Components of Optical Networks

Based on:
Optical Components

- Couplers
- Isolators/Circulators
- Multiplexers/Filters
- Optical Amplifiers
- Transmitters (lasers, LEDs)
- Detectors (receivers)
- Switches
- Wavelength Converters
Directional coupler is used to combine and split optical signals.

- Coupling length
  
- $C = \alpha A + (1-\alpha)B$
  
- $D = \alpha B + (1-\alpha)A$

$\alpha$ is called the coupling ratio.
Couplers

- Can be:
  - Wavelength independent ($\alpha$ is independent of the wavelengths)
  - Wavelength selective ($\alpha$ is wavelength dependent)
Wavelength Independent Couplers

- 3dB coupler ($\alpha=0.5$) can be used to build $n \times n$ couplers (e.g., $n \times n$ star coupler)

- Can also be used to tap off a small portion of light ($\alpha=0.9−0.95$), e.g., for monitoring purposes.
4x4 Star Coupler

Power is split equally among the outputs...
Wavelength Dependent Coupler

- Used to combine signals at 1310nm and 1550nm (two different bands) together without loss. It may only have one output.
- Can be used to separate optical signals of different bands.
- Also used for mixing the pumping signal for EDFA.
Isolators

- Allows “light-flow” in one direction but blocks it in the other (nonreciprocal device).
- Used after EDFA and lasers to improve performance.
- Insertion loss: loss in forward direction (~1dB)
- Isolation: loss in reverse direction (~40-50dB)
Circulators

- Isolator with multiple ports (e.g., 3, 4).
- Helpful in constructing optical add/drop elements.
Filters

- Essential to selecting (dropping) wavelengths from the fibre (demultiplexing).

- Filters can be tuneable
- Essential to combine wavelengths onto one fibre.
Static Wavelength Crossconnects

- The crossconnect pattern is established at manufacturing and cannot be changed dynamically. Example:
Optical Amplifiers

- Since optical signals are attenuated by fibre and insertion losses of other components, signals may become too weak to be detected.
- It is possible to do 1R regeneration optically (with all its benefits and drawbacks).
- Furthermore optical amplifiers have large gain bandwidths (one regenerator is enough for the entire band).
- But, they introduce additional noise (noise that accumulates). (Gain should be also flat over the entire band and insensitive to the input signal).
Types of optical amplifiers:

- Erbium-doped fibre amplifiers (silica fibre doped with Erbium ions. Laser pumps are needed)
- Raman amplifiers (using the Raman scattering non-linear effect. Needs laser pump source but it can be used at all bands).
- Semiconductor optical amplifiers (earlier technology, using p-n junctions of semiconductors to amplify light. No pump source is needed).
Transmitters - LEDs

- Light Emitting Diodes are inexpensive but have a wide spectrum and work only in the \(~800\text{nm}\) range.
- LEDs cannot be directly modulated at high data rates.
Transmitters - Lasers

- Lasers are used as transmitters and pump sources for EDFA and Raman amplification (higher power is required).
- Semiconductor lasers are the most commonly used, essentially they are semiconductor optical amplifiers with positive feedback (very effective and efficient).
- Erbium lasers are EDFAs positively fed back but need pumping source (semiconductor laser)
Transmitters - Lasers

- Need to produce high output (0-10dBm)
- Have to have narrow spectral bandwidth (for WDM)
- Have to be stable in the transmitting wavelength (lifetime drifting needs to be small)
- Need to be easily modulated.
Transmitters – Tunable Lasers

- Highly desirable components:
  - For a 100-channel WDM system 100 types of conventional lasers have to be stocked (extensive inventory)
  - Key elements of reconfigurable optical networks (less lasers than wavelengths; switching times: \( \sim \)ms)
  - Also essential for efficient optical packet switched networks (switching times: \( \sim \)ns)
- Still in research labs but soon to be available.
Detectors - Receivers

- For O-E conversion.

- Tunable receivers are available.
Wavelength Converters

- Converts data on optical signal for incoming wavelength to another outgoing wavelength.

- Can be used:
  - between legacy and WDM systems (transponder).
  - Within the network to improve on utilization.
  - Between boundaries of networks belonging to different carriers, who do not coordinate assignment of wavelengths.
Wavelength Converters

- Can be classified:
  - Fixed-input, fixed-output
  - Variable-input, fixed-output
  - Fixed-input, variable-output
  - Variable-input, variable-output

- Can be:
  - Optoelectronic (2R/3R OEO conversion, usually VIFO)
  - Optical grating (VIFO or VIVO)
  - Interferometric (Optical 2R)
  - Wave mixing (truly transparent, $\lambda$-s have to be close)
Switches
Switches

- **Applications:**
  - Provisioning
  - Protection switching
  - Packet switching
  - External modulation
Provisioning Switching

- Provisioning of lightpaths.
- Switches are used inside wavelength crossconnects to reconfigure them to support new lightpaths.
- These switches replace manual patch-panels, thus requiring additional control software but enable easy and fast reconfiguration.
- Switching times of a couple of ms are acceptable.
- Challenge is to realize large switches.
Protection Switching

- Switch the entire traffic of a primary fibre to another fibre in case the primary fibre fails.
- Switching time is in order of couple of ms. (The entire protection operation should be done in a couple 10ms).
- Switch sizes may vary from 2 ports up to several thousand ports (when used in wavelength crossconnects)
Packet Switching

- High-speed optical packet switching switches, switching on a packet-by-packet basis.
- Switching times should be as small as a couple of ns. (at 10Gbps 53bytes correspond to 42ns).
- This is the switching technology of the future...
External Modulator Switches

- To turn off and on the laser beam after the laser transmitter (to reduce laser’s spectral bandwidth, thus to reduce chromatic dispersion).

- Switching time is around 10ps (rise and fall time) for a 10Gbps signal (1bit time = 100ps, switching time has to be at least an order of magnitude less).
## Switches - comparison

<table>
<thead>
<tr>
<th>Application</th>
<th>Switching time</th>
<th>Number of ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provisioning</td>
<td>1-10ms</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Protection</td>
<td>1-10ms</td>
<td>2-1000</td>
</tr>
<tr>
<td>Packet switching</td>
<td>1ns</td>
<td>&gt;100</td>
</tr>
<tr>
<td>External modulation</td>
<td>10ps</td>
<td>1</td>
</tr>
</tbody>
</table>
Parameters of Switches

- Extinction ratio: output power on state/output power off state (40-50dB for mechanical switches, 10-25dB for high-speed modulators).
- Insertion loss: loss should be uniform over all paths (determined by the architecture mainly not the technology).
- Crosstalk: calculated by the output power of all input ports not switched to that output port.
Parameters of Switches

- Polarization dependence should be negligible.
- Latching: switching remains intact even if power supply is turned off.
- Monitoring: switching state should be monitorable.
- Reliability: long-term history is desired. Short term reliability is tested by switching through states a couple million times. In provisioning although it is important that the switch remains capable of switching even after spending years at a given state.
Large Optical Switches

- Number of ports: $n \times 100 - n \times 1000$ (couple of fibres carrying several tens to hundreds of wavelengths).

- Properties of large optical switches:
  - Number of switching elements required.
  - Loss uniformity.
  - Number of crossovers.
  - Blocking characteristics.
Large switches are built up by multiple small switch elements (e.g. 2*2 or 1*n elements).

Cost and complexity depend on the number of switching elements.
Loss Uniformity

- The problem of loss uniformity (as mentioned before) is exacerbated for large switches.
- Can be measured, e.g., by counting the minimum and maximum number of switch elements in the optical path for different inputs/outputs.
Number of Crossovers

- Some switches are manufactured on a single substrate on a single(!) layer. If paths of waveguides cross it will introduce two undesirable effects:
  - Power Loss and
  - Crosstalk.
- Thus crossovers have to be minimized (eliminated).
- It is not an issue with free space propagation, i.e., with MEMS.
Switch Blocking Characteristics

- Switches can be of two types:
  - Non-blocking: an unused input can be connected to any unused output, thus every (possible) interconnection pattern can be realized.
  - Blocking: some interconnection patterns cannot be realized (e.g., there is no way of connecting input fibre one to output fibre 6 on wavelength 3).
Non-blocking Switches

- Can be further characterized into:
  - Wide-sense non-blocking: every input can be connected to every output without rerouting any ongoing connections but employing some kind of sophistication for establishing connections to begin with.
  - Strict-sense non-blocking: any input can be connected to any output without rerouting and without added sophistication.
  - Rearrangeably non-blocking: ongoing connections may be interrupted and rerouted which may not be acceptable but uses fewer switching elements and more sophisticated control is needed).
## Basic Switch Architectures

<table>
<thead>
<tr>
<th>Non-block. type</th>
<th>Number Switches</th>
<th>Max. Loss</th>
<th>Min. Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossbar 2x2</td>
<td>$n^2$</td>
<td>2$n-1$</td>
<td>1</td>
</tr>
<tr>
<td>Clos 2x2</td>
<td>$4\sqrt{2n^{1.5}}$</td>
<td>$5\sqrt{2n-5}$</td>
<td>3</td>
</tr>
<tr>
<td>Spanke 1xn</td>
<td>2$n$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Beneš 2x2</td>
<td>$n(2\log_2 n-1)/2$</td>
<td>$2\log_2 n-1$</td>
<td>$2\log_2 n-1$</td>
</tr>
<tr>
<td>Spanke-Beneš 2x2</td>
<td>$n(n-1)/2$</td>
<td>$n$</td>
<td>$n/2$</td>
</tr>
</tbody>
</table>
Crossbar Switch

- No crossovers but not loss uniform
- Used in Clos switches
Clos Switch

- Used in practice for large switches.
- 3 parameters: m, k, and p.
- 1\textsuperscript{st} and 3\textsuperscript{rd} stage have k \((m\times k)\) switches, 2\textsuperscript{nd} stage has p \((k\times k)\) switches.
- If p\(\geq\)2m-1 then switch is strictly non-b, thus usually p=2m-1.
- Individual switches are usually designed by crossbar switches.
- Loss uniformity is better than with crossbar.
- Number of switching elements is less than that of a crossbar.
A three stage 1024 port switch:
Spanke Switch

- Becoming more and more popular.
- \( n \times n \) switch is established by \( n \) (1\( \times \)n) switches and \( n \) (n\( \times \)1) switches.
- These elements can be built (e.g., using MEMS technology).
- Only 2n switches are needed (linear!) and all paths cross through only 2 elements.
- Loss uniformity can be achieved and insertion loss is small.
Spanke Switch

Diagram of a Spanke Switch with inputs and outputs labeled.
Beneš

- Rearrangeably non-blocking and very efficient in the number of 2*2 switches (waveguide crossovers are needed)
Spanke-Beneš

- Rearrangeably non-blocking, efficient in the number of 2*2 switches (no waveguide crossovers – n-stage planar architecture). Not loss uniform.
Optical Switching Technologies

- Bulk Mechanical Switches
- Micro-Electro-Mechanical System (MEMS)
- Bubble-Based Waveguide Switch
- Liquid Crystal Switches
- Electro-Optic Switches
- Thermo-Optic Switches
- Semiconductor Optical Amplifier Switches
- Electro-Holographic Switches
Mechanical Switches

- Examples include:
  - Moving mirrors in and out of the optical path
  - Bending or stretching fibre in a coupler changing the $\alpha$ value of coupling.

- Low insertion loss, low crosstalk and relatively inexpensive and well suited for crossbars. Switching times of few ms and little port counts (small crossconnects, protection, provisioning). Long term reliability? Can be cascaded but there are better ways...
MEMS Switches

- Small mechanical devices on silicon substrates. In optical networking MEMS refers to small mirrors of a few hundred micrometers. Several of these mirrors can be put on one substrate with common semiconductor manufacturing techniques.

- Mirrors can be digital (only two positions – for crossbar architectures) or analogue (several positions – for 1*n switches) controlled.
Pop-up (Digital) MEMS
Pop-up (Digital) MEMS

- Practical size: 32x32
Analogue Beam Steering Mirror

- Also called a Gimbel mirror or 3D mirror.
- Control is difficult sophisticated servo control is needed (high voltages with mV scales).
- Suited to realize Spanke architectures with hundreds to thousands of ports.
- Challenges: control, reliability, stability to temperature, humidity and vibration
Analogue Beam Steering Mirror
Analogue Beam Steering Mirror
Analogue Beam Steering Mirror

A.S. Morris, “In Search of Transparent Networks,”
IEEE Spectrum, October 2001
Bubble-Based Waveguide Switch

- Technology is similar to what is used in inkjet printers!
- Trenches are filled with index matching fluid (that can be vaporized or moved).
- Small crossbar switches (32x32) can be built efficiently with switching times of >10ms.
Bubble-Based Waveguide Switch

Non-switched signal

Switched signal

Liquid Crystal Switches

- Make use of polarization effects. LC cells can be used to rotate polarization (or not). Different polarizations of the same signal then can be used to cancel each other out.

- Can be produced in volume with low cost (32x32 size)
Liquid Crystal Switches

(a) Polarization beam splitter

Fiber in

Polarization beam combiner

Rotation off

Liquid crystal cell

Rotation off

Liquid crystal cell

Fiber out 1

Fiber out 2

(b) Polarization beam splitter

Fiber in

Polarization beam combiner

Rotation on

Liquid crystal cell

Rotation on

Liquid crystal cell

Fiber out 1

Fiber out 2
Electro-Optic Switches

- Based on directional couplers with varying coupling ratio ($\alpha$) using a voltage.
- Made with lithium niobate (usually)
- Capable of rapid changes (<1ns).
- High loss, high complexity and high polarization dependent loss.
Electroholographic Switches

- A switch matrix is created by ferroelectric crystals (e.g., lithium niobate) (basically electro-optic switches).
- Rows correspond to fibers, while columns correspond to wavelengths (!)
- They claim it is going to be fast enough for photonic packet switching.
- Do not scale well, PDL, sophisticated focusing is needed, etc.
Electroholographic Switches

Large Electronic Switches

- Today most practical crossconnects still use OEO switching elements.
- Clos architecture is preferred (strict non-blocking).
- Cost is mainly determined by the number of OEO conversions not the switching fabric.
- High data rate streams may be spliced into lower rate parallel streams. But today 64*64 crossbar ICs operating at 2.5Gbps are available (dissipates 25W !!).
Large Electronic Switches

- A 1024x1024 switch needs about 100 such ICs => power dissipation is around 25kW (cooling is needed) (with 3D MEMS it would be ~3kW and would be significantly more compact).

- Connections between boards and racks at these high speeds becomes a problem => not scalable. (Can be done optically with less dissipation and interference while at a longer range.)
Categorization of Optical Switching Techniques
Reconfigurable Switches

- Switches may be called routers, cross-connects or ADMs (add-drop multiplexers).
- Optical switches keep the data stream in the optical domain, although they still may be controlled by electronics.
- Currently these equipment are common in a backbone (core) network.
Switching Techniques in Networks

- Circuit Switching
- Packet Switching
- Burst Switching
Circuit Switching

3 steps:
1. Circuit set-up
2. Data transfer
3. Circuit tear down

Good for constant bit rate.

Circuit set up time has to be significantly less than data transfer time.

No processing needed at the intermediate nodes, once a circuit is established, thus does not heavily rely on fast switches nor does it need to buffer data (no delay jitter).

Routing is part of circuit set-up.
Fast Circuit Switching

- First step does the routing but does not set-up a circuit.
- Circuit set-up (or tear down) is done at the transmission of the bursts by employing a short control message.
- Circuit set-up can also be a “one-way” process, where no acknowledgement from the network is needed prior sending the burst.
Packet Switching

- Data is sent w/o setting up a circuit.
- Usually employs distributed routing control.
- Store-and-forward mechanism needs buffering and dynamically (re)configures the switches.
- Good for bursty traffic => allows statistical sharing. Requires buffers and quick switching.
- Message switching: large sized packets are assembled together at the end-nodes. Requires larger buffers and message delay will be high(er).
Datagram Based Packet Switching

- Packet header (control information) and payload are sent over the same channel. Headers are “glued” to the payloads. (E.g., IP)
Virtual Circuit based Packet Switching

- Two (3) phases:
  1. Setting up a VC (or routing)
  2. Sending packets over the VC (switching)
  3. (tearing down the VC)

- Setting up a VC does not require dedicated bandwidth – just an entry in the routing tables of intermediate nodes along the selected path. These entries map the VC identifier (sent together with each packet) to the route it has to go on to. This table lookup is easier than making a routing decision. (E.g., ATM has this capability)
Multiprotocol Label Switching (MPLS)

- [Callon, 1997] is currently standardized by IETF.
- Similar to VC packet switching.
- Label-switched paths (LSPs) are established (instead of VCs). Routing decision is made only once at the establishment of the LSP.
- MPLS can handle different traffic types (packets belonging to the same source and destination pairs can have different LSPs depending on their importance – and routing can consider these metrics).
Multiprotocol Label Switching (MPLS)

- The establishment of LSPs can be:
  - control driven (performed by the network according to its topology)
  - Or data-driven (e.g., the first couple of packets are routed by IP at each node, but when the destination receives a given amount of packets it triggers the establishment of an LSP (e.g., for one TCP stream).
Burst Switching

- Packets to the same destination are assembled into bursts, that are sent over the network with one connection set-up (routing).

- One-way reservation: no acknowledgment from the network is needed, thus pre-transmission delay of the burst is reduced.
Burst Switching

Three variations for bandwidth releasing:

Tell-and-go (TAG): as soon as burst is transmitted the sender sends an explicit release message to tear down the circuit (like circuit switching).

Reserve-a-fixed-duration (RFD): each set-up request specifies the duration for the circuit.

In-band-terminator (IBT): a burst contains a header and tail (terminator) to indicate the end of the burst. (like packet-switching)
Burst Switching

- Let $T$ be the time between the issuance of the set-up request and the transmission begin of data.
- $T$ can be shorter with on-way reservation and TAF or RFD than the time required to set up all immediate switches.
- Although, if $T$ is too small, buffering is needed. Virtual cut-trough is the technique where if the next hop is established the burst can be sent right away (even when it is still being received).
Switching in Optical Networks
Wavelength Routing

- Basically circuit switching in an optical network.
- All-optical path (no OEO conversions are needed) and is established before data can be sent.
- They provide high speed high-bandwidth "pipes".
- Lightpaths may be dynamically established.
- Not efficient for bursty Internet traffic.
Optical Packet/Label Switching

- Data remains in the optical domain while headers may be processed electronically (or optically – not mature yet).

- Since limited optical processing is available, VC based packet switching is more popular than datagram (NO OPTICAL RAM).
Optical Burst Switching (OBS)

- Provides temporary solution between label and wavelength switching.
- It is difficult to optically recognize ends of bursts, thus OBS is likely to be TAG and RFD.
RFD based OBS - JET

- Just Enough Time (JET) [qiao, 1997]
- Offset time between message and control-message is greater than equal to the sum of set-up times for the switches involved.
- Burst is buffered at the source => no buffers or delay lines (FDL) are needed.
- If the requested bandwidth is not available the burst is blocked (and will be dropped if no buffering is available).
RFD based OBS - JET

\[ T = \sum_{h=1}^{H} \delta(h) \]
TAG based OBS vs. JET

- Explicit tear down signal is used.
- Since loss of tear down signal would result in wasting the bandwidth, each source is required to periodically refresh ongoing reservations (timeouts).
- JET is more bandwidth efficient.
Prioritized JET, where two classes of bursts are distinguished:
- Best-effort
- Real-time

For real-time bursts, T is expanded by an offset, enabling the network to make reservations way ahead of time.

The selection of the offset is a trade off between independence of the two types of burst handlings and induced delay for real time traffic.