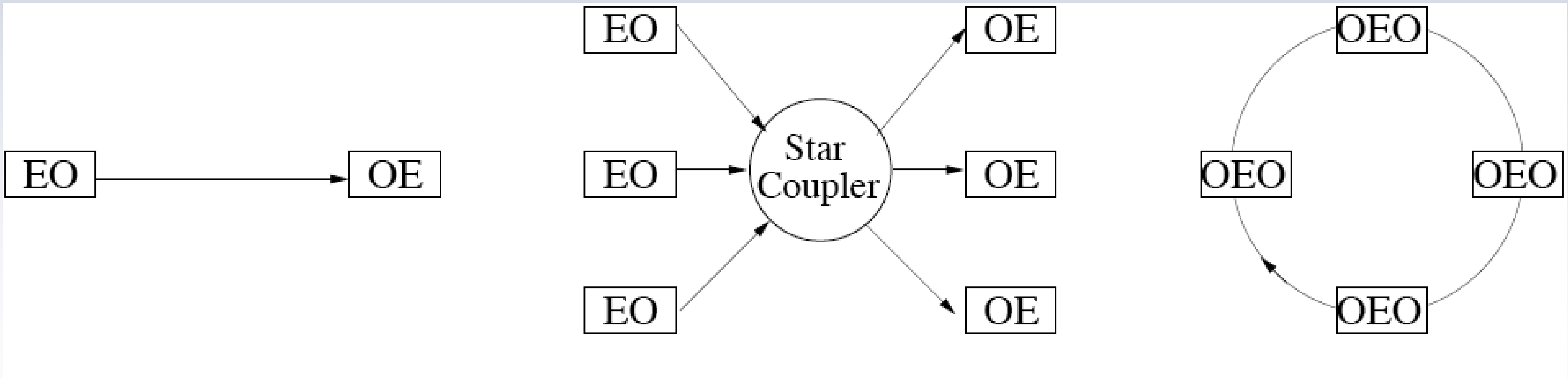
Historical overview of optical networks

Historical overview of optical networks

- Optical fiber provides several advantages
  - Unprecedented bandwidth potential far in excess of any other known transmission medium
  - A single strand of fiber offers a total bandwidth of 25 000 GHz <=> total radio bandwidth on Earth <25 GHz
  - Apart from enormous bandwidth, optical fiber provides additional advantages (e.g., low attenuation)
- Optical networks aim at exploiting unique properties of fiber in an efficient & cost-effective manner

Historical overview of optical networks

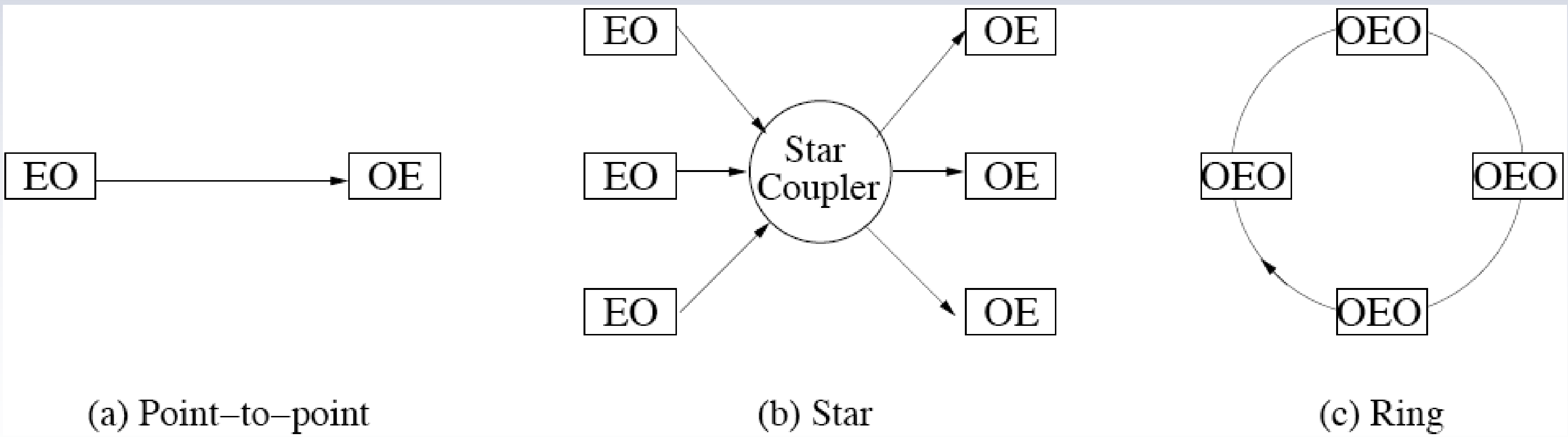
- Optical networks
  - (a) Point-to-point link
    - Initially, optical fiber used for point-to-point transmission systems between pair of transmitting and receiving nodes
    - Transmitting node: converts electrical data into optical signal (EO conversion) & sends it on optical fiber
    - Receiving node: converts optical signal back into electrical domain (OE conversion) for electronic processing & storage



