



The Future of Optical Networks

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Technology Trends
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- Why optical?
- Optical transmission basics
- Optics in:
 - Core networks
 - Metro networks
 - Access networks
- Summary

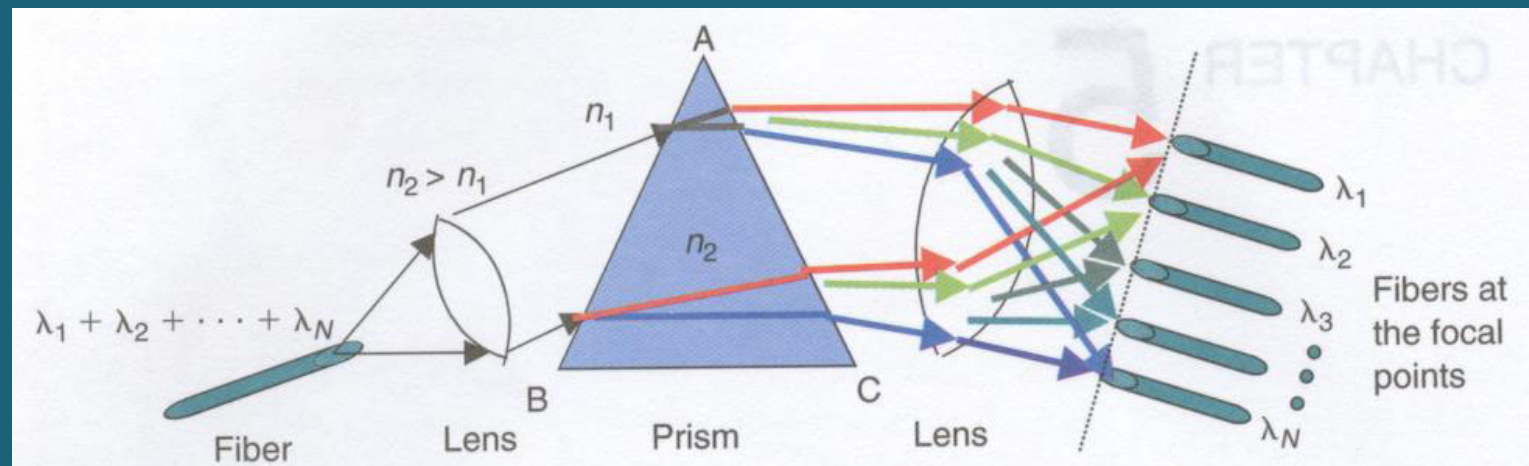
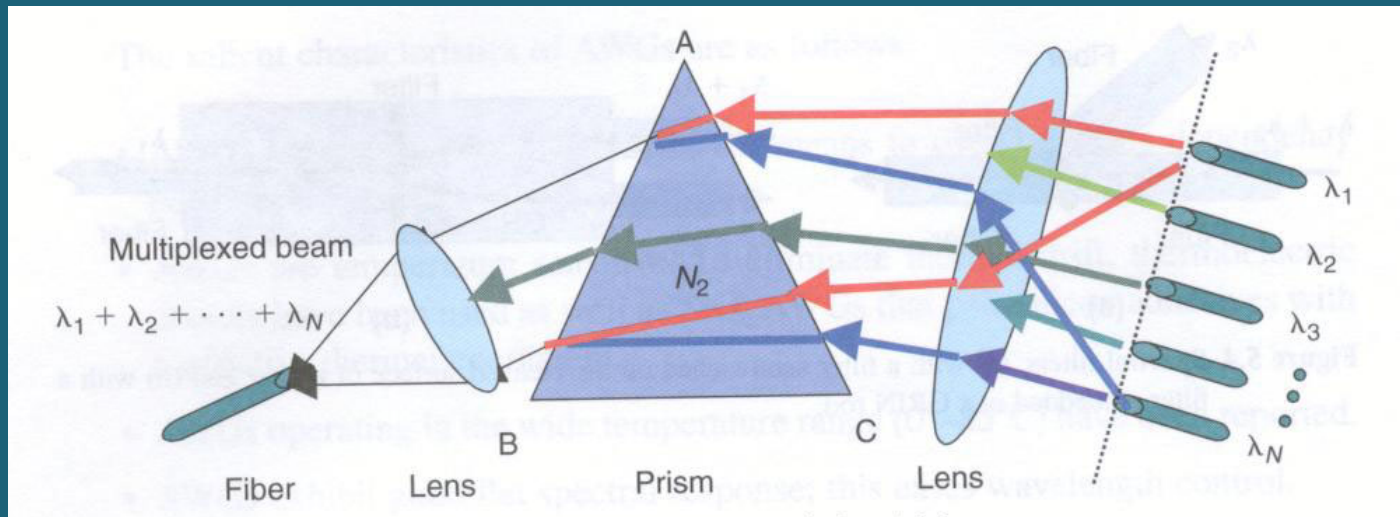
- Why optics?
 - Optical fibre capacity potential: ~ 50 Tbps
 - Low losses: ~ 0.2 dB/km
 - Low bit error rates: $\sim 10^{-11}$
 - Low power requirements: ~ 100 photons/bit
 - Immunity to electromagnetic interference
 - Low cross-talk
 - Repeater-less amplification (EDFA)
 - Low cost, maintenance



Harnessing the optical bandwidth

- Electronics too slow! – the electro-optic bottleneck
- Wavelength Division Multiplexing (WDM)
 - Coarse (CWDM): $\sim 12 \lambda$
 - Dense (DWDM): $\sim 64 \lambda$
 - Ultra-dense (UDWM): $> 100 \lambda$
 - » 1999: Lucent demonstrates 1022λ on one fibre
 - » 2002: Lucent shows $64\lambda \times 40\text{Gbps}$ over distance of 4000km

WDM: optical mux/demux





Quick history

- **1958: Laser** discovered
- **Mid-60s: Guided wave optics** demonstrated
- **1970: Production of low-loss fibers**
 - Made **long-distance** optical transmission possible!
- **1970: invention of semiconductor laser diode**
 - Made optical **transceivers** highly refined!
- **70s-80s: Use of fiber in telephony: SONET/SDH**
- **Mid-80s: LANs/MANs: broadcast-and-select architectures**
- **1988: First trans-atlantic optical fiber** laid
- **Late-80s: EDFA (optical amplifier)** developed
 - Greatly alleviated distance limitations!
- **Mid/late-90s: DWDM systems** explode
- **Late-90s: Optical switching** systems develop

