Optical switching
References

Keshav doesn’t cover this (except brief reference on p. 15)

Other courses: e.g. ELEC9350/9355

Overviews:

• Cisco’s *Fundamentals of DWDM Technology*


LightReading.com – Industry news
References about specific technologies

Outline

Optical components
Optical switching overview
Wavelength-routed networks
• Optical demultiplexing / filtering
• Switch construction
• Wavelength assignment problem & conversion
All-wavelength switching
Photonic packet switching
Dealing with contention
Optical fibre

Fibre consists of:

- Glass (silica) core: 2 - 125µm in diameter.
- Glass cladding:
  Thicken fibre to make it less fragile.
  \( n_{\text{cladd}} < n_{\text{core}} \Rightarrow \text{internal reflection} \)
- Plastic jacket:
  Protection

Rays ("modes") of light are confined to fibre by total internal reflection
Using a thin core restricts propagation to one mode only. Such "single mode fibre"
offers higher data rates/distance than multi-mode fibre (but is more expensive)
Evaluation of optical fibre

• Fibre doesn’t conduct electricity
  ✖ Often need separate cable to provide power to devices.
  ✔ Good for insulating, e.g. protect computer from lightning striking outdoors antenna by connecting with fibre
  ✔ Immune to electromagnetic noise
  ✔ Low attenuation for wide bandwidth …
Fibre – Attenuation in silica

0.85µm band (cheap LEDs)  1.3µm and 1.5µm bands (lasers)

Bandwidth of tens of THz (tens of Tb/s with simple modulation)
Erbium Doped Fibre Amplifiers (EDFAs)

- Amplify (30dB+) signals (including noise, no regeneration)
- Cover a broad bandwidth, e.g. 35nm

Operation: pump @ 980 or 1480nm, signal @ 1525-1560nm

Switching relevance:
- Many fabrics exhibit high loss ⇒ amplify with EDFA after switching
- EDFA forms a basic electronically-controlled on/off gate for switching
- EDFAs are the original “transparent” all-optical network element for trans-oceanic links ⇒ motivate all-optical networks & all-optical switching.
Mismatch between fibre and transceivers

40Tb/s of fibre >> 10Gb/s optoelectronics (today)
+ fibre is often scarce
⇒ use multiple optoelectronic systems tx/rx @ different λs
⇒ **Wavelength Division Multiplexing**
  (optical equivalent of FDM in the RF domain)

![Diagram of Wavelength Division Multiplexing](image)

Wavelengths = “lambdas” (λ)
(sometimes spelled lamda)

Figure from Cisco
WDM technology

Wavelengths = “lambdas” (\(\lambda\))

DWDM = Dense WDM, e.g. 0.8nm spacing

Example of state of the art (March 2002):
- 64 channels @ 40Gb/s (2.56Tb/s) over 4000km

**Tunable transmitters** (multiple or tunable laser)
- Tuning times range from \(ns\) (Distributed feedback) to ms (mechanical/acousto)

**Tunable receivers** – Burst mode can synchronize quickly, unlike continuous mode.

Figure from Cisco
Broadcast and select network using tunable tx/rx

Combiner  Fibre  Splitter

Tunable lasers  Broadcast medium  Tunable filters  Photodiodes

× poor signal power because of broad splitting
Outline
Motivation for all-optical networks

Benefits:

✓ High transmission speed
  (switching speed may not be as impressive, e.g. Gb/s throughput on each port, but reconfiguration (changing port mappings) only once per ms)

✓ Eliminate optoelectronics from network
  ✓ Low cost network

✓ Transparency: Payload rate and format can change (with OE progress) without changing network elements.
  • Network must recognize control rate and format for packet switching.
  • Particularly for trans-oceanic cables – original motivation for EDFA amplifiers

Costs:

✗ Add optical switching equipment
✗ Analog: Signals are amplified, not regenerated
✗ Error rate monitoring is hard
Summary of applications

- **OADM** = Optical Add-Drop Multiplexer
- **OXC** = Optical Cross-Connect

Figure from LightReading
Summary of technologies

MEMS = MicroElectroMechanical Systems

Figure from LightReading

Copyright © 2005 Tim Moors
How the optical domain differs

- **High-rate transmission**
- **Processing**
  - e.g. optical address matching
- **Buffering**

Re-evaluate decisions made in electronic networks

Electronic: Packet switching uses processing (routing decisions) to save bandwidth
Optical: Circuit switching is currently more cost effective

Electronic: Route along shortest path (to save transmission) and buffer when \( \exists \) contention on that path (buffering is cheap).
Optical: Deflection routing: Use longer path to avoid buffering
Outline
Wavelength routed networks

- Motivated by WDM – not all wavelengths may have same destination.
- Directing signal propagation alleviates power problems of broadcast-and-select network.
- Components are also called “wavelength selective”
Optical (de)multiplexing

Multiplexing is trivial: Combine signals by splicing fibres together

“Optical Add-Drop Multiplexer” (OADMs):

• Drop wavelengths (demux)
• Add wavelengths (mux)
• Many access ports; few wavelengths change

Figure from Cisco
Static demultiplexing ...

**Static demultiplexers:** Physical configuration assigns $\lambda$s to ports. Generally require precise physical alignment
- need to assess thermal stability
- might achieve precision by using photolithography

... using refraction:

Figure from Cisco

Copyright © 2005 Tim Moors
... using diffraction

Diffraction grating

Figure from Cisco
... using diffraction grating and waveguide

Diffraction grating with waveguide
“Arrayed Waveguide Grating” (AWG) aka “optical waveguide router”!
up to 250 ports

Input cavity: diffracts light into waveguides
Waveguides have differing lengths ⇒ delays
Delayed waveforms interfere in output cavity
Position output ports @ points of max. interference
... using interference

Interference filters transmit light of one wavelength, and reflect others.