(a) Point–to–point (b) Star (c) Ring

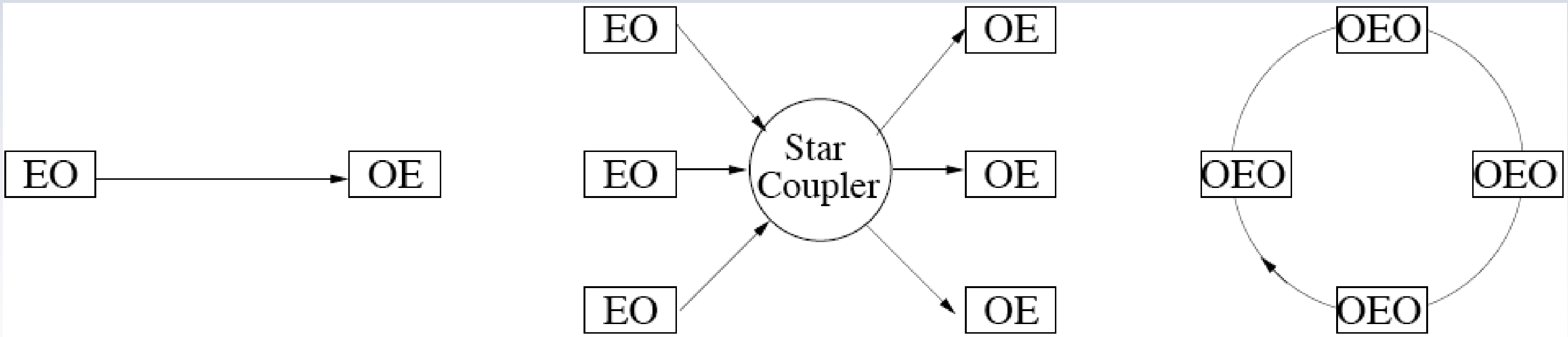
Historical overview of optical networks

- Optical networks
  - (b) Star network
    - Multiple point-to-point links are combined by a star coupler to build optical single-hop star networks
    - Star coupler is an optical broadcast device that forwards an optical signal arriving at any input port to all output ports
    - Similar to point-to-point links, transmitters perform EO conversion and receivers perform OE conversion



Historical overview of optical networks

- Optical networks
  - (c) Ring network
    - Interconnecting each pair of adjacent nodes with point-to-point fiber links leads to optical ring networks
    - Each ring node performs OE and EO conversion for incoming & outgoing signals, respectively
    - Combined OE & EO conversion is called OEO conversion
    - Real-world example: fiber distributed data interface (FDDI)



(a) Point–to–point (b) Star (c) Ring

Historical overview of optical networks

- SONET/SDH
  - Synchronous optical network (SONET) & its closely related synchronous digital hierarchy (SDH) standard is one of the most important standards for optical point-to-point links
  - Brief SONET history
    - Standardization began during 1985
    - First standard completed in June 1988
    - Standardization goals were to specify optical point-to-point transmission signal interfaces that allow
      - interconnection of fiber optics transmission systems of different carriers & manufacturers
      - easy access to tributary signals
      - direct optical interfaces on terminals
      - to provide new network features

