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

• 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

- Workstation
- Supercomputer
- Multimedia terminal
- ONN - Optical Network Node
- NAS - Network Access Station
- LAN - Local Area 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
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
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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
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 $\approx 0.08$ nm and 100 GHz $\approx 0.8$ 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

\[ \lambda \text{-channel spacing for separability at receivers} \]

Unusable spectrum

\[ \lambda_1, \lambda_2, \ldots, \lambda_n \]

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

10 GHz

0.08 nm

Wavelength and waveband partitioning of the optical spectrum

\[ \lambda \text{-channel spacing for separability at network nodes} \]

\[ \lambda_1, \lambda_2, \ldots, \lambda_n \]

\[ f/\lambda \]

100 GHz

0.8 nm

Wavelength and waveband partitioning of the optical spectrum

\[ \lambda_{w_1, w_2, w_3, \ldots, w_m} \]

\[ f/\lambda \]

10 GHz

0.08 nm

100 GHz

0.8 nm

200 GHz

0.16 nm
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.
  - => 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.
  - => wavelength routed solutions have lower throughput than waveband routed solutions.

Network based on spectrum partitioning

- Single waveband
- Wavelength-routed
- Waveband-routed
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  – Network Access Stations
  – Electrical domain resources
• Network Connections

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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
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 NxN 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 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)

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
  \[
  a_{ij} = \begin{cases} 
  \frac{1}{NR}, & \text{if switch (i,j) is on} \\
  0, & \text{otherwise}
  \end{cases}
  \]
**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
- \( \delta - \sigma \) linear divider-combiner
- Generalized optical switch
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 $M$ 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 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
  - \(2^{R \times N\text{M}}\) connection states (if used as a generalized switch)
  - each connection state can carry (at most) \(R \times M\) simultaneous multi-cast connections
  - representation of a connection state by a M RxN connection matrices

\[
\begin{array}{cccc}
1 & w_1, \ldots, w_4 & 1' \\
2 & w_1, \ldots, w_4 & 2' \\
3 & w_1, \ldots, w_4 & 3' \\
4 & w_1, \ldots, w_4 & 4'
\end{array}
\]

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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

![Diagram](image)

- **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:
  - **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)

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

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  – 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

Connection Graph

Bipartite representation
Connection Hypergraph (CH)

- Representing *multipoint* connectivity between end systems

![Connection Hypergraph](image1)

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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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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