Introduction to Multiwavelength Optical Networks

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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
  – “The information superhighway is still a dirt road; more accurately, it is a set of isolated multiline highways with cow paths for entrance.”

• Why not yet ?
  – optical last mile (also known as 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 multiline 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 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, slitting 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
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 \(\Rightarrow 9,999\) 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
Network links

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 ($\lambda$-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 $\lambda$-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 $f \lambda = c$, where $c$ is the velocity of light in the medium, we have the relation
  \[ \Delta f = \frac{c \Delta \lambda}{\lambda^2} \]

- Thus, 10 GHz = 0.08 nm and 100 GHz = 0.8 nm in the range of 1,550 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

\[
\begin{array}{c}
\lambda_1 \\
\lambda_2 \\
\cdots \\
\lambda_n \\
\end{array}
\]

Unusable spectrum

\[
\text{f/\(\lambda\) [GHz/nm]}
\]

\[
\begin{array}{c}
10 \text{ GHz} \\
0.08 \text{ nm}
\end{array}
\]

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

\[
\begin{array}{c}
\lambda_1 \\
\lambda_2 \\
\cdots \\
\lambda_n \\
\end{array}
\]

\[
\text{f/\(\lambda\) [GHz/nm]}
\]

\[
\begin{array}{c}
100 \text{ GHz} \\
0.8 \text{ nm}
\end{array}
\]

Wavelength and waveband partitioning of the optical spectrum

\[
\begin{array}{c}
\lambda_{1.1} \\
\lambda_{2.1} \\
\cdots \\
\lambda_{n.1}
\end{array}
\]

\[
\text{f/\(\lambda\) [GHz/nm]}
\]

\[
\begin{array}{c}
10 \text{ GHz} \\
0.08 \text{ nm}
\end{array}
\]

\[
\begin{array}{c}
100 \text{ GHz} \\
0.8 \text{ nm}
\end{array}
\]

\[
\begin{array}{c}
W_1 \\
W_2 \\
\cdots \\
W_m
\end{array}
\]

\[
\begin{array}{c}
100 \text{ GHz} \\
100 \text{ GHz}
\end{array}
\]

\[
\begin{array}{c}
200 \text{ GHz} \\
0.16 \text{ nm}
\end{array}
\]
Connection 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.

Channel spacing cannot be as dense in the network nodes as in the end-receivers

Loss of transport capacity

Capacity losses can be avoided by switching wavebands (composed of a number of wavelengths) instead of individual wavelengths

Waveband routed solutions have lower throughput than wavelength 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

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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 crossconnect (OXC))
    - NxN permutation switch
    - RxN generalized switch
    - RxN linear divider-combiner (LDC)
  - with wavelength selectivity
    - NxN wavelength selective crossconnect (WSXC) with M wavelengths
    - NxN wavelength interchanging crossconnect (WIXC) with M wavelengths
    - RxN waveband selective LDC with M wavebands

Wavelength multiplexer and demultiplexer

\[
\begin{align*}
\lambda_1, \ldots, \lambda_4 & \quad \lambda_1, \ldots, \lambda_4 \\
\lambda_1 & \quad \lambda_2 \\
\lambda_3 & \quad \lambda_4
\end{align*}
\]
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 N×N 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 N×N **wavelength router** with N wavelengths can carry
  - wavelengths from the different inputs are routed 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 1×N WDMUX’s
  - N N×1 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 N×N **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 \(N \times N\) connection matrix (exactly one connection “1” per each row and column)

Generalized switch

- Dynamic RxN generalized switch (e.g. crossbar switch)
  - any input/output pattern possible (incl. one-to-many and many-to one connections)
  - \(2^R\) connection states
  - each connection state can carry (at most) \(R\) simultaneous multicast optical connections
  - a connection state represented by a \(R \times N\) connection matrix
  - Input/output power relation \(P' = AP\) with NxR power transfer matrix \(A = [a_{ij}]\), where
    \[a_{ij} = \begin{cases} \frac{1}{NR} & \text{if switch (i,j) is on} \\ 0, & \text{otherwise} \end{cases}\]
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

- Directional couplers
- **$\delta \cdot \sigma$** linear divider-combiner
- Generalized optical switch

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Wavelength selective cross-connect (WSXC)

- Dynamic NxN wavelength selective crossconnect (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 $M \times NxN$ connection matrices

Wavelength interchanging cross-connect (WIXC)

- Dynamic NxN wavelength interchanging crossconnect (WIXC) with M wavelengths
  - includes N 1xM WDMUXs, 1 NM x NM permutation switch, NM WCs, 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 $NM\times NM$ 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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  – Electrical domain resources
• Network Connections
Network access stations (1)

- **Network Access Station (NAS)** operates in the logical connection, transmission channel and \( \lambda \)-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

![Diagram of electronic wires and optical fibers]

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:
- **WDMUX** 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
Wavelength add-drop multiplexer (WADM)

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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 unicast
    - (single) multicast
    - multiple multicasts

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

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

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Connection Graph (CG)

- Representing **point-to-point** connectivity between end systems

![Connection Graph](attachment://connection_graph.png)
Connection Hypergraph (CH)

- Representing **multipoint** connectivity between end systems

Connection hypergraph

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  - Connectivity
  - **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 \(b\)
  - \((a, b)_{\lambda_k}\) = 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 \(b\)
  - \((a, b)_{w_k}\) = 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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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