Historical overview of optical networks

- SONET/SDH
  - SONET defines
    - standard optical signals
    - synchronous frame structure for time division multiplexed (TDM) digital traffic
    - network operation procedures
  - SONET based on digital TDM signal hierarchy with periodically recurring time frame of 125 μs
  - SONET frame structure carries payload traffic of various rates & several overhead bytes to perform network operations (e.g., error monitoring, network maintenance, and channel provisioning)

Historical overview of optical networks

- SONET/SDH
  - Globally deployed by large number of major network operators
  - Typically, SONET point-to-point links used to build optical ring networks with OEO conversion at each node
  - SONET rings deploy two types of OEO nodes
    - Add-drop multiplexer (ADM)
      - Usually connects to several SONET end devices
      - Aggregates or splits SONET traffic at various speeds
    - Digital cross-connect system (DCS)
      - Adds and drops individual SONET channels at any location
      - Able to interconnect a larger number of links than ADM
      - Often used to interconnect SONET rings

Historical overview of optical networks

- Multiplexing
  - Rationale
    - Huge bandwidth of optical fiber unlikely to be used by single client or application => bandwidth sharing among multiple traffic sources by means of multiplexing
  - Three major multiplexing approaches in optical networks
    - Time division multiplexing (TDM)
    - Space division multiplexing (SDM)
    - Wavelength division multiplexing (WDM)

Historical overview of optical networks

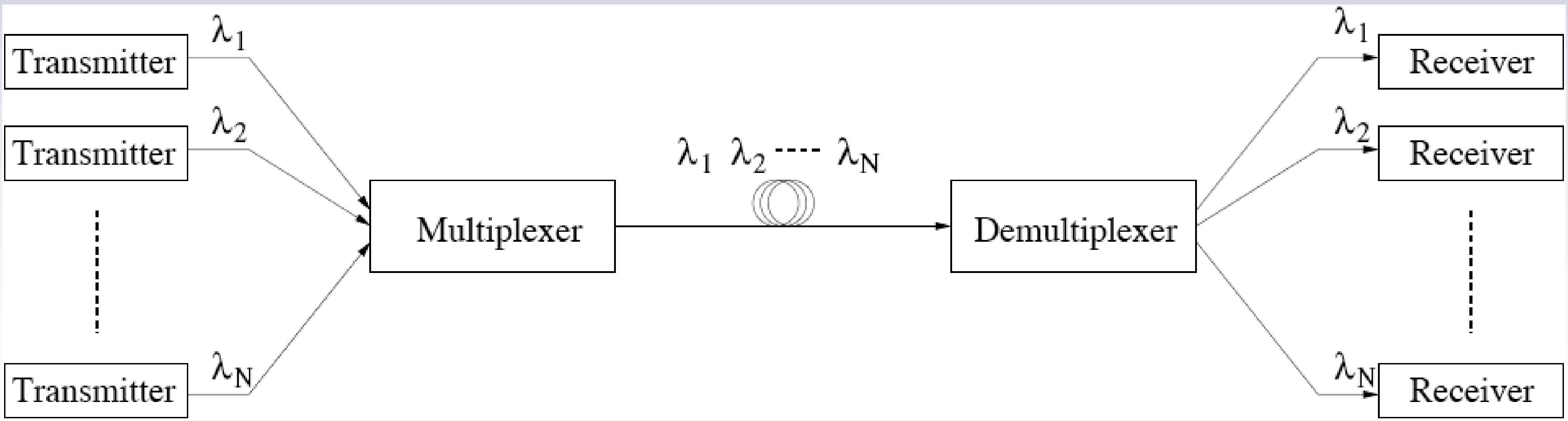
- Multiplexing
  - Time division multiplexing (TDM)
    - SONET/SDH is an important example of optical TDM networks
    - TDM is well understood technique used in many electronic network architectures throughout 50-year history of digital communications
    - In high-speed optical networks, however, TDM is limited by the fastest electronic transmitting, receiving, and processing technology available in OEO nodes, leading to so-called electro-optical bottleneck
    - Due to electro-optical bottleneck, optical TDM networks face severe problems to fully exploit enormous bandwidth of optical fibers

