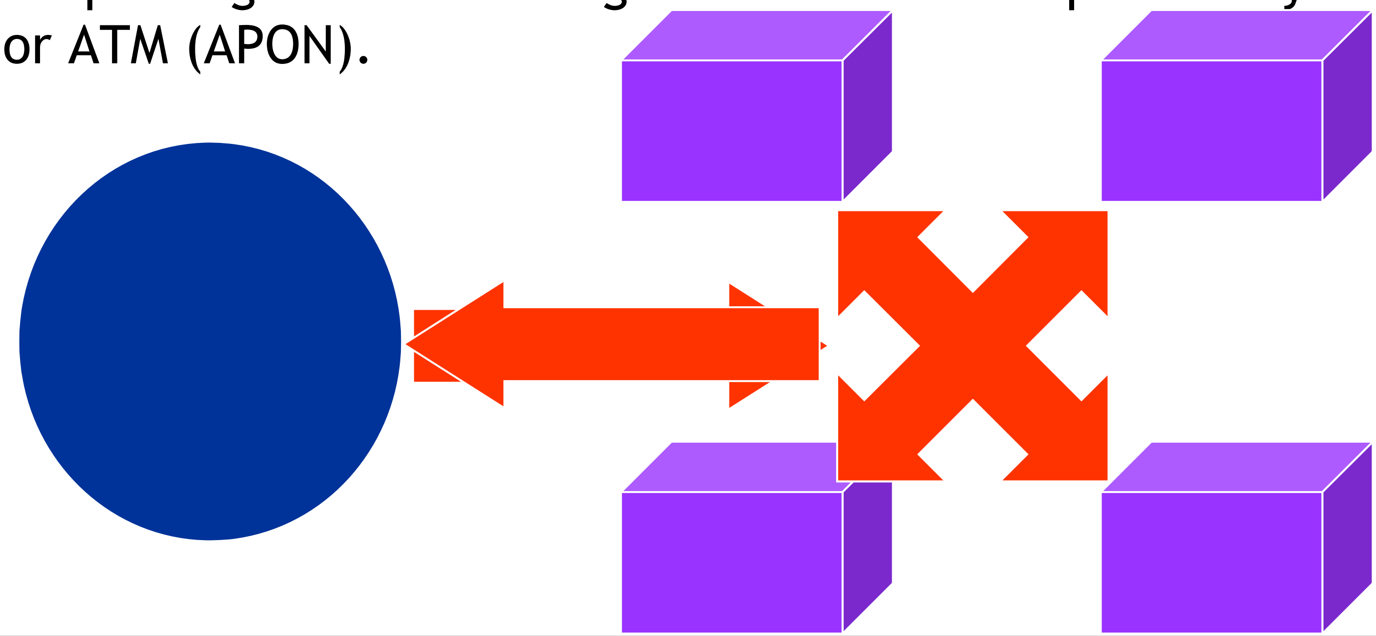
Photonic Point to Point



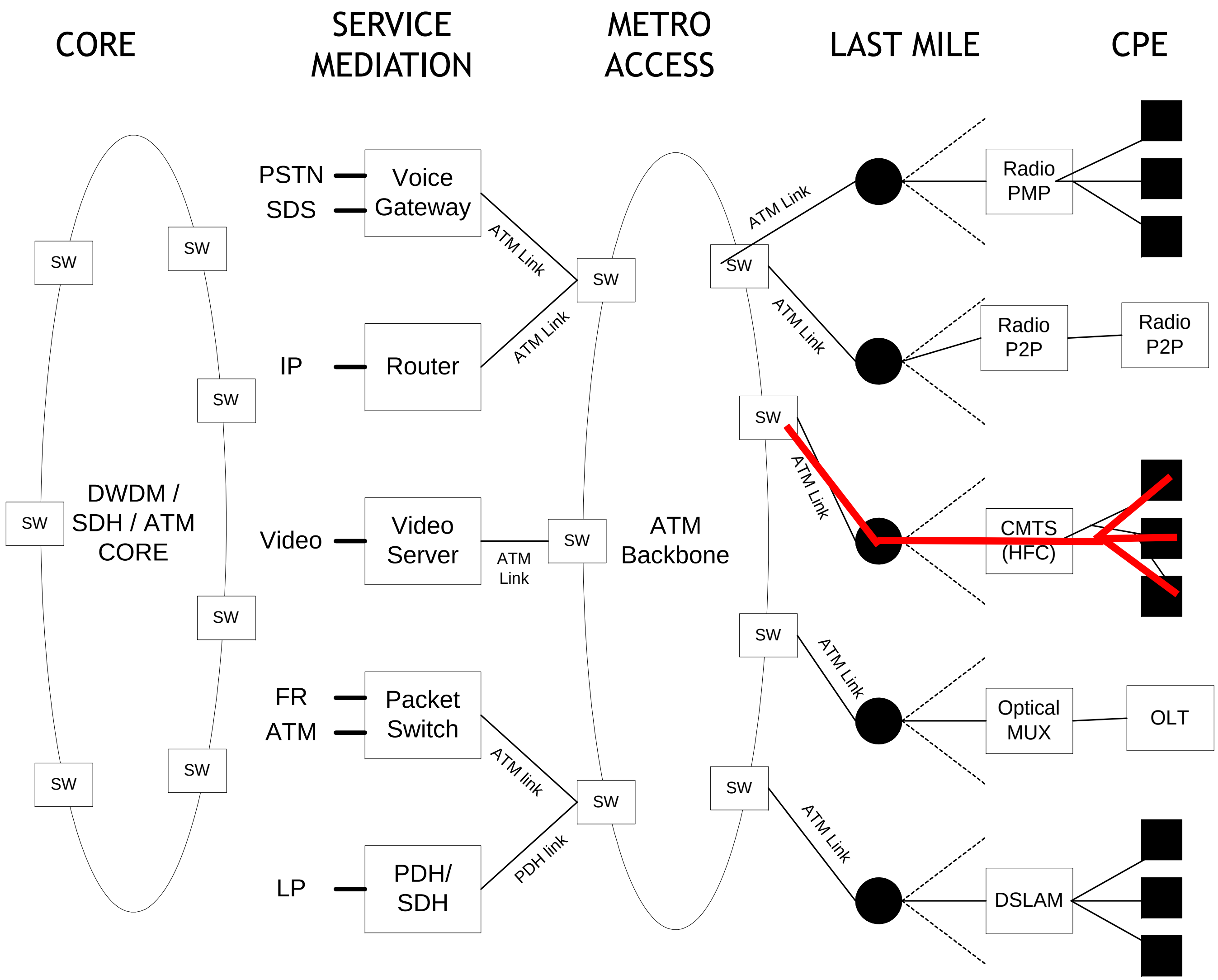
Services	
Without IAD	With IAD
FR IP PL ATM	Voice ATM ISDN FR IP PL
PL FR ATM	Voice ATM IP ISDN PL FR
CATV IP Voice PL & FR with TDM (CBR)	
PL FR ATM	Voice ATM IP ISDN PL FR
FR Voice IP	PL Voice ISDN IP CATV FR ATM

Photonic Point to Multipoint (Passive Optic Networks PONs)

- The access networks borrow the asymmetric principle found in DSL and Cable-modem Internet services.
- There is a large distribution station connected to a single fiber and the signal is distributed by passive couplers.
- The return path is also accomplished by using a single fiber with couplers.
- The multiplexing of different signals can be accomplished by using TDMA or ATM (APON).



Photonic Point to Multipoint

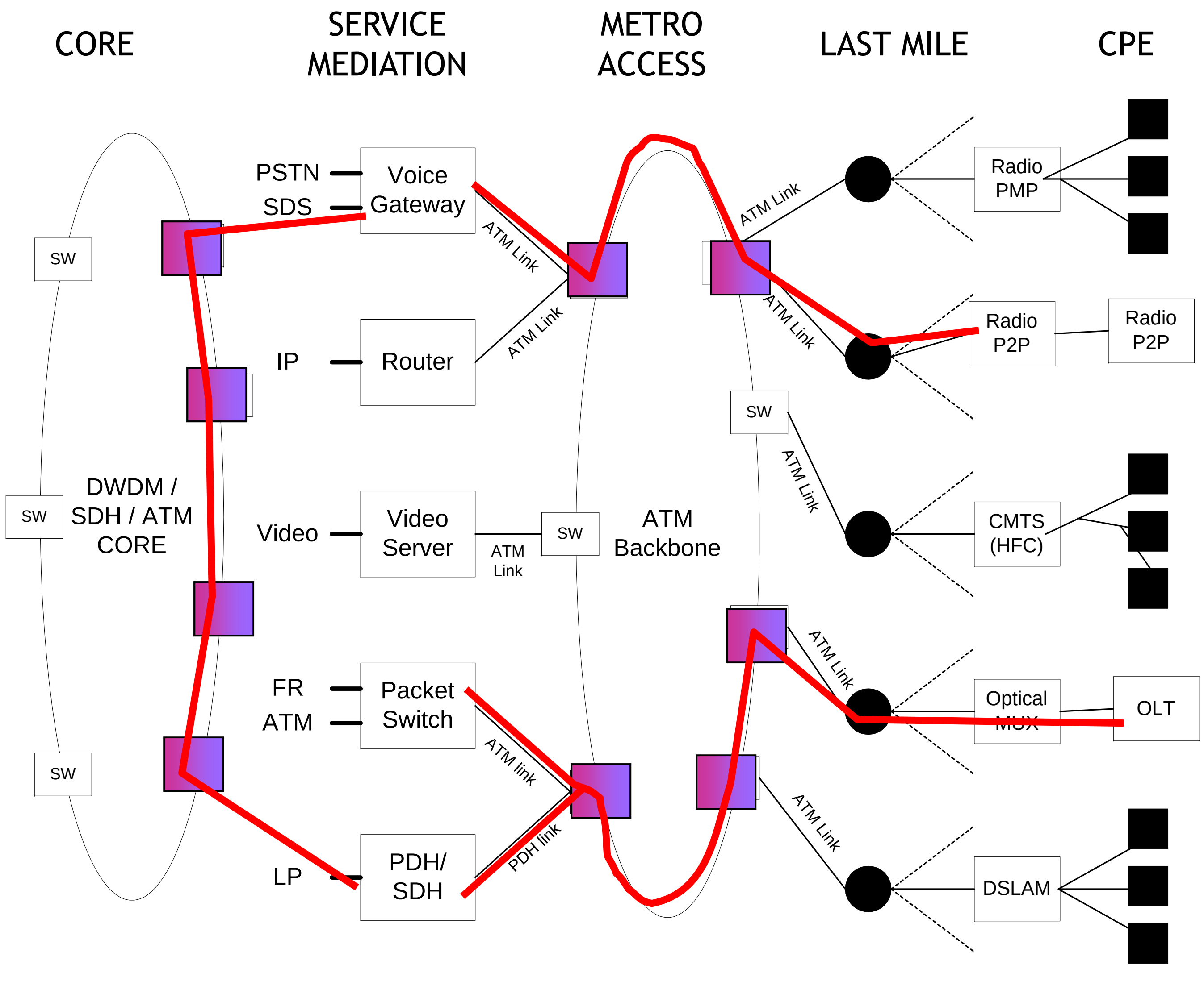


Services	
Without IAD	With IAD
FR IP PL ATM	Voice ATM ISDN FR IP PL
PL FR ATM	Voice ATM IP ISDN PL FR
CATV IP Voice PL & FR with TDM (CBR)	
PL FR ATM	Voice ATM IP ISDN PL FR
FR Voice IP	PL Voice ISDN IP CATV FR ATM

Optical Cross Connects (OXCs)

- An evolution of optical networks that allows the optical rerouting of signals.
- The nodes can behave as full switches or as Add-Drop multiplexers.
- The configuration of the light paths is done manually or as a separate provisioning process.

Photonic Cross Connect

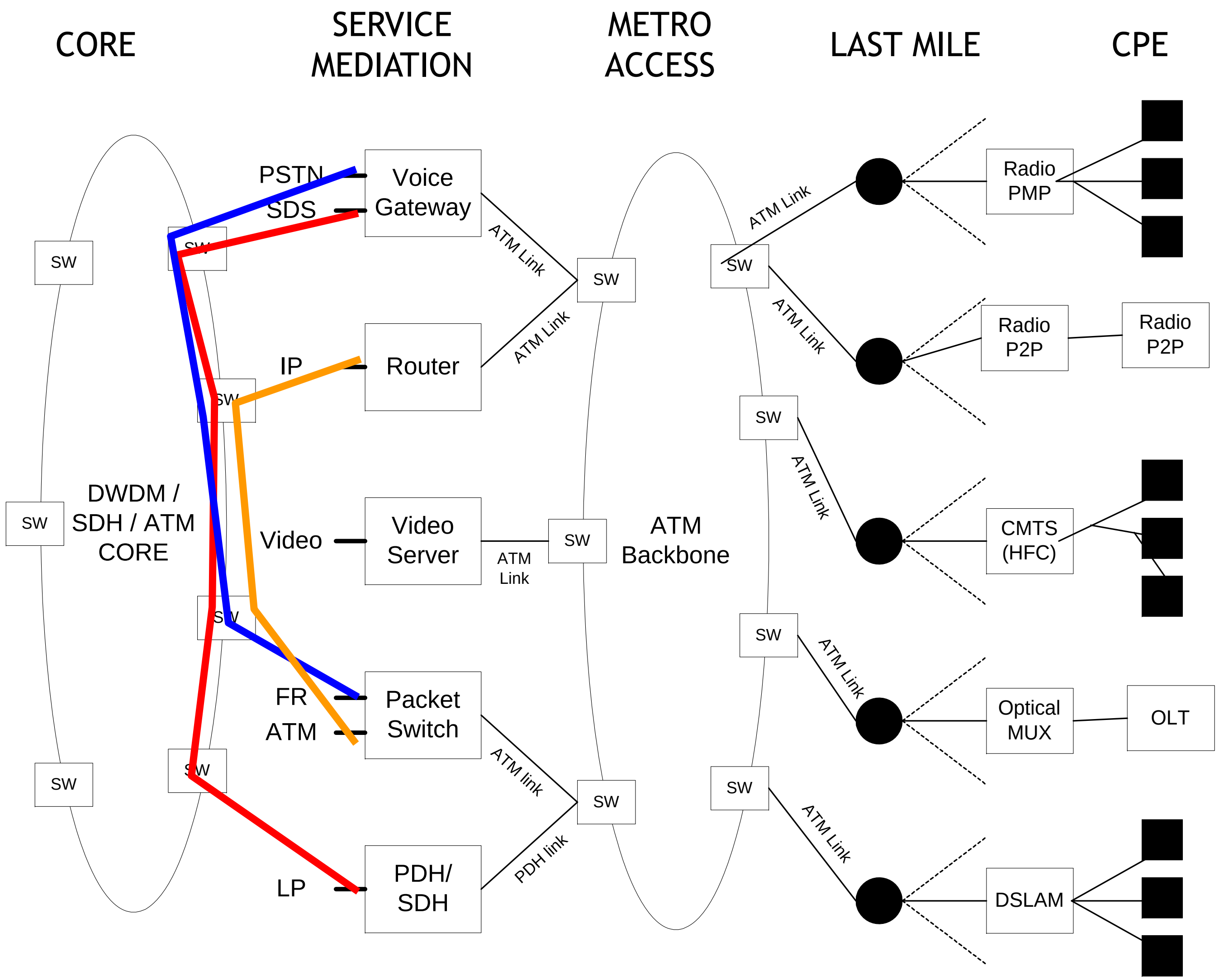


Services	
Without IAD	With IAD
FR IP PL ATM	Voice ATM ISDN FR IP PL
PL FR ATM	Voice ATM IP ISDN PL FR
CATV IP Voice PL & FR with TDM (CBR)	
PL FR ATM	Voice ATM IP ISDN PL FR
FR Voice IP	PL Voice ISDN IP CATV FR ATM

Optical Circuit Switching

- In an Optical Circuit Switched network the establishment and tear down of circuits is done automatically on demand. This requires a signaling mechanism between the customer device and the optical network.

Optical Circuit Switching



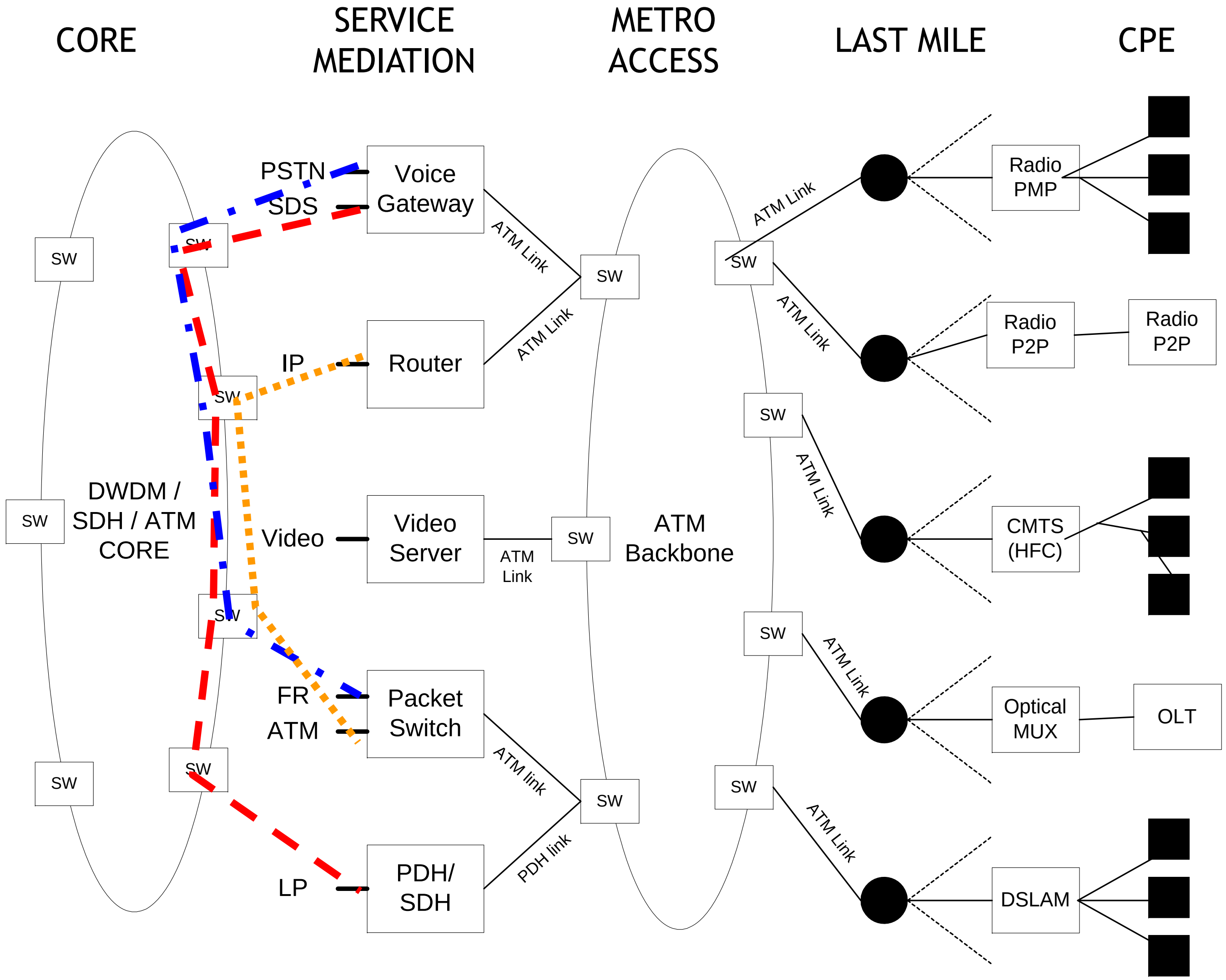
Services	
Without IAD	With IAD
FR IP PL ATM	Voice ATM ISDN FR IP PL
PL FR ATM	Voice ATM IP ISDN PL FR
CATV IP Voice PL & FR with TDM (CBR)	
PL FR ATM	Voice ATM IP ISDN PL FR
FR Voice IP	PL Voice ISDN IP CATV FR ATM

VPIphotonics™

Photonic Packet Switching

- In the Optical Packet network each unit of information contains a header that allows it to be properly routed to the destination. This methodology is still under research.
- Current limited by the lack of practical optical buffers

Photonic Packet Switching

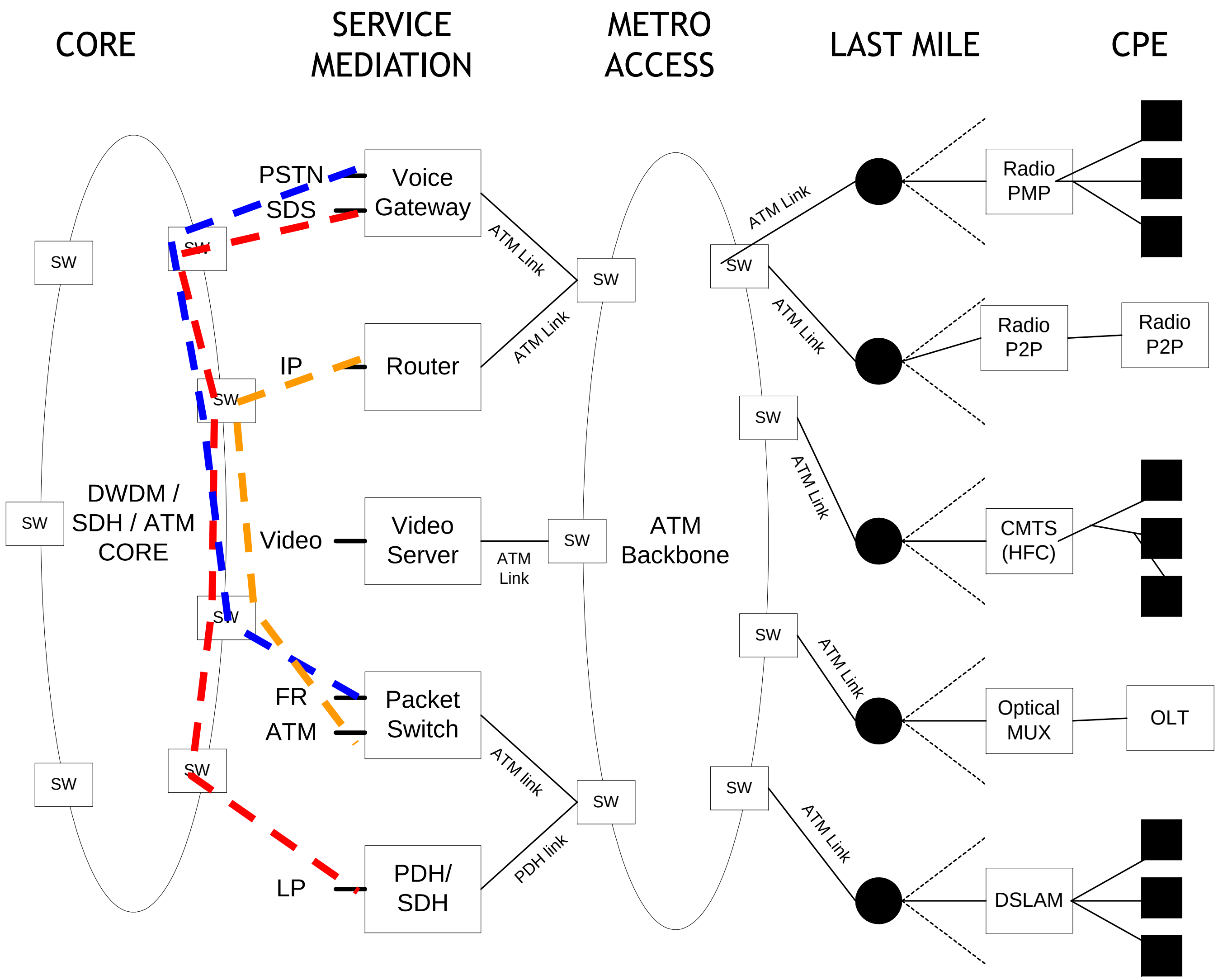


Services	
Without IAD	With IAD
FR IP PL ATM	Voice ATM ISDN FR IP PL
PL FR ATM	Voice ATM IP ISDN PL FR
CATV IP Voice PL & FR with TDM (CBR)	
PL FR ATM	Voice ATM IP ISDN PL FR
FR Voice IP	PL Voice ISDN IP CATV FR ATM

Burst Switching

- This is an intermediate approach between the optical circuits and packets. The assumption is that multiple packets going between the same source and destination could behave as a short lived circuit.
- Therefore the first packet will establish the path and the remaining packets will follow. It is like a train, the engine will start the path and the rest of the cars will follow the same trajectory.

Optical Burst Switching



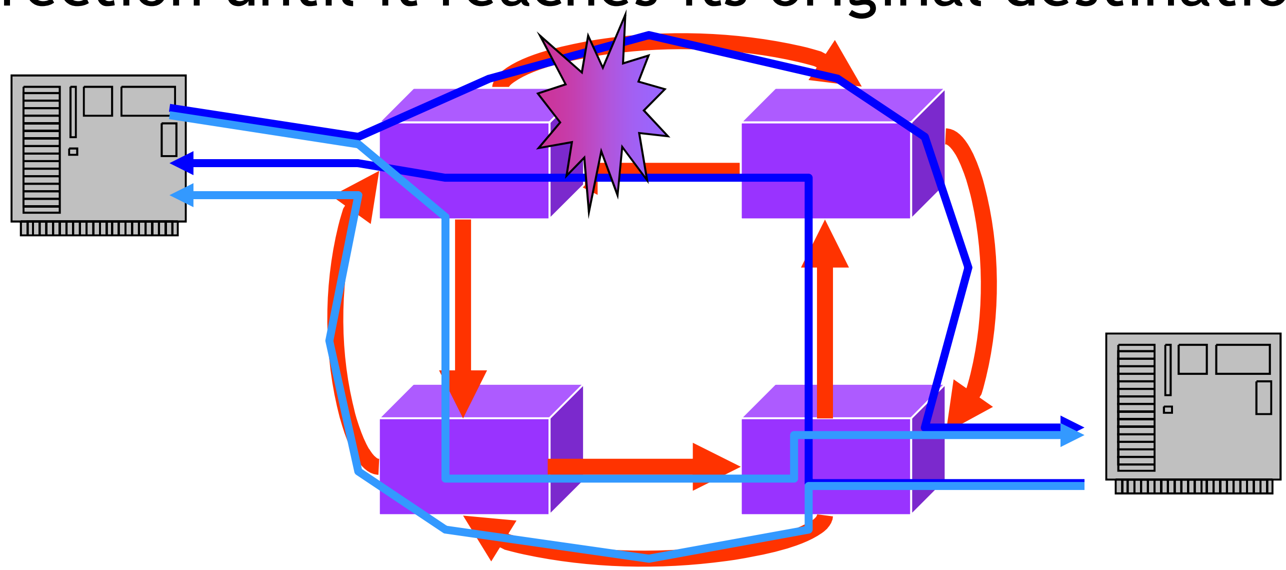
Services	
Without IAD	With IAD
FR IP PL ATM	Voice ATM ISDN FR IP PL
PL FR ATM	Voice ATM IP ISDN PL FR
CATV IP Voice PL & FR with TDM (CBR)	
PL FR ATM	Voice ATM IP ISDN PL FR
FR Voice IP	PL Voice ISDN IP CATV FR ATM

Protection and Survivability

- One of the major design targets of all transmission networks is to maintain the services running
- The network must survive problems due to failures, external events or simple maintenance.
- Protection mechanisms automatically reroute the signals to an alternative route.
- Target restoration time should be less than 50ms. This was defined to be the maximum time that an interruption would not be perceived in a telephone conversation.
- Data applications should include mechanisms to acknowledge and retransmit damaged packets.

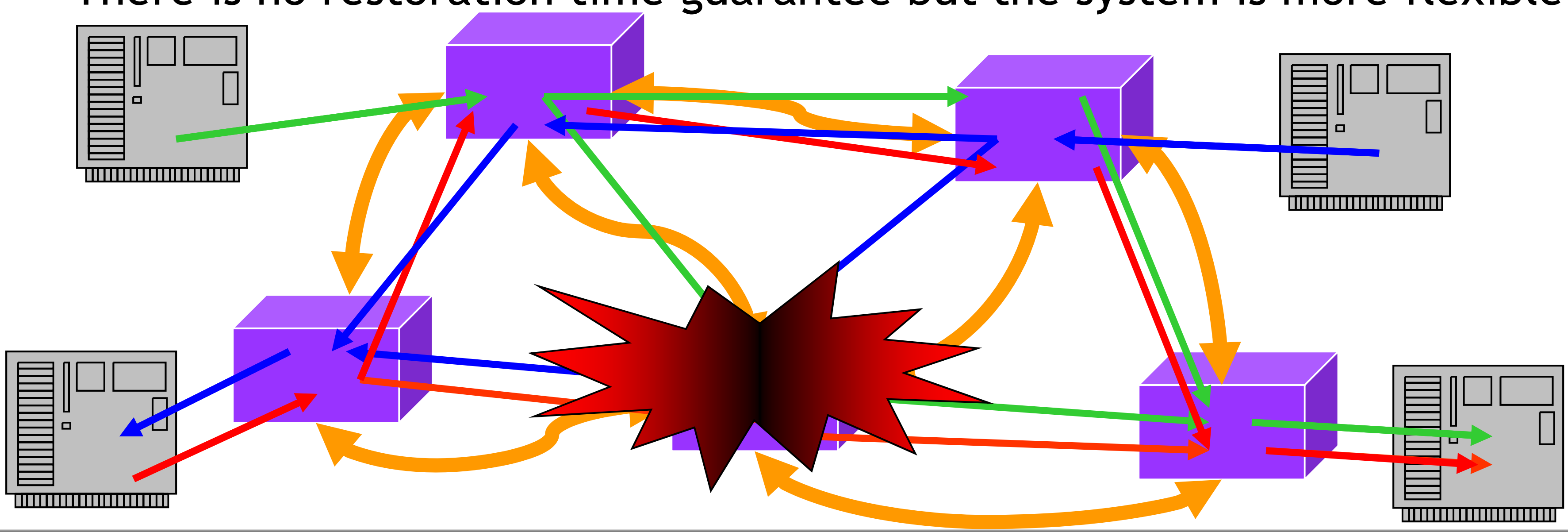
SONET / SDH Protection

- The topology of SONET creates a ring connecting different nodes. The ring is occupied up to half capacity.
- SONET / SDH framing includes constant monitoring of the links between devices. If an error is detected a corrective action is taken.
- In case of a failure, the signal is redirected in the opposite ring direction until it reaches its original destination.



Restoration in IP Based Networks

- IP based networks only use optical links on a point to point basis. All the IP packets get converted back to electronic domain and are processed in the routers.
- Routers constantly exchange information regarding their routing tables, link status and cost metrics.
- In case of a failure the routers will update their tables and will compute again the best available path for each destination.
- There is no restoration time guarantee but the system is more flexible



Optical Layer Restoration Schemes

- Protection in the case of an all optical network could follow the same two approaches:
  - Ring restoration
  - Mesh restoration
- In the ring restoration the optical signal will be automatically redirected to the alternate path. This method is very fast and requires little intelligence by the network. The disadvantage is the waste of capacity just to maintain the protection.
- The mesh restoration requires that multiple switches cooperate and each optical path must be recalculated. This is a slower method but wastes fewer resources in large networks.

Design Issues

- The design of optical networks requires the consideration of several elements:
  - The upper electronic networks, such as IP, ATM or SONET have their own routing or switching capabilities. The amount and type of information between those nodes should be determined.
  - The optical network looks like a simple set of point to point connections between the electronic nodes. However modern optical devices can provide reconfigurable connections and protection.
  - A lightpath is a transparent optic link between two electronic nodes and arbitrarily set through the optic network.
  - Each lightpath will need one or more wavelengths assigned through different segments of the network.
- The Lightpath Topology Design (LTD) defines the optical links that will optimize the use of the electronic nodes reducing their load and required ports.
- The Routing and Wavelength Assignment (RWA) establishes the allocation of resources in the optical layer to realize the lightpath.

Summary

- **Networking concepts**
- **Optical network technology components**
- **Types of optical networks**
- **Protection Mechanisms**
- **Design Issues**

Proceed with the *Interactive Learning Module*

Bibliography

- Ramaswami, R. and K. N. Sivarajan (2002). *Optical networks: a practical perspective*. San Francisco, Morgan Kaufmann Publishers.
- Stallings, W. (2004). *Data and computer communications*. Upper Saddle River, N.J., Pearson/Prentice Hall.
- Hioki, W. (2001). *Telecommunications*. Upper Saddle River, N.J., Prentice Hall.

Glossary

A800	Advanced 800 service	**LAN**	Local Area Network	**ROI**	Return Over Investment
ADM	Add-Drop Multiplexer	**LD**	Long Distance service	**SDH**	Synchronous Digital Hierarchy
API	Application Interface	**MEMS**	Micro Electro-Mechanical System	**SDS**	Switched Digital Services
ATM	Asynchronous Transfer Mode	**MPLS**	Muti-Protocol Label Switching	**SLA**	Service Level Agreement
CATV	Cable Television	**MZI**	Mach – Zehnder Interferometer	**SOA**	Semiconductor Optical Amplifier
CDMA	Code Division Multiple Access	**OC1, OC3, OC12, OC48, …**	North American synchronous digital frame formats	**SONET**	Synchronous Optical Network
CPE	Costumer Premises Equipment	**OEO**	Optical – Electrical – Optical	**STM1, STM4, STM16, …**	ITU synchronous digital frame formats
DSL	Digital Subscriber Loop	**OLT**	Optical Line Terminal	**T1, T2, T3, …**	North American digital frame formats
DWDM	Dense WDM	**OOO**	Optical – Optical – Optical	**TDM**	Time Division Multiplexing
E1, E2, E3, …	ITU Digital frame formats (International)	**OXC**	Optical cross-connect	**TNM**	Telecommunications Network Management
EDFA	Erbium Doped Fiber Amplifier	**PDA**	Personal Digital Assistant	**VNS**	Virtual Network Service (voice)
FDM	Frequency Division Multiplexing	**PL / LP**	Private Line	**VPN**	Virtual Private Network (data)
FR	Frame Relay	**POP**	Point Of Presence	**WAN**	Wide Area Network
HDTV	High Definition Television	**POTS**	Plain old Telephone Service	**WDM**	Wavelength Division Multiplexing
ISDN	Integrated Services Digital Network	**PSTN**	Public Switched Telephone Network	**xDSL**	Any standard DSL variation
ITU	International Telecommunications Union	**RF**	Radio Frequency		