Optical transmission windows

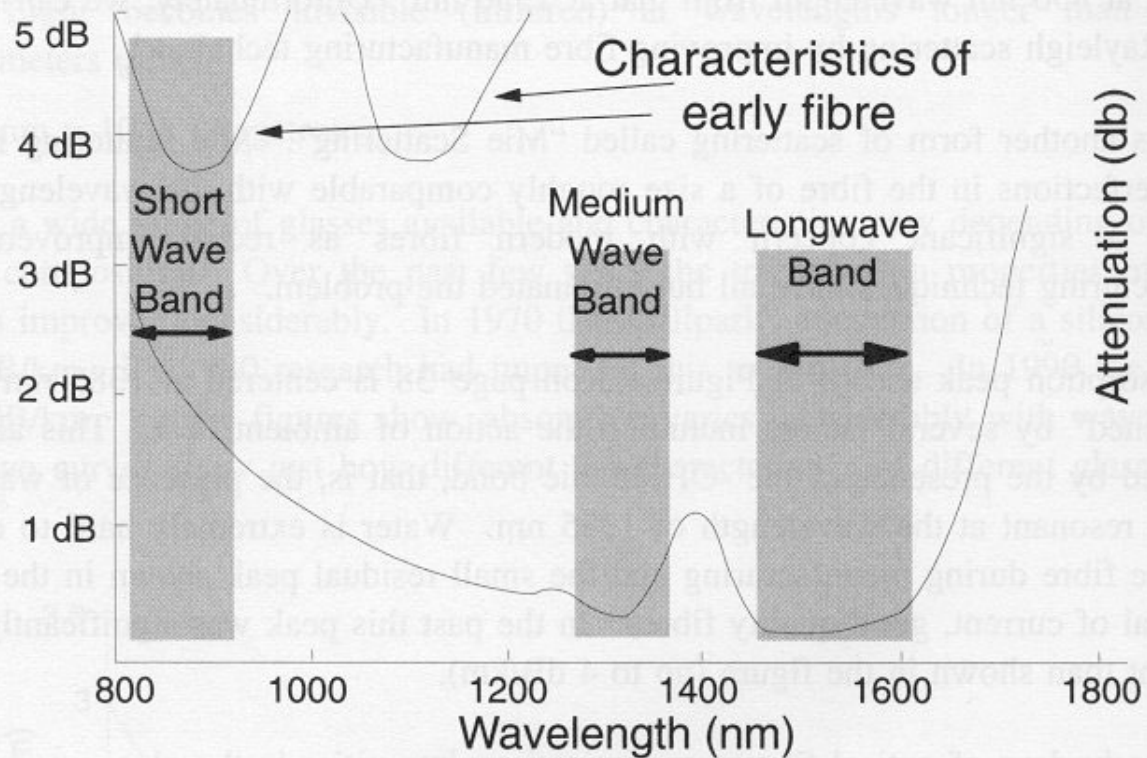


Figure 14. Transmission Windows. The upper curve shows the absorption characteristics of fibre in the 1970s. The lower one is for modern fibre.

Transmission in optical fibre

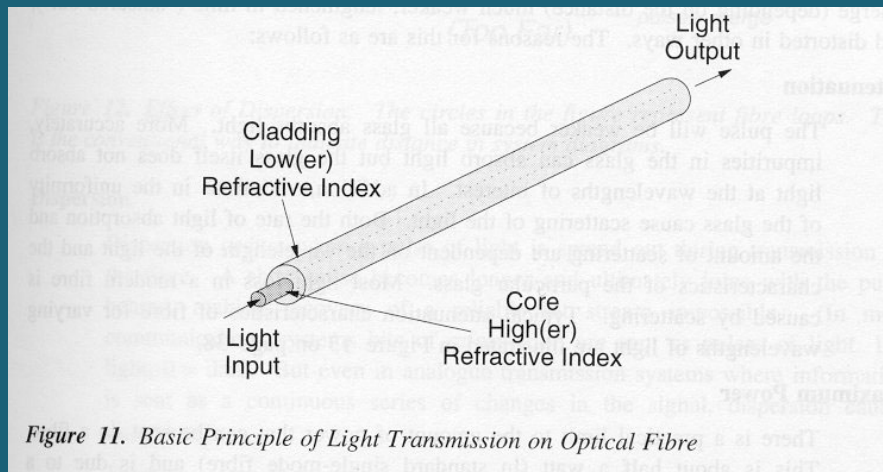
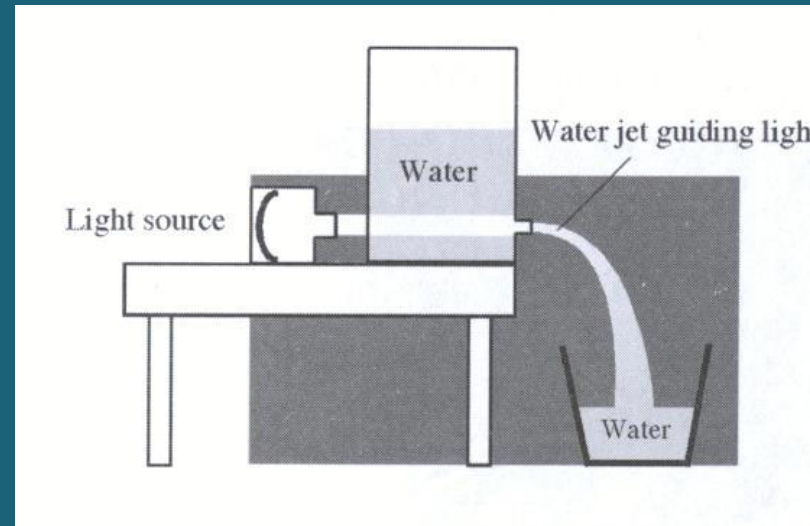


Figure 11. Basic Principle of Light Transmission on Optical Fibre

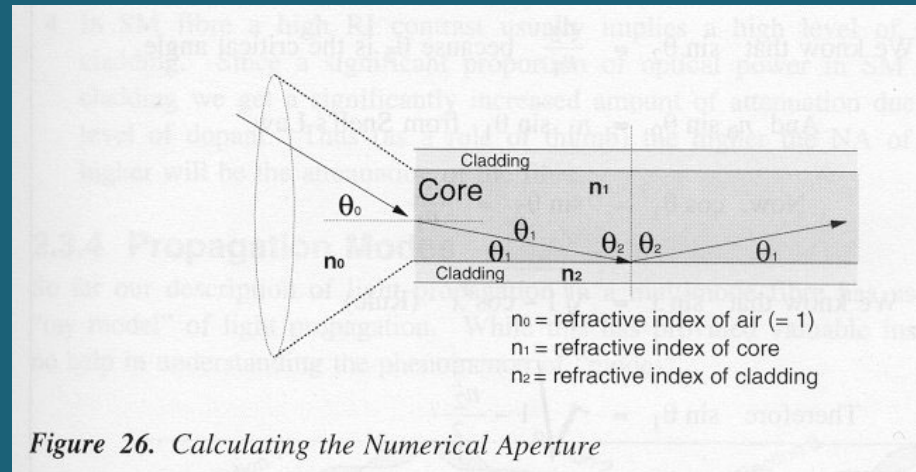
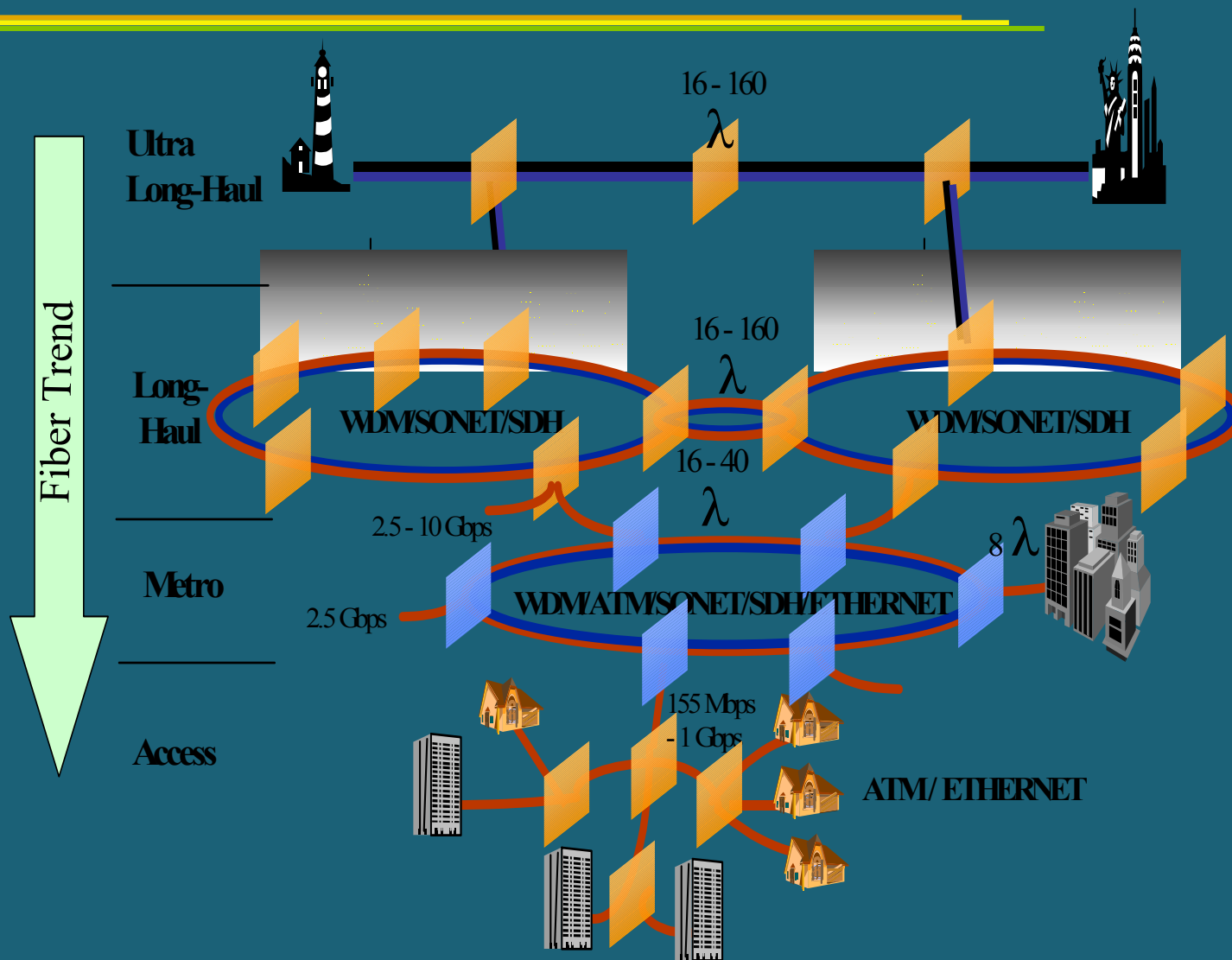


Figure 26. Calculating the Numerical Aperture

Optics: where in the network?





Core optical networks

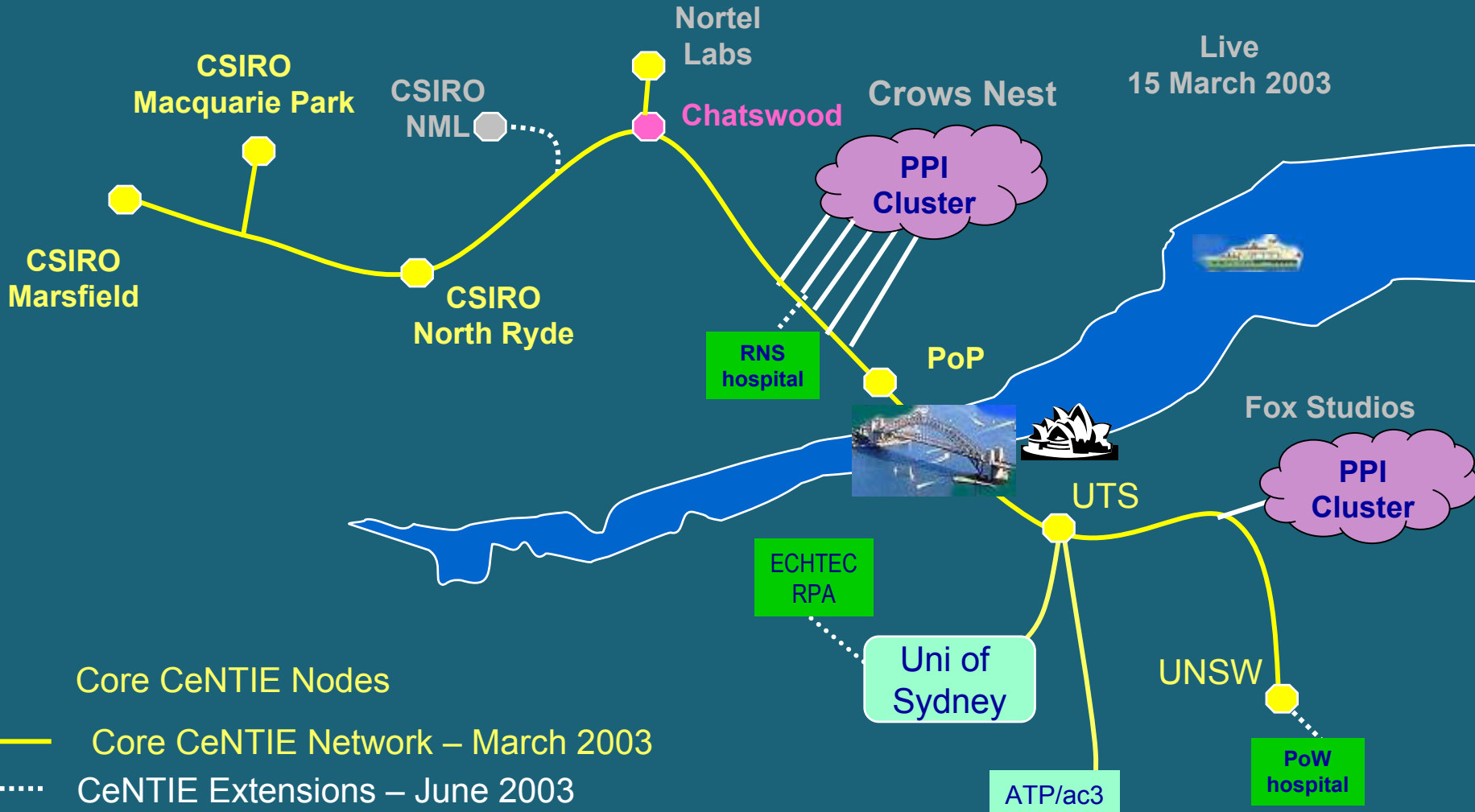
- High data rates! (Tbps)
 - WDM is ideal
- Requirements:
 - 600km to 6000km
 - 10Gbps to 40Gbps per λ
 - 16 to 160 λ
 - Mesh networks