Historical overview of optical networks

- Multiplexing
  - Space division multiplexing (SDM)
    - SDM is straightforward solution to electro-optical bottleneck
    - In SDM, single fiber is replaced with multiple fibers used in parallel, each operating at any arbitrary line rate (e.g., electronic peak rate of OEO transceiver)
    - SDM well suited for short-distance transmissions
    - SDM becomes less practical and more costly for increasing distances since multiple fibers need to be installed and operated

Historical overview of optical networks

- Multiplexing
  - Wavelength division multiplexing (WDM)
    - WDM can be thought of as optical FDM where traffic from each client is sent on different wavelength
    - Multiplexer combines wavelengths onto common outgoing fiber link
    - Demultiplexer separates wavelengths and forwards each wavelength to separate receiver



Historical overview of optical networks

- Multiplexing
  - WDM appears to be the most promising approach to tap into vast amount of fiber bandwidth while avoiding shortcomings of TDM and SDM
    - Each WDM wavelength may operate at arbitrary line rate well below aggregate TDM line rate
    - WDM takes full advantage of bandwidth potential without requiring multiple SDM fibers => cost savings
  - Optical WDM networks widely deployed & studied by network operators, manufacturers, and research groups worldwide
  - Existing & emerging high-performance optical networks are likely to deploy all three multiplexing techniques, capitalizing on the respective strengths of TDM, SDM, and WDM

Historical overview of optical networks

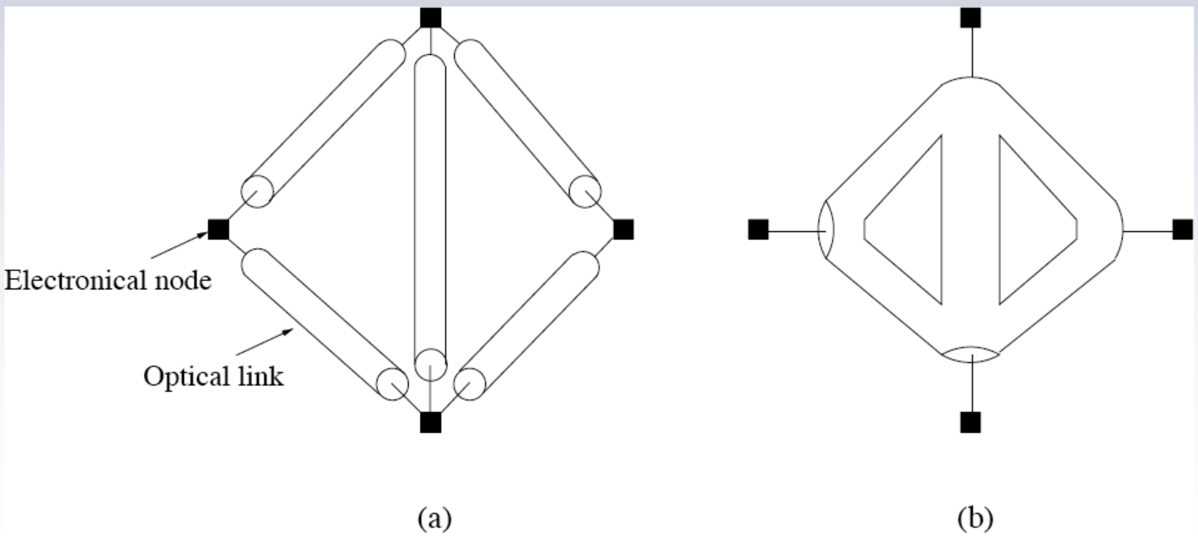
- Optical TDