The Optical Internet
Wavelength Division Multiplexing (WDM) and Lambda Switching

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WDM: Wavelength Division Multiplexing

Transmission of multiple light signals (wavelengths) on the same strand of fiber

- **DWDM** - Dense WDM
  - More sophisticated → more expensive

- **CWDM** - Coarse WDM
  - Lower number of wavelengths → cheaper
Initial WDM Application

Increase transmission capacity of fiber

- Increase the utilization (ROI: return of investment) of [existing] fiber
- Point to point configurations
“Interim” WDM Application

Add/drop multiplexing

- Ring topologies with WDM add/drop multiplexers
  - Optical Add-Drop Multiplexer (OADM)
  - Inserting wavelengths on the ring
  - Extracting wavelengths from the ring

- Mostly static or semipermanent interconnection configurations
  - Reconfigurable OADM (ROADM)
Ultimate WDM Application

Wavelength switched networks

- Arbitrary mesh topologies of WDM links and wavelength switches
  - A.k.a. wavelength routers, lambda routers, lambda switches
  - Mostly ("only") optical cross connects
- Optical Switching – Wavelength switching
Wavelength Switching
What to do with Optical Switches?

= WDM Terminal

= IP Router or ATM Switch
Optical Switching

- Fiber cross-connect
  - the whole signal from an input fiber switched to an output fiber
  - Micro-electro-mechanical systems (MEMS)

- Wavelength cross-connect without wavelength conversion
  - one (or more) wavelengths from an input fiber to an output fiber
  - WDM de-multiplexer+MEMS
  - amplification before or/and after switching
    - OEO (optical-electrical-optical) conversion with electrical regeneration
    - optical amplification
Optical Switching

- Wavelength cross-connect with wavelength conversion
  - one (or more) wavelengths from an input fiber to other one (or others) on an output fiber
  - OEO (optical-electrical-optical) conversion with electrical switching
  - easier signal monitoring
  - forward error correction (FEC) possible to reduce Bit Error Ratio (BER)
Dynamic Optical Switching

- Wavelength switch without wavelength conversion
  - switch configuration is changed dynamically
    - by management
    - by time of day
    - every packet!?! …
  - WDM de-multiplexer+MEMS, electroholography, bubbles

- Wavelength switch with wavelength conversion
  - OEO (optical-electrical-optical) conversion with electrical switching
  - circuit switching (SONET/SDH)
\[ \lambda \text{ Switching: the } N^2 \text{ Problem} \]

\[ 20 \lambda s = N \cdot (N-1) \approx N^2 \]
Wavelength Conversion

- Complex
  - OEO conversion
    - expensive
    - non data transparent $\rightarrow$ does not scale
  - Does not require the same wavelength end-to-end

- No wavelength assignment problem
  - $N^2$ problem
IP over Glass? Not Exactly

- Demand for Virtual Networks
- Demand for Raw Bandwidth! Mesh restored
- **Fundamental Demand for Internet Applications**
- Demand for Ring Protection
What is Expected from the Optical Network?

- **Provisioning** and **protection** of lightpaths *end-to-end*
- Client equipment (e.g. routers) to provision optical layer lightpaths
- Cost-effective deployment of flexible networks
Provisioning

Step 1 - Request Bandwidth

Step 2 - Provide New Channel

IP Router

Optical Switch

Control Channel
Provisioning

Step 5 - Release Bandwidth

Step 6 - Disconnect Channel and Use Elsewhere

IP Router

Control Channel
Protection/Restoration

- Protection: pre-determined action
  - non-optimal resource utilization
- Restoration: dynamically determined action
  - optimization of resource utilization

Step 3 - Fiber Cut - Hold off

Step 4 - Restore Connection

Control Channel
Protection/Restoration

- Multiple levels of protection:
  - Layer 1 optical, e.g. SONET-like
  - Layer 2 data link bundle
  - Layer 2.5 protected MPLS LSPs
  - Layer 3 routing

- Can trigger multiple layers of restoration
  - each has different timescales for detection and repair

- Must avoid:
  - unnecessary traffic shifting
    - packet loss, reordering, control plane churn
  - pathological feedback
    - non self-stabilizing
Signaling: What Optical Switches Need

- Resource discovery
  - Topology
  - Access points and node identification
  - Resource usage

- Connection management
  - Lightpath setup
  - Lightpath take down
  - Lightpath modification

- Mesh/ring network protection and recovery
  - Distributed routing

- Establishment of protection service classes
Signaling: What Optical Users Need

- Resource discovery
  - Address of users reachable through the optical network

- Manage lightpaths
  - Lightpath setup
  - Lightpath take down
  - Lightpath modification

- Negotiate protection service classes
  - Protected, unprotected, best effort lightpaths

Does all this sound familiar? ATM
Signaling: How to Do It

- How is the optical layer controlled?
  - Layer 3 control plane?
  - MPLS/LDP?
    - LSPs mapped over wavelengths
  - OSPF, BGP4?
  - New signaling and routing standards?
  - Proprietary vendor specific?

- Out of band or in-band
  - Ethernet control channel