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
• fibres
• amplifiers
• transmitters, receivers

Optical switching overview

Wavelength-routed networks
• Optical demultiplexing / filtering
• Switch construction
• Wavelength assignment problem & conversion

All-wavelength switching (MEMS)

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
    - ✓ Comms cables won’t spread high voltages from failing machines in factories
  - ✓ 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)

Approximate wavelengths of visible light:
- 167 THz
- 121 THz

Bandwidth of tens of THz (tens of Tb/s with simple modulation)

Monochrome figure from Cisco http://www.cisco.com/univercd/illus/4/87/48087.gif
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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
$\Rightarrow$ use multiple optoelectronic systems tx/rx @ different $\lambda$s
$\Rightarrow$ **Wavelength Division Multiplexing**
(optical equivalent of FDM in the RF domain)

Wavelengths = “lambdas” ($\lambda$)
(sometimes spelled lamda)
WDM technology

DWDM = Dense WDM, e.g. 0.8nm spacing ⇒ about 64λs (Coarse DWM: 12λs, Ultra Dense WDM >100λs)

Example of state of the art [Lucent press release, 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

Tunable lasers  Broadcast medium  Tunable filters  Photodiodes

✗ poor signal power because of broad splitting
Outline
Optoelectronic networks

- Simplest use of optics to networking merely involves replacing wired links with fibre. Where link joins switch, signal is translated between optical and electronic forms.

- Expensive optoelectronic parts are replicated
- Electronics (particularly energy flow: power in, heat out) limits switch throughput
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
Where are optical networks used?

**LANs:** Rarely is optical switching needed (exception: CERN, NSA?!)  

**Access networks:** Passive Optical Networks (PONs) (see next slide)  

**Metropolitan Area Networks**  
- Traditionally SDH – optoelectronic rings (s.t. can adapt around single failure)  
- Uncertainty about provisioning rings (e.g. how much BW needed?) can be accommodated by subdividing rings adding lambdas to serve new rings.

**Long haul** (e.g. inter-city): Optical transmission preferable because of high bandwidth for low attenuation.

**Core networks** (e.g. switch in Sydney switching traffic between Melbourne, Canberra, Brisbane):  
- High transmission speeds  
- But reconfiguration needn’t be frequent.
Passive Optical Networks (PONs)

Why?: Higher rates to subscribers than wire

Options:

- Individual fibres from Exchange to $N$ subscribers
  - $N$ fibres to Exchange (Central Office – CO)
  - $2N$ transceivers
- Fibre to the curb, switch to fibres to subscribers
  - 1 fibre to Exchange
  - $2N$+2 transceivers
  - Either optoelectronic switch (may fail, expensive optoelectronic tx/rx) or photonic switch (advanced technology)
- ✓ Fibre $\rightarrow$ curb + passive optical splitter to subs
  - 1 fibre to Exchange
  - $N$+1 transceivers
  - Power loss from splitting limits fan-out; need to deal with shared medium (security, MAC)

Terms: Fibre To The $x$ (FTTx): Home, Building, Premises, Curb, ...

Image from slides by Vijay Sivaraman
For more, see www.ponforum.org
Forms of optical switches

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

Figure from LightReading

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Optical switching technologies

MEMS = MicroElectroMechanical Systems

Figure from LightReading
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 transmission capacity
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
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
... 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° phase difference ⇒ 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 \( \lambda \) 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 $\propto 4 \sqrt{I} \Rightarrow \text{ms switching times}$
(too slow for burst or packet switching)
Loss of approx 1.25dB / 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
MEMS switches

2D

3D

Figures from Chu02

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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.

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**Figure from Blumenthal94**

† Distinct from optoelectronic
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 $v_0 = 3 \times 10^8$

In silica: slower than in a vacuum: $n_{SO_2} = 1.5$,

$v_{SO_2} = 2 \times 10^8 m/s$

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: 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
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
Summary of optical switching

- Switching at the “physical” layer
- Fibre enables massive transmission capacity, but optical processing and buffering are difficult.
- WDM allows many flows to share one fibre
- Various types of demultiplexers based on refraction, diffraction, interference
- MicroElectroMechanical Systems: Slow reconfiguration, but no optoelectronic conversion bottleneck
- Packet switching is possible, but is it out of context?