Introduction to Multiwavelength Optical Networks

Switching Technology S38.3165
http://www.netlab.hut.fi/opetus/s383165

Source: Stern-Bala (1999), Multiwavelength Optical Networks

Contents

- The Big Picture
- Network Resources
- Network Connections
Optical network

• Why?
  – technology push, but no significant demand pull yet
  – evolving bandwidth hungry applications
  – optical transport already in the trunk network
• Why not yet?
  – optical last mile (a.k.a. the first mile) solutions still relatively primitive
  – still too expensive
  – administrative, political, etc. reasons

=> “The information superhighway is still a dirt road; more accurately, it is a set of isolated multilane highways with cow paths for entrance.”
• However, development getting pace

Optical network (cont.)

• An optical network is defined to be a telecommunications network
  – with transmission links that are optical fibers, and
  – with an architecture designed to exploit the unique features of fibers
• The term optical network (as used here)
  – does not necessarily imply a purely optical network,
  – but it does imply something more than a set of fibers terminated by electronic devices
• The “glue” that holds the purely optical network together consists of
  – optical network nodes (ONN) connecting the fibers within the network
  – network access stations (NAS) interfacing user terminals and other non-optical end-systems to the optical network
Optical network (cont.)

ONN (Optical Network Node)
- provides switching and routing functions to control optical signal paths, configuring them to create required connections

NAS (Network Access Station)
- provides termination point for optical paths within the optical network layer

Basic types of optical networks
- transparent (purely optical) networks
  - Static network = broadcast-and-select network
  - Wavelength Routed Network (WRN)
  - Linear Lightwave Network (LLN) = waveband routed network
- hybrid optical network = layered optical network
  - Logically Routed Network (LRN)

Physical picture of the network
A wish list of optical networks

- **Connectivity**
  - support of a very large number of stations and end systems
  - support of a very large number of concurrent connections including multiple connections per station
  - efficient support of multi-cast connections

- **Performance**
  - high aggregate network throughput (hundreds of Tbps)
  - high user bit rates (few Gbps)
  - small end-to-end delay
  - low error rate (digital) / high SNR (analog)
  - low processing load in nodes and stations
  - adaptability to changing and unbalanced loads
  - efficient and rapid means of fault identification and recovery

A wish list of optical networks (cont.)

- **Structural features**
  - scalability
  - modularity
  - survivability (fault tolerance)

- **Technology/cost issues**
  - access stations: small number of optical transceivers per station and limited complexity of optical transceivers
  - network: limited complexity of the optical network nodes, limited number and length of cables and fibers, and efficient use (and reuse) of optical spectrum
Optics vs. electronics

Optical domain
• photonic technology is well suited to certain simple (linear) signal-routing and switching functions
• static photonic devices offer
  • optical power combining, splitting and filtering
  • wavelength multiplexing, demultiplexing and routing
• channelization needed to make efficient use of the enormous bandwidth of the fiber
  • by wavelength division multiplexing (WDM)
  • many signals operating on different wavelengths share each fiber

=> optics is fast but dumb
=> connectivity bottleneck

Optics vs. electronics (cont.)

Electrical domain
• electronics is needed to perform more complex (nonlinear) functions
  • signal detection, regeneration and buffering
  • logic functions (e.g. reading and writing packet headers)
• however, these complex functions limit the throughput
• electronics also gives a possibility to include in-band control information (e.g. in packet headers)
  • enabling a high degree of virtual connectivity
  • easier to control

=> electronics is slow but smart
=> electronic bottleneck
Optics and electronics

Hybrid approach:
- a multiwavelength purely optical network as a physical foundation
- one or more logical networks (LN) superimposed on the physical layer, each
  - designed to serve some subset of user requirements and
  - implemented as an electronic overlay
- an electronic switching equipment in the logical layer acts as a middleman
  - taking the high-bandwidth transparent channels provided by the physical layer and
  organizing them into an acceptable and cost-effective form

Why hybrid approach?
- purely optical wavelength selective switches offer huge aggregate throughput of few connections
- electronic packet switches offer large number of relatively low bit rate virtual connections
- hybrid approach exploits the unique capabilities of optical and electronic switching while circumventing their limitations