CeNTIE

in Sydney

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Example ISP core network

Sprint US backbone network

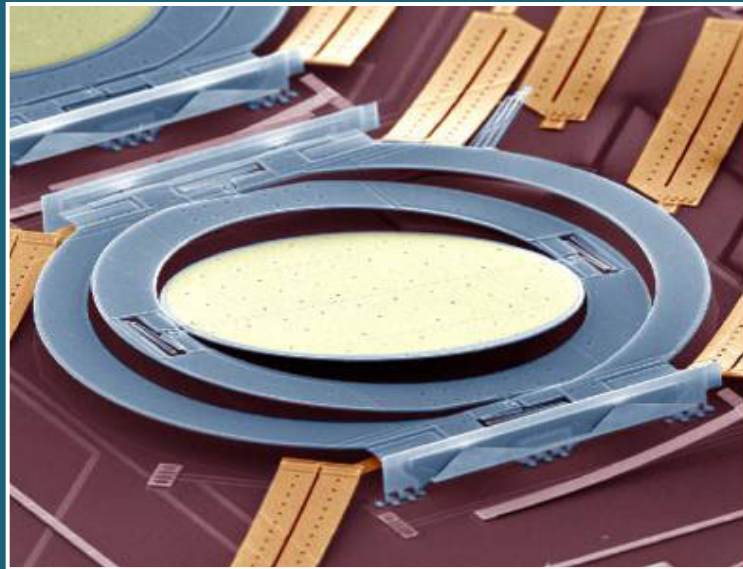




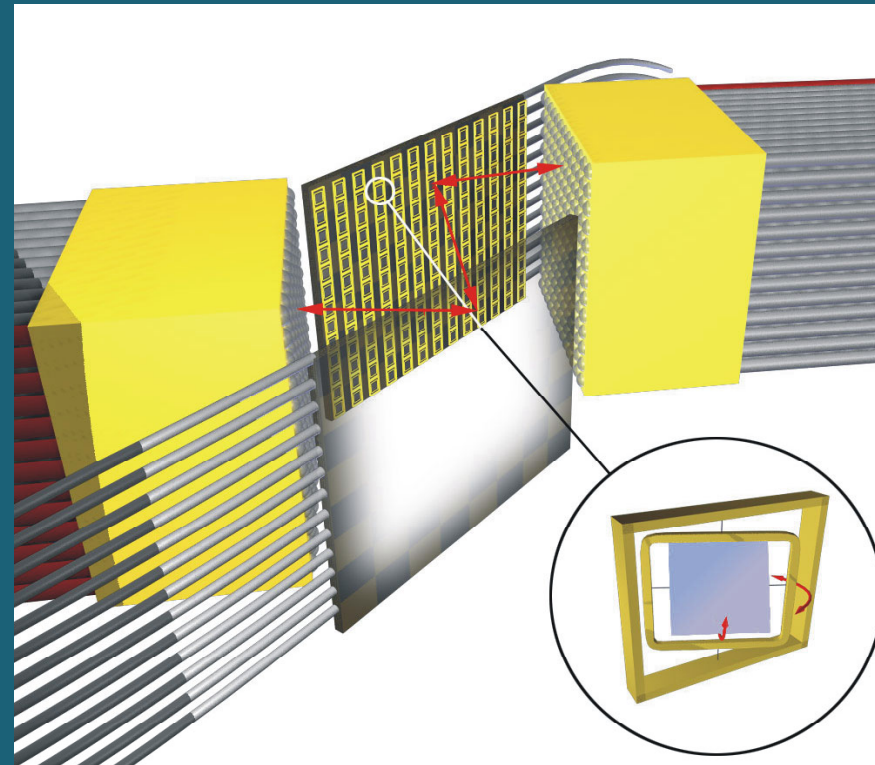
From Transmission to Switching

- First generation optical networks: **Opaque**
 - Opt-elect-opt (OEO) conversion at intermediate node
 - Switching/routing/buffering in electronics
 - » Scaling electronics to high data rates is challenging
 - » Power consumption / heat dissipation difficult to control
 - » No future-proofing due to dependencies on data rate/format
 - » Cost of transceivers adds significantly to expense
- Second generation optical networks: **Transparent**
 - Requires optical switching!

How to switch light?



Lucent's "LambdaRouter" Device



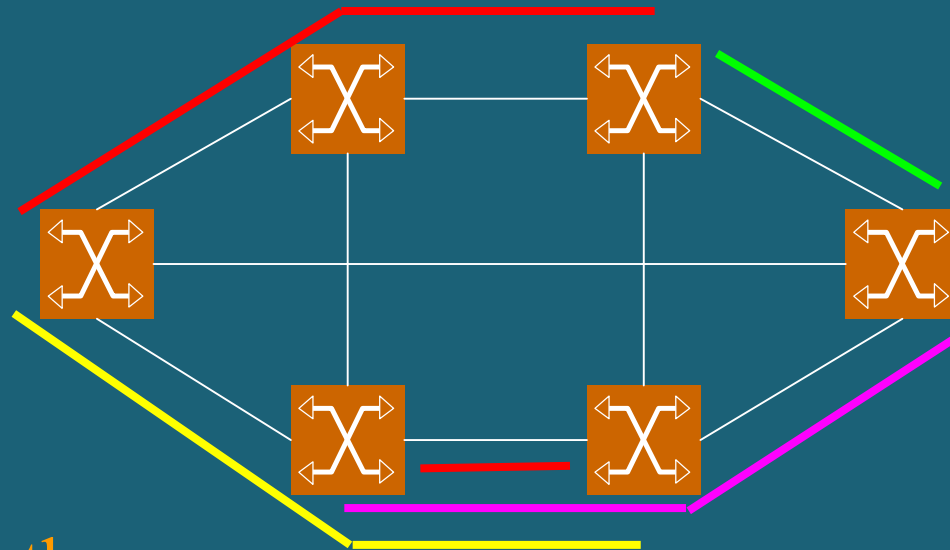
- Deflection, no regeneration



Optical Switching Technologies

- Mechanical: MEMS mirrors, Directional couplers
 - Electro-optic: couplers with changeable refractive index
 - Thermo-optic: refractive index function of temperature
 - Semiconductor Optical Amplifier (SOA): voltage controlled
 - Liquid crystals, Bubbles, Holography!
-
- Performance metrics:
 - Switching speed
 - Size scalability
 - Reliability and durability
 - Losses
 - Cost / power consumption

Transparent Optical Networks



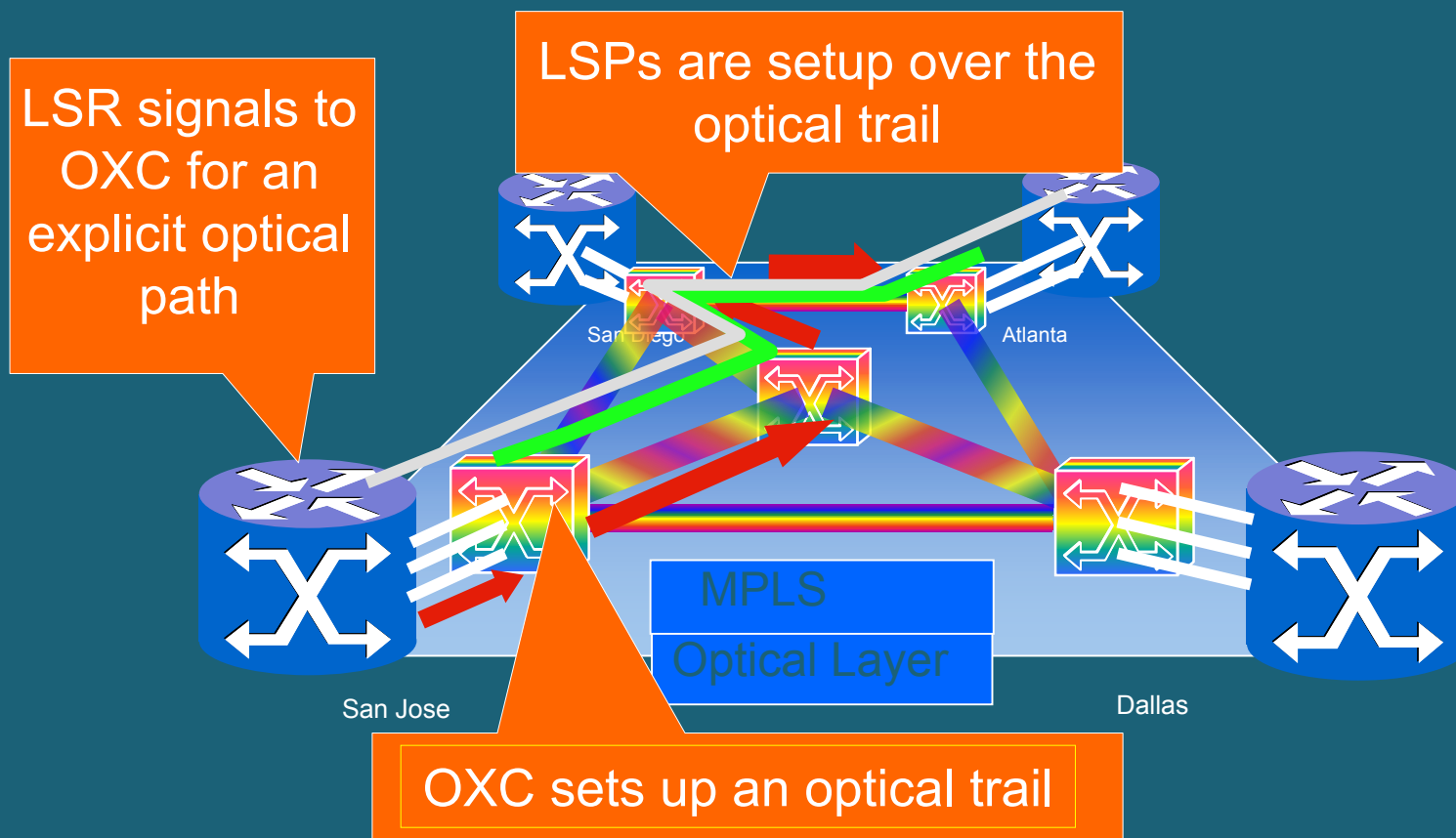
- **Lightpaths:**
 - Switch wavelength/fibre (circuit-switching)
 - End-to-end optical connection spanning multiple links
 - Signal in optical form throughout; no electronics involved
- Lightpaths define logical (virtual) connectivity



Wavelength routed networks

- Current state:
 - Pseudo-static virtual topology
 - Off-line design
 - » Routing and Wavelength assignment (RWA)
 - » Wavelength conversion: dense, sparse, full, limited
- Emerging: Intelligent Optical Networks (ION)
 - Rapid provisioning and restoration of connections
 - Dynamic virtual topology
 - Requires intelligent and unified control plane

GMPLS: the unifying control plane?