✓ Good thermal stability (variation of vertical/horizontal dimensions handled by filters having vertical range) and isolation between channels, at moderate cost.

✗ High loss, *e.g.* (yellow) wavelength that is reflected many times.
Controllable refractive indices

Control the refractive index of the medium by applying:

- **Electric field** (electro-optic)
  - *e.g.* Lithium Niobate (LiNbO$_3$) or liquid crystal
    - ✓ ns switching times
    - ✗ substantial loss

- **Sound** (acousto-optic), 10us switching times

- **Heat** (thermo-optic), ms switching times
  - Silica has lower optical loss than polymer, but requires more heat and conducts heat more (⇒ switch requires more space)

Form basic switching element using interferometers...
Electro/Acousto/Thermo-optic switches

Mach-Zehnder interferometer:
**Controllable** delay element determines relative phase of combined wavelengths.

$180^\circ$ phase difference $\Rightarrow$ filtered out

**Drawbacks:**

- Few ports (2×2)
- Crosstalk between outputs
Building a switch from filters/gates

Power budget:
- Each input is split between $n$ outputs (like B&S) ($n=2$ in this example)
- Combiner has only 1 active input ⇒ readily amplify using EDFA
Wavelength assignment problem

Can concurrently use the same wavelength in spatially separate areas of the network

Q: What λ should be used for each lightpath?
A: Complex optimisation problem.

Wavelength assignment can be simplified with expensive wavelength converters.
Wavelength converters

**Primitive:** Perform opto-electronic-opto conversion, and use different $\lambda$ for output laser

**Better:** Electrical signal directly modulates laser

**Best:** Optical conversion using coherence effects
- From non-linear response of medium in the presence of multiple waves.
- *e.g.* Four-Wave-Mixing, Difference Frequency Generation
Outline
MicroElectroMechanical Systems (MEMS)

It’s all done with mirrors…

Mechanical ⇒ switching time ∝ \(4\sqrt{I}\) ⇒ ms switching times
(too slow for burst or packet switching)
Loss of approx 1.25\(dB\) / mirror

Photos from Lucent
MEMS

Implemented on silicon using photolithography technology
✓ precise positioning of mirrors
✓ can integrate mechanical system with electronics
✓ density should advance with progress in photolithography technology (driven by VLSI)

Current densities of 256-1024 mirrors

“We have built MEM mirrors on an 8-in. wafer with a million MEM mirrors on it, each individually moveable”
Jeffrey Jaffe, president of research and advanced technologies at Bell Labs in J. Ribeiro: 'Bell Labs grapples with VoIP, open-source', Jan. 05 2005
MEMS switches

Figures from Chu02
Other switching technologies

- Bubble (see Agilent Video)
- Liquid crystal attenuators/switches
- Liquid crystal gratings
- Holograms

- Wavelength-selective technologies
  - electro/thermo/acousto-optics
Outline
Electro-optic packet switching

**Payload** travels over a “lightpath” from source to destination; no optoelectronic conversion within network switching elements. **Control** information *may* incur optoelectronic conversion, may even flow on auxiliary electronic control network.

Figure from Blumenthal94

* Payload
  * Fiber coupler
  * Wavelength demultiplexer
  * Semiconductor optical amplifier

* Control
  * LiNbO3 Mach–Zehnder gate
  * LiNbO3 directional coupler
  * Semiconductor laser amplifier gate
Outline
Ways to deal with contention

• Time domain: optical buffering …
• Space domain: deflection routing …

• Frequency domain: Wavelength conversion
  • Creates more options, but may still have contention for specific frequency on output port.
Optical buffering

Long loops of fibre form delay lines

How long?

*Electricity travels a foot in a nanosecond.*”

– G. Hopper

In vacuum $v_0=3\times10^8$

In silica: slower than in a vacuum: $n_{SO_2}=1.5$, $v_{SO_2}=2\times10^8$ m/s

e.g. 1500B Ethernet frame (12kb) @ 1Gb/s (1ns/b) = 12us delay = 2.4km

Information continuously physically moves (c.f. electronic buffers)

Memory provides *sequential*, not random, access

But that’s fine for queueing/buffering

Photo from www.go4fiber.com/bargain/image/products/50ss.jpg
Optical buffering (continued)

Problems:
- Attenuation in delay lines
- Complexity
- Some say: unnecessary – modeled on electronic networks
Optical buffer implementation

Fibre delay line
- Capacity ∝ length ∝ loss

Programmable fibre delay line
- Enables control of holding time.
- Loss from splitting signal
  (Time-slot-interchange switch)

Active recirculating delay line
- Enables control of holding time.
- Amp noise limits recirculations

Figure from Blumenthal94
Deflection routing

Route some inputs (●) on shortest path
Deflect others to other outgoing ports (longer paths)

Links between switches effectively become passive delay line buffers for deflected packets

Often prioritise packets:
- Better service for originally high priority packets,
- Escalate priority after deflect s.t. not deflected endlessly.

Assume that the ports are bidirectional but can only support one flow in either direction
Deflection routing: Evaluation

✖ Reduces network throughput because packets take longer paths

  Manhattan street network (regular mesh) & deflection: 55-70% of throughput with infinite buffering.

✖ May deflect back onto short path ⇒ mis-sequence packets

✔ Deflecting towards source further increases path length, but creates backpressure & may provide congestion control
The end

(References at beginning of lecture.)