Example LAN interconnection
- Consider a future WAN serving as a backbone that interconnects a large number of high-speed LANs (say 10,000), accessing the WAN through LAN gateways (with aggregate traffic of tens of Tbps)
- Purely optical approach
  - each NAS connects its LAN to the other LANs through individual optical connections ⇒ 9 999 connections per NAS
  - this is far too much for current optical technology
- Purely electronic approach
  - electronics easily supports required connectivity via virtual connections
  - however, the electronic processing bottleneck in the core network does not allow such traffic
- Hybrid approach: both objectives achieved, since
  - LN composed of ATM switches provides the necessary connectivity
  - optical backbone at the physical layer supports the required throughput
A large number of concurrent connections can be supported on each network link through successive levels of **multiplexing**

- **Space division multiplexing** in the fiber layer:
  - a cable consists of several (sometimes more than 100) fibers, which are used as bi-directional pairs

- **Wavelength division multiplexing** (WDM) in the optical layer:
  - a fiber carries connections on many distinct wavelengths (λ-channels)
  - assigned wavelengths must be spaced sufficiently apart to keep neighboring signal spectra from overlapping (to avoid interference)

- **Time division multiplexing** (TDM) in the transmission channel sublayer:
  - a λ-channel is divided (in time) into frames and time-slots
  - each time-slot in a frame corresponds to a transmission channel, which is capable of carrying a logical connection
  - location of a time-slot in a frame identifies a transmission channel
Fiber resources

Optical spectrum

- Since wavelength $\lambda$ and frequency $f$ are related by $f = \frac{c}{\lambda}$, where $c$ is the velocity of light in the medium, we have the relation

$$\Delta f \approx -\frac{c \Delta \lambda}{\lambda^2}$$

- Thus, 10 GHz $\approx 0.08$ nm and 100 GHz $\approx 0.8$ nm in the range of 1550 nm, where most modern lightwave networks operate.

- The 10-GHz channel spacing is sufficient to accommodate $\lambda$-channels carrying aggregate digital bit rates on the order of 1 Gbps
  - modulation efficiency of 0.1 bps/Hz typical for optical systems

- The 10-GHz channel spacing is suitable for optical receivers, but much too dense to permit independent wavelength routing at the network nodes
  - for this, 100-GHz channel spacing is needed.

- In a waveband routing network, several $\lambda$-channels (with 10-GHz channel spacing) comprise an independently routed waveband (with 100-GHz spacing between wavebands).
Wavelength partitioning of the optical spectrum

\( \lambda \)-channel spacing for separability at receivers

Usable spectrum

\[ \lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_m \]

10 GHz/0.08 nm

\( f/\lambda \) [GHz/nm]

\( \lambda \)-channel spacing for separability at network nodes

\[ \lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_m \]

100 GHz/0.8 nm

\( f/\lambda \)

Wavelength and waveband partitioning of the optical spectrum

\[ \lambda_{1,1} \quad \lambda_{2,1} \quad \cdots \quad \lambda_{10,1} \]

10 GHz/0.08 nm

100 GHz/0.8 nm

\( f/\lambda \)

\[ W_1 \quad W_2 \quad \cdots \quad W_m \]

200 GHz/1.6 nm

100 GHz

100 GHz
Capacity of wavelength and waveband routed networks

- Connections in optical networks usually require wavelength continuity, i.e., signal generated at a given wavelength must remain on that wavelength from source to destination.
- Due to the current state of technology, imperfections in signal resolution at network nodes result in signal attenuation, distortion and cross-talk, which accumulate along the path.
  - \( \Rightarrow \) channel spacing cannot be as dense in the network nodes as in the end-receivers.
  - \( \Rightarrow \) loss of transport capacity.
- Capacity losses can be avoided by switching wavebands (composed of a number of wave lengths) instead of individual wavelengths.
  - \( \Rightarrow \) wavelength routed solutions have lower throughput than waveband routed solutions.

Network based on spectrum partitioning

- Single waveband
- Wavelength-routed
- Waveband-routed
Contents

- The Big Picture
- **Network Resources**
  - Network Links: Spectrum Partitioning
  - **Layers and Sublayers**
  - Optical Network Nodes
  - Network Access Stations
  - Electrical domain resources
- Network Connections

Layered view of optical network (1)
Layers and sublayers

- Main consideration in breaking down optical layer into sublayers is to account for
  - multiplexing
  - multiple access (at several layers)
  - switching
- **Using multiplexing**
  - several logical connections may be combined on a $\lambda$-channel originating from a station
- **Using multiple access**
  - $\lambda$-channels originating from several stations may carry multiple logical connections to the same station
- **Through switching**
  - many distinct optical paths may be created on different fibers in the network, using (and reusing) $\lambda$-channels on the same wavelength
Typical connection

ES = End System
LSN = Logical Switching Node
NAS = Network Access Station
ONN = Optical Network Node
OA = Optical Amplifier

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Optical network nodes (1)

- **Optical Network Node (ONN)** operates in the optical path sublayer connecting N input fibers to N outgoing fibers
- ONNs are in the optical domain

- **Basic building blocks:**
  - wavelength multiplexer (WMUX)
  - wavelength demultiplexer (WDMUX)
  - directional coupler (2x2 switch)
    - static
    - dynamic
  - wavelength converter (WC)

Optical network nodes (2)

- **Static nodes**
  - without wavelength selectivity
    - NxN broadcast star (= star coupler)
    - Nx1 combiner
    - 1xN divider
  - with wavelength selectivity
    - NxN wavelength router (= Latin router)
    - Nx1 wavelength multiplexer (WMUX)
    - 1xN wavelength demultiplexer (WDMUX)
Optical network nodes (3)

• Dynamic nodes
  – without wavelength selectivity (optical cross-connect (OXC))
    • NxN permutation switch
    • RxN generalized switch
    • RxN linear divider-combiner (LDC)
  – with wavelength selectivity
    • NxN wavelength selective cross-connect (WSXC) with M wavelengths
    • NxN wavelength interchanging cross-connect (WIXC) with M wavelengths
    • RxN waveband selective LDC with M wavebands

Wavelength multiplexer and demultiplexer

[Diagram of WDMUX and WMUX]
Directional Coupler (1)

- **Directional coupler** (= 2x2 switch) is an optical four-port
  - ports 1 and 2 designated as input ports
  - ports 1’ and 2’ designated as output ports

- Optical power
  - enters a coupler through fibers attached to input ports
  - divided and combined **linearly**
  - leaves via fibers attached to output ports

- Power relations for input signal powers $P_1$ and $P_2$ and output powers $P_1’$ and $P_2’$ are given by

\[ P_1’ = a_{11}P_1 + a_{12}P_2 \]
\[ P_2’ = a_{21}P_1 + a_{22}P_2 \]

- Denote **power transfer matrix** by $A = [a_{ij}]$ and **power matrix** by $P = [P_i]$ $\Rightarrow P’ = AP$

### Directional Coupler (2)

- Ideally, the power transfer matrix $A$ is of the form

\[ A = \begin{bmatrix}
1-\alpha & \alpha \\
\alpha & 1-\alpha
\end{bmatrix}, \quad 0 \leq \alpha \leq 1 \]

- If parameter $\alpha$ is fixed, the device is **static**, e.g. with $\alpha = 1/2$ and signals present at both inputs, the device acts as a 2x2 star coupler

- If $\alpha$ can be varied through some external control, the device is **dynamic** or controllable, e.g. add-drop switch

- If only input port 1 is used (i.e., $P_2 = 0$), the device acts as a 1x2 **divider**

- If only output port 1’ is used (and port 2’ is terminated), the device acts as a 2x1 **combiner**
Add-drop switch

Add-drop state

Bar state

OR - Optical Receiver
OT - Optical Transmitter

Broadcast star

- Static NxN broadcast star with N wavelengths can carry
  - N simultaneous multi-cast optical connections (= full multipoint optical connectivity)
- Power is divided uniformly
- To avoid collisions each input signal must use different wavelength
- Directional coupler realization
  - \((N/2) \log_2 N\) couplers needed

broadcast star realized by directional couplers
**Wavelength router**

- Static NxN **wavelength router** with N wavelengths can carry
  - wavelengths from the different inputs so that identical wavelengths do not enter the same outputs (Latin square principle)
  - $N^2$ simultaneous **unicast** optical connections (= full point-to-point optical connectivity)
- Requires
  - N 1xN WDMUX's
  - N Nx1 WMUX's

**Crossbar switch**

- Dynamic RxN **crossbar switch** consists of
  - R input lines
  - N output lines
  - RN crosspoints
- Crosspoints implemented by **controllable** optical couplers
  - RN couplers needed
- A crossbar can be used as
  - a NxN **permutation switch** (then $R = N$) or
  - a RXN **generalized switch**
**Permutation switch**

- Dynamic NxN **permutation switch** (e.g. crossbar switch)
  - unicast optical connections between input and output ports
  - N! **connection states** (if nonblocking)
  - each connection state can carry N simultaneous unicast optical connections
  - representation of a connection state by a NxN **connection matrix** (exactly one connection “1” per each row and column)

- **Input/output power relation** \( P' = AP \) with NxR power transfer matrix \( A = [a_{ij}] \), where
  \[
  a_{ij} = \begin{cases} 
  \frac{1}{NR}, & \text{if switch } (i,j) \text{ is on} \\
  0, & \text{otherwise}
  \end{cases}
  \]

**Generalized switch**

- Dynamic RxN **generalized switch** (e.g. crossbar switch)
  - any input/output pattern possible (incl. one-to-many and many-to one connections)
  - \( 2^{NR} \) **connection states**
  - each connection state can carry (at most) R simultaneous multicast optical connections
  - a connection state represented by a RxN **connection matrix**

- **Input/output power relation** \( P' = AP \) with NxR power transfer matrix \( A = [a_{ij}] \), where
Linear Divider-Combiner (LDC)

- **Linear Divider-Combiner** (LDC) is a generalized switch that
  - controls power-dividing and power-combining ratios
  - less inherent loss than in crossbar
- Power-dividing and power-combining ratios
  - \( \delta_{ij} \) = fraction of power from input port \( j \) directed to output port \( i' \)
  - \( \sigma_{ij} \) = fraction of power from input port \( j \) combined onto output port \( i' \)
- In an ideal case of lossless couplers, we have constraints

\[
\sum_i \delta_{ij} = 1 \quad \text{and} \quad \sum_j \sigma_{ij} = 1
\]

- The resulting power transfer matrix \( A = [a_{ij}] \) is such that

\[
a_{ij} = \delta_{ij} \sigma_{ij}
\]

LDC and generalized switch realizations

- \( \delta - \sigma \) linear divider-combiner
- Generalized optical switch
Wavelength selective cross-connect (WSXC)

• Dynamic NxN **wavelength selective cross-connect** (WSXC) with M wavelengths
  – includes N 1xM WDMUXs, M NxN permutation switches, and N Mx1 WMUXs
  – \((N!)^M\) connection states if the permutation switches are nonblocking
  – each connection state can carry NM simultaneous unicast optical connections
  – representation of a connection state by M NxN **connection matrices**

Wavelength interchanging cross-connect (WIXC)

• Dynamic NxN **wavelength interchanging cross-connect** (WIXC) with M wavelengths
  – includes N 1xM WDMUXs, 1 NM x NM permutation switch, NM WC's, and N Mx1 WMUXs
  – \((NM)!\) connection states if the permutation switch is nonblocking
  – each connection state can carry NM simultaneous unicast connections
  – representation of a connection state by a NMxNM **connection matrix**
Waveband selective LDC

- Dynamic RxN waveband selective LDC with M wavebands
  - includes R 1xM WDMUXs, M RxN LDCs, and N Mx1 WMUXs
  - \(2^{RNM}\) connection states (if used as a generalized switch)
  - each connection state can carry (at most) RM simultaneous multi-cast connections
  - representation of a connection state by a M RxN connection matrices

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Network access stations (1)

- **Network Access Station (NAS)** operates in the logical connection, transmission channel and λ-channel sublayers
- NASs are the gateways between the electrical and optical domains

**Functions:**
- interfaces the external LC ports to the optical transceivers
- implements the functions necessary to move signals between the electrical and optical domains

Network access stations (2)

**Transmitting side** components:
- **Transmission Processor** (TP) with a number of LC input ports and transmission channel output ports connected to optical transmitters (converts each logical signal to a transmission signal)
- **Optical Transmitters** (OT) with a laser modulated by transmission signals and connected to a WMUX (generates optical signals)
- **WMUX** multiplexes the optical signals to an outbound access fiber

**Receiving side** components:
- **WMUX** demultiplexes optical signals from an inbound access fiber and passes them to optical receivers
- **Optical Receivers** (OR) convert optical power to electrical transmission signals, which are corrupted versions of the original transmitted signals
- **Reception Processor** (RP) converts the corrupted transmission signals to logical signals (e.g. regenerating digital signals)
Elementary network access station

Non-blocking network access station

OR - Optical Receiver
OT - Optical Transmitter
RP - Reception Processor
TP - Transmission Processor
Wavelength add-drop multiplexer (WADM)

WADM combined with NAS

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End System

- **End systems** are in the electrical domain
- In transparent optical networks, they are directly connected to NASs
  - purpose is to create full logical connectivity between end stations
- In hybrid networks, they are connected to LSNs
  - purpose is to create full virtual connectivity between end stations

Logical Switching Node (LSN)

- **Logical switching nodes** (LSN) are needed in hybrid networks, i.e. in *logically routed networks* (LRN)
- LSNs operate in the electrical domain
- Examples of LSNs are
  - SONET digital cross-connect systems (DCS)
  - ATM switches
  - IP routers
Logically routed network

Contents

- The Big Picture
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- **Network Connections**
  - Connectivity
  - Connections in various layers
  - Example: realizing full connectivity between five end systems
Connectivity

- Transmitting side:
  - one-to-one
    - (single) unicast
  - one-to-many
    - multiple unicasts
    - (single) multicast
    - multiple multicasts

- Receiving side:
  - one-to-one
    - (single) unicast
  - many-to-one
    - multiple unicasts
    - multiple multicasts

- Network side:
  - point-to-point
  - multipoint

Connection Graph (CG)

- Representing point-to-point connectivity between end systems

```
1 - 2
   |
   v
4 - 3

transmitting side            receiving side

1  2  3  4
```

Connection graph
Bipartite representation
Connection Hypergraph (CH)

- Representing *multipoint* connectivity between end systems

![Connection hypergraph](image)

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  - *Connections in various layers*
  - Example: realizing full connectivity between five end systems
Connections in various layers

- **Logical connection** sublayer
  - Logical connection (LC) is a unidirectional connection between external ports on a pair of source and destination network access stations (NAS)

- **Optical connection** sublayer
  - Optical connection (OC) defines a relation between one transmitter and one or more receivers, all operating in the same wavelength

- **Optical path** sublayer
  - Optical path (OP) routes the aggregate power on one waveband on a fiber, which could originate from several transmitters within the waveband

Notation for connections in various layers

- **Logical connection** sublayer
  - \([a, b]\) = point-to-point logical connection from an external port on station \(a\) to one on station \(b\)
  - \([a, \{b, c, \ldots\}\] = multi-cast logical connection from \(a\) to set \(\{b, c, \ldots\}\)
    - station \(a\) sends the same information to all receiving stations

- **Optical connection** sublayer
  - \((a, b)\) = point-to-point optical connection from station \(a\) to station \(b\)
  - \((a, b)_k\) = point-to-point optical connection from \(a\) to \(b\) using wavelength \(\lambda_k\)
  - \((a, \{b, c, \ldots\})\) = multi-cast optical connection from \(a\) to set \(\{b, c, \ldots\}\)

- **Optical path** sublayer
  - \(<a, b>\) = point-to-point optical path from station \(a\) to station \(b\)
  - \(<a, b>_k\) = point-to-point optical path from \(a\) to \(b\) using waveband \(w_k\)
  - \(<a, \{b, c, \ldots\}>\) = multi-cast optical path from \(a\) to set \(\{b, c, \ldots\}\)
Example of a logical connection between two NASs

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  - Connections in various layers
  - **Example: realizing full connectivity between five end systems**
Example: realization of full connectivity between 5 end systems

Solutions

- **Static network** based on star physical topology
  - full connectivity in the logical layer (20 logical connections)
  - 4 optical transceivers per NAS, 5 NASs, 1 ONN (broadcast star)
  - 20 wavelengths for max throughput by WDM/WDMA

- **Wavelength routed network** (WRN) based on bi-directional ring physical topology
  - full connectivity in the logical layer (20 logical connections)
  - 4 optical transceivers per NAS, 5 NASs, 5 ONNs (WSXCs)
  - 4 wavelengths (assuming elementary NASs)

- **Logically routed network** (LRN) based on star physical topology and unidirectional ring logical topology
  - full connectivity in the virtual layer but only partial connectivity in the logical layer (5 logical connections)
  - 1 optical transceiver per NAS, 5 NASs, 1 ONN (WSXC), 5 LSNs
  - 1 wavelength
Solution markings

- End station
- Logical switching node, e.g. ATM switch
- Network access station
- Wavelength switching equipment, e.g. star coupler or wavelength selective cross-connect

Static network realization

- 5x5 broadcast star
- LCG
Wavelength routed network realization

Logically routed network realization