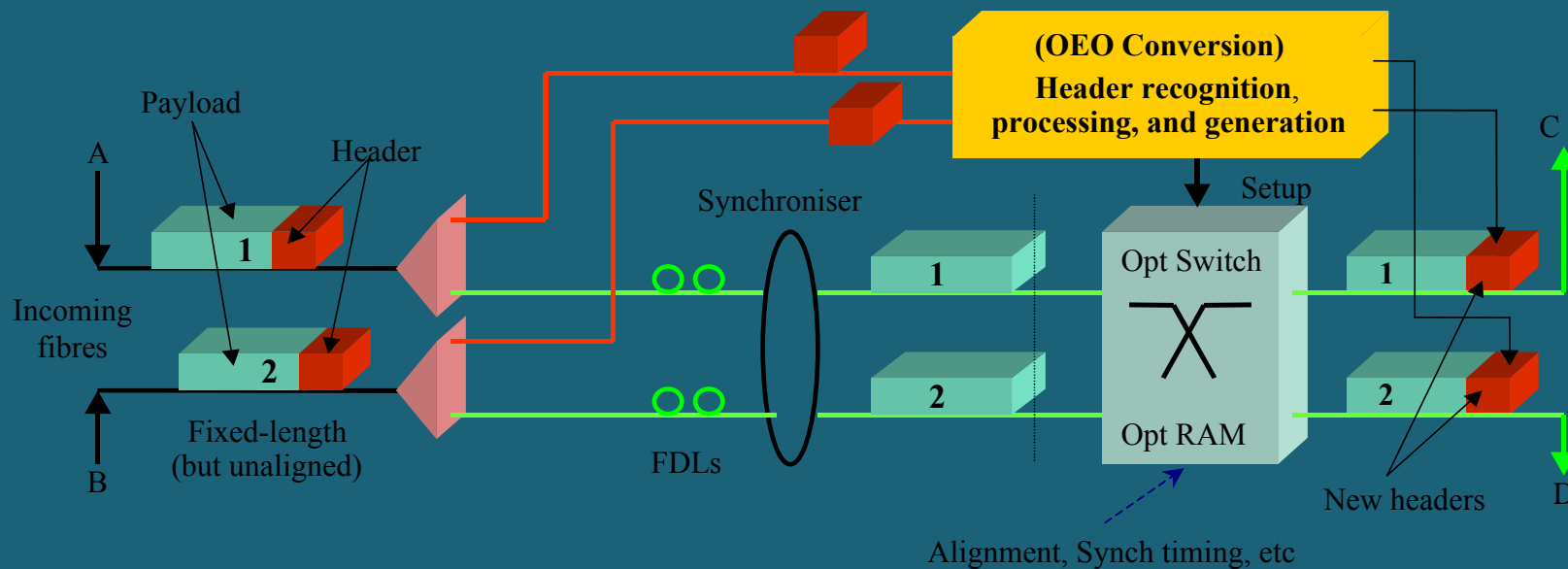


Transparency: Pros and Cons

- Pros:
 - Clear channel
 - » No limit on throughput
 - » No restriction on data rates or formats
 - No signal processing required
 - » Switches feasible to implement using current technology
 - » cost / space / power efficient
- Cons:
 - Impairments (noise, crosstalk, dispersion) accumulate
 - Cannot use in-band information while signal in optical form
 - » Cannot do sub-wavelength multiplexing \Rightarrow inefficient!

The Ultimate All-Optical network?

- Optical Packet Switching (OPS): switch **packets** all-optically!
- Challenge: how to process packet header optically
 - Optical computing?
 - In the interim: OEO conversion?





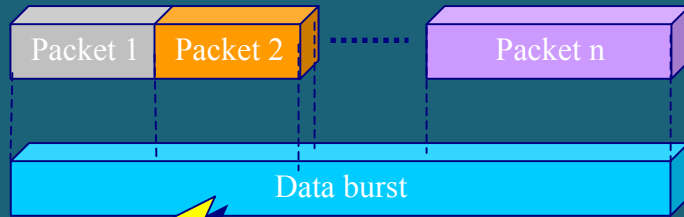
OPS: the big challenge

- How to resolve contentions?
 - Optical RAM: will it happen?
 - Interim contention-resolution solutions:
 - » Time: Fibre drums (FDLs), photonic crystals?
 - Problem: 1km of fibre holds light for 5us
 - » Space: send on a different fibre (deflection routing)
 - » Wavelength: convert and send on another wavelength
 - Remains the biggest challenge to realizing OPS



OBS: an interim solution?

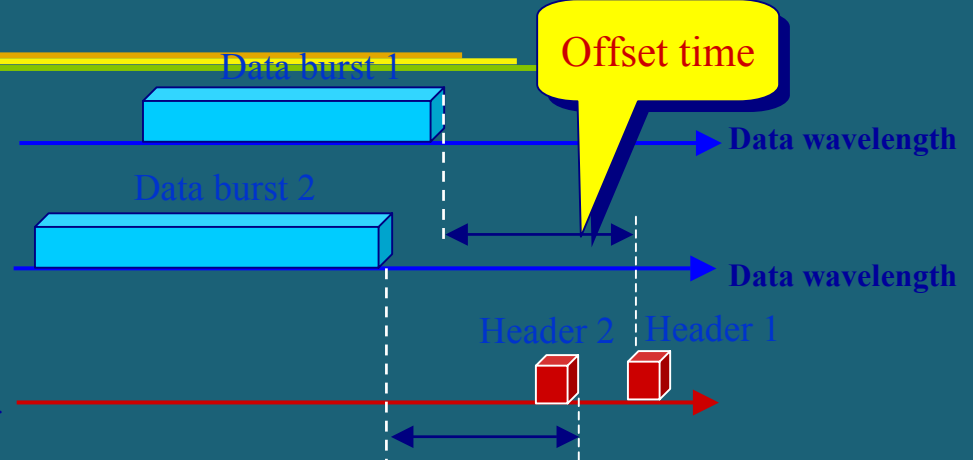
- Same destination
- Same packet type



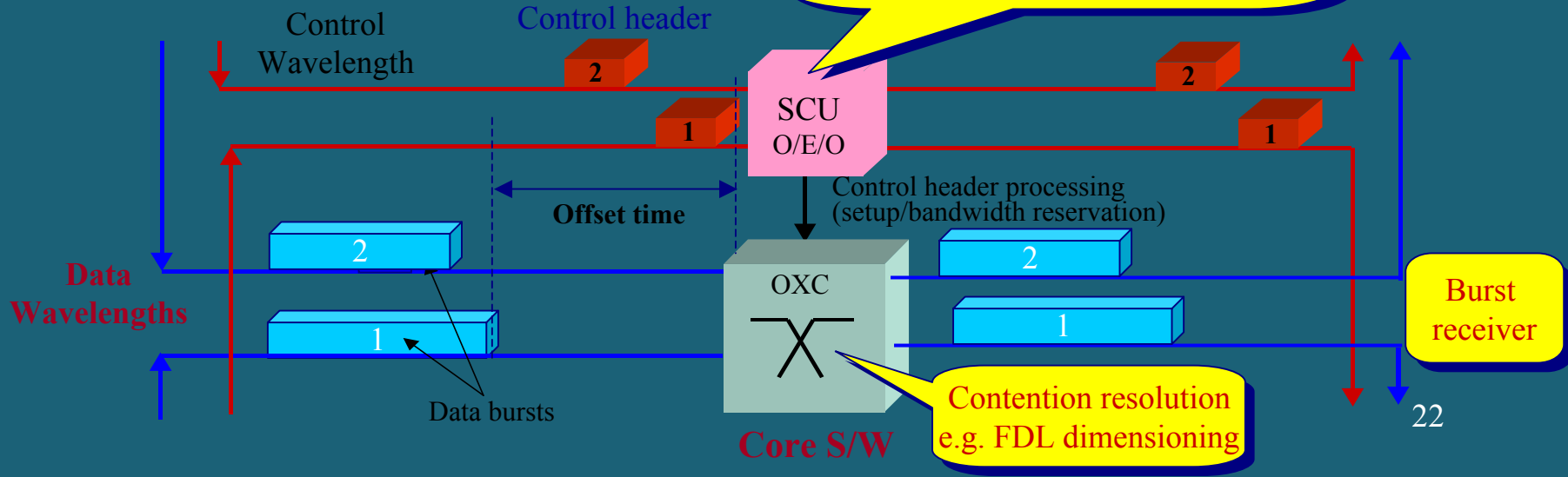
Edge device: "Burstification"

- Burst assembly
- Offset time management

- +
- Control Header
 - burst duration
 - offset time
 - src/dest addr
 - QoS parameters

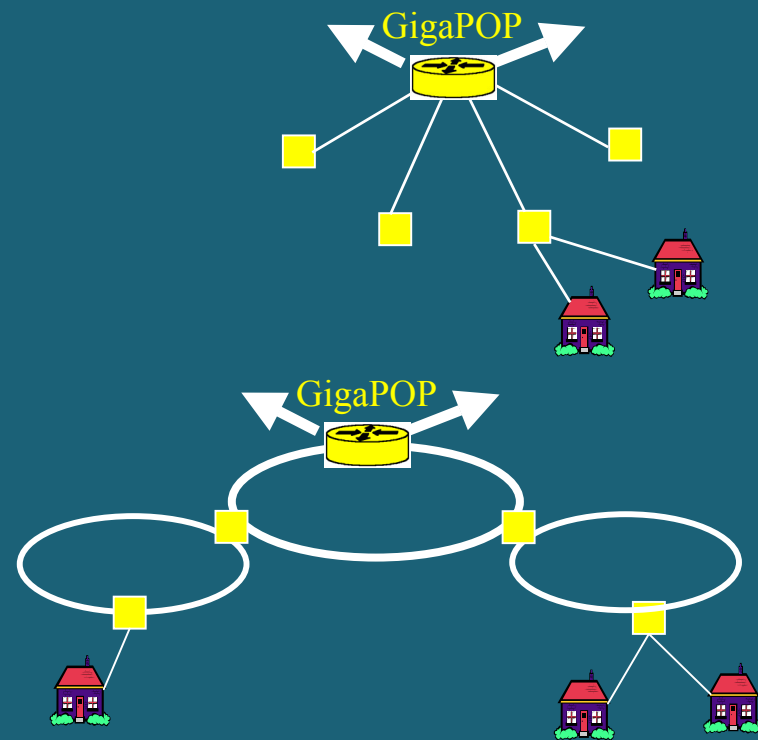


- Control scheduling
- Data scheduling
- Protection & Restoration
- Resv' Mech' & Contention resolution



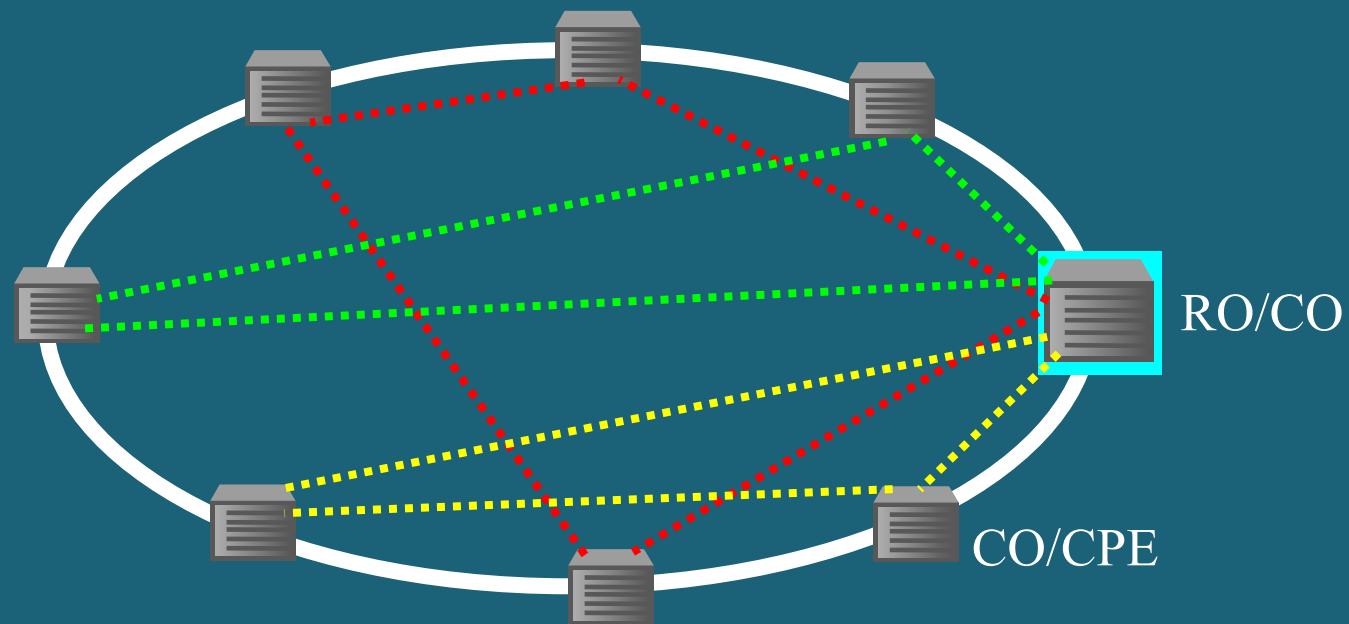
Metro Optical Networks

- Customer premises (CP) to central office (CO)
- Central offices (CO) to a regional office (RO)
- Hub-and-spoke architecture:
 - Typically GigEth
 - High port densities
 - No resilience
 - Not well-suited for voice
- Ring architecture
 - Typically SONET/SDH
 - Reliability, lower port count
 - “ring of rings”



WDM in the Metro

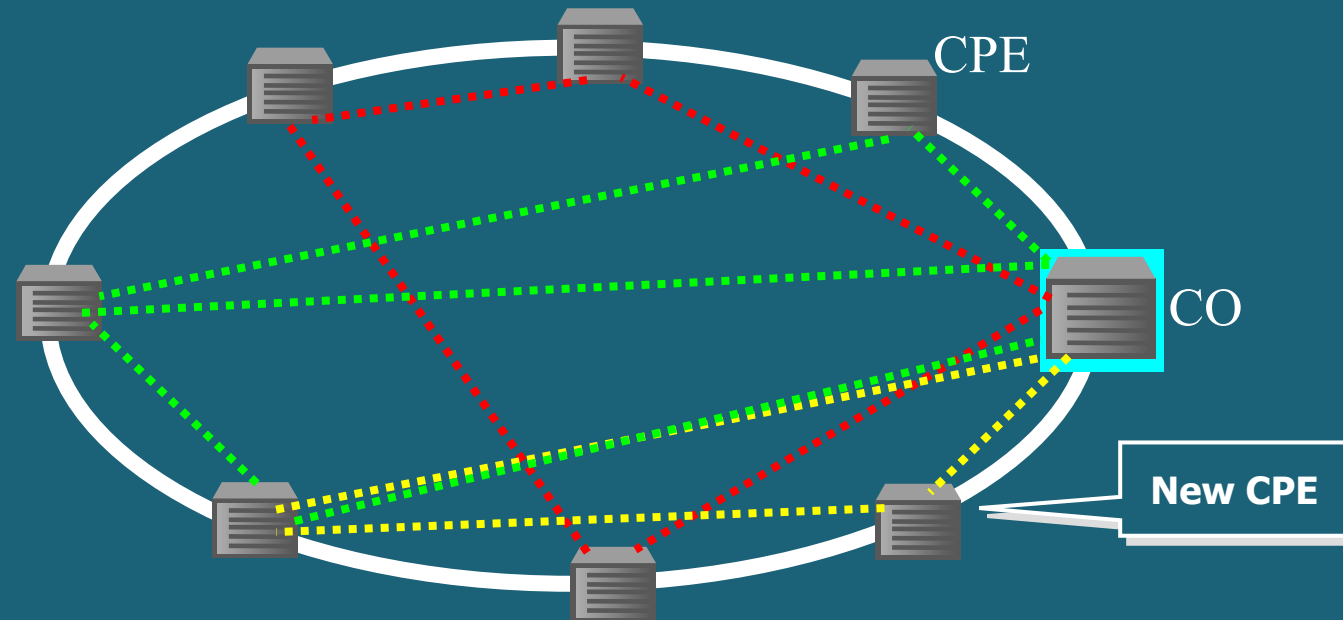
- WDM well suited for ring topology
 - allows “logical” rings on separate wavelengths
 - Bypass wavelengths not processed



Metro Challenges

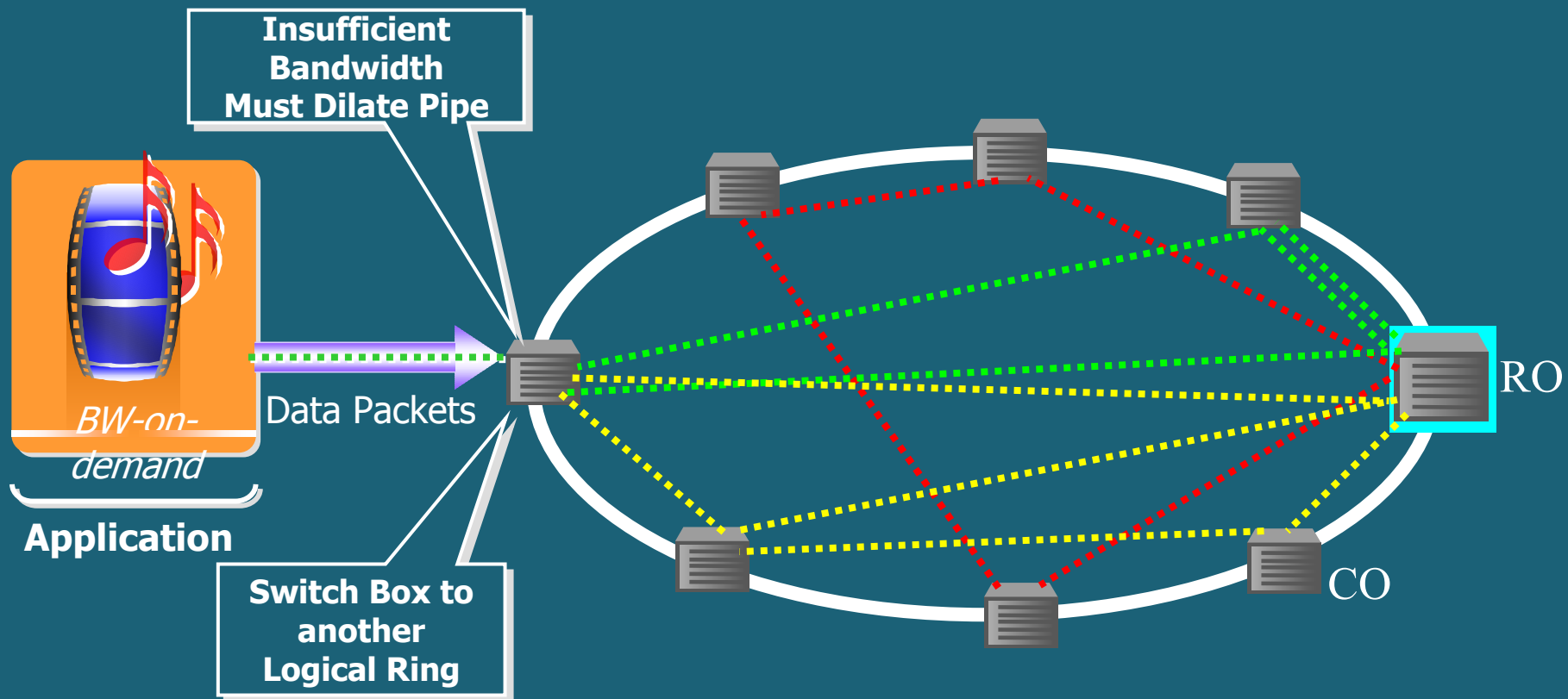
- To be competitive, a metro provider needs:
 - **Scaling**: gradually raise network bandwidth as users increase
 - **Service agility**: Dynamically reprovise network to adapt to bandwidth demands fluctuations
- Enabling technology: **tunable wavelength transceivers**
 - Lasers with rapidly changeable transmit λ (within usecs)
 - Higher CapEx than fixed-wavelength-lasers, but starting to become cost competitive
 - Provide flexibility that lead to lower OpEx
- Elegantly solves the above metro challenges

Tunable Optical Scaling



- Incremental deployment of bandwidth
 - All operations done at RO \Leftrightarrow no truck-rolls

Tunable Optical Provisioning



- Dynamic (manual/auto) movement of bandwidth
 - No truck-rolls; all operations done from RO

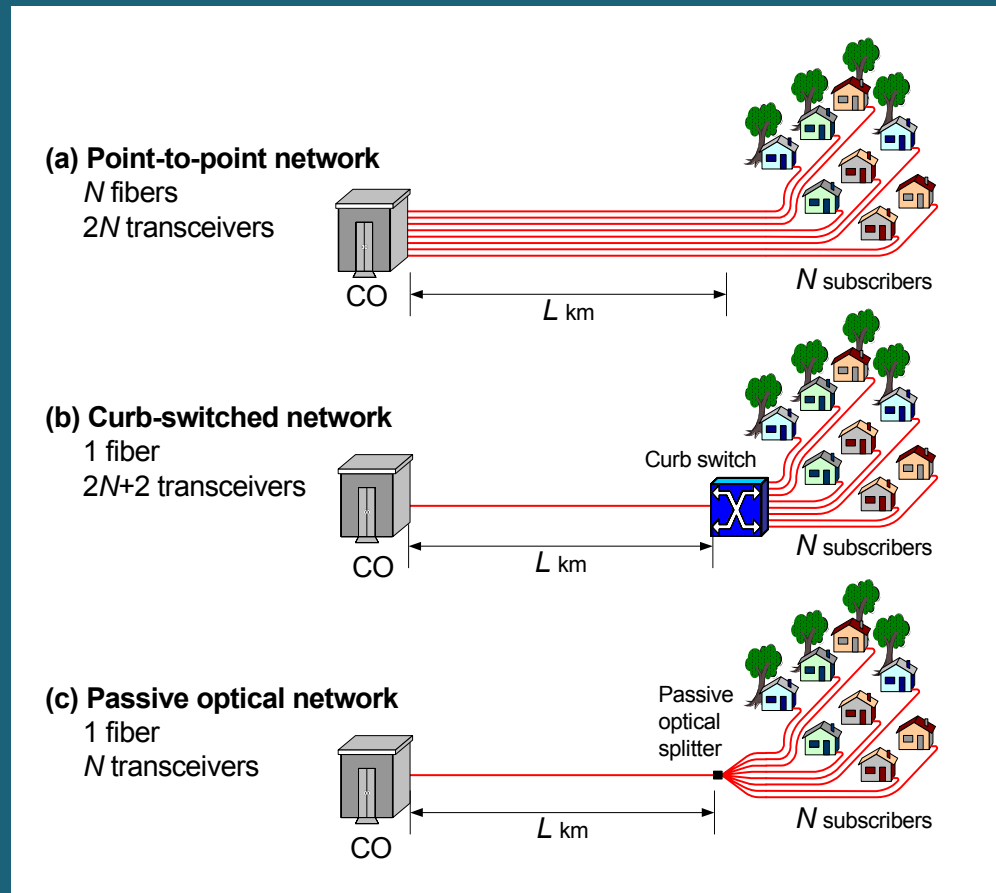


Access Networks: FTTH

- Why Fibre-to-the-Home (FTTH / FTTP) ?
 - User pressure for higher bandwidth
 - » Remove last mile bottleneck between multi-Gbps worlds
 - Overcome Copper limitations
 - » Bandwidth
 - » Distance
 - » Noise / crosstalk / asymmetry
 - Convergence: voice, video, data

FTTH Technology

- (a) P2P (Point-to-Point) network
- (b) AON (Active Optical Network)
- (c) PON (Passive Optical Network)
 - E-PON: Ethernet based (10-1000 Mbps each way)
 - A-PON: ATM based
 - » B-PON (622 Mbps down / 155 Mbps up)
 - » G-PON (2.4 Gbps down / 622 Mbps up)



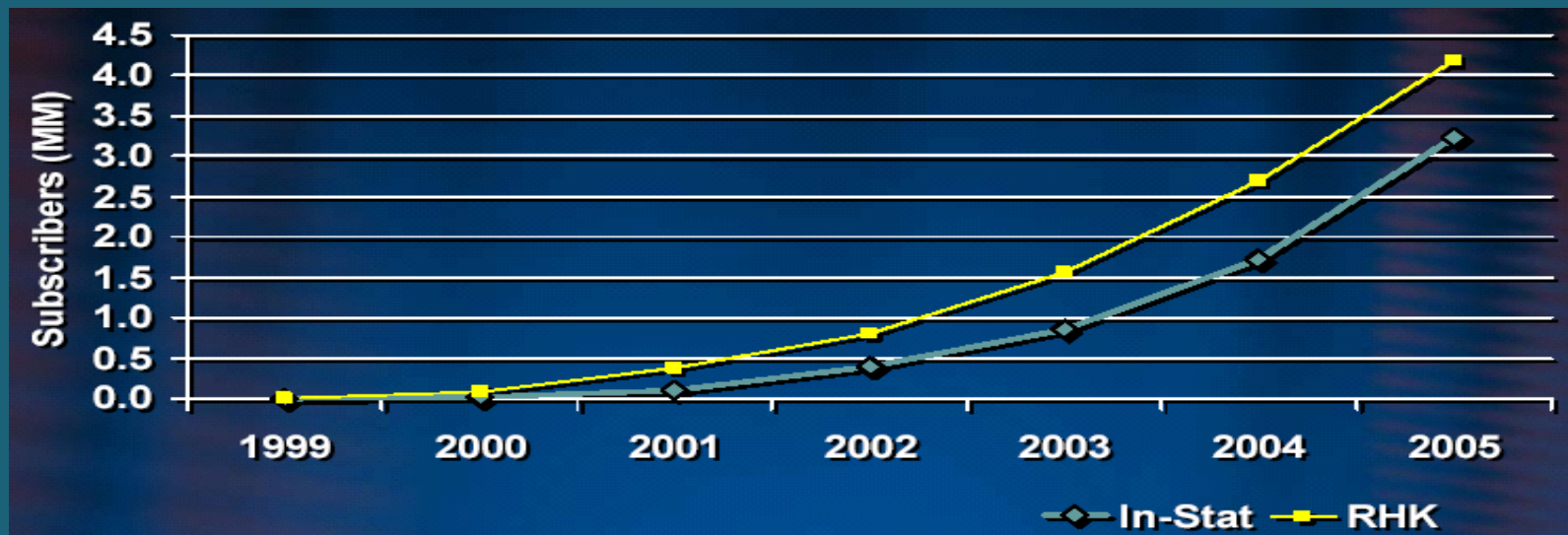


PONs: Pros and Cons

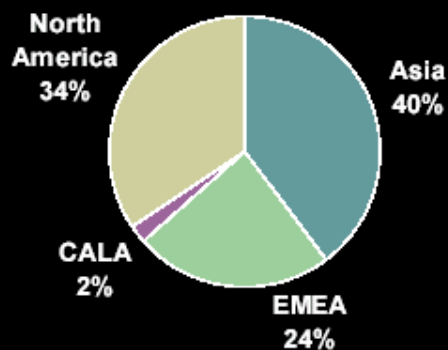
- Lower network build-out costs:
 - less fibre (single fibre shared by 16-64 customers)
 - shared transceiver at CO (less lasers)
- Passive components:
 - lower ongoing maintenance costs: no power required
 - more reliable
- Multi-service broadband access: voice, video, data
- Cons:
 - Shared medium \Rightarrow broadcast \Rightarrow security issue (encryption)
 - Shared medium \Rightarrow MAC contention resolution mechanisms
 - Splitting power loss \Rightarrow limited fan-out per fibre



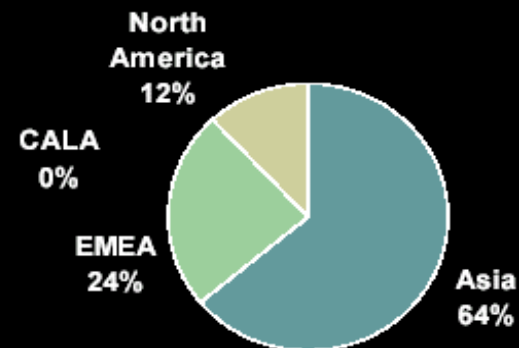
FTTH: Worldwide take-up



Broadband lines by region



FTTH lines by region





Challenge: Fibre Installation

- Direct burial
 - Trenching / plowing / boring
 - Hazards: dig-up, ground lightning, rodents, rocky soils
- Duct
 - Cables inside pre-existing conduits (concrete, steel, plastic, ...)
- Aerial
 - Pole / tower placement, self-supporting optical cable
 - Hazards: moving objects, weather, lightning, squirrels
- Special:
 - Grooves cut in pavement
 - Drainpipes / sewer pipes / natural gas pipelines
 - » FAST: Fibre Access Through Sewer Tubes



Summary

- Optical networking:
 - Motivation: ~50Tbps per fibre, low loss, low interference
 - Transmission principles, WDM
- Core:
 - First-generation: use fibre as replacement for copper
 - Second generation: optical switching based on lightpaths
 - Future challenge: Optical packet switching
 - » Needs breakthroughs in optical buffering and optical processing
- Metro:
 - Competitive success in metro demands service agility and graceful scaling
 - WDM using tunable wavelength lasers will provide the solution
- Access:
 - FTTH is inevitable, desirable, and happening today
 - Highest cost is upfront in fibre layout and equipment
 - Government policies have to be favorable to create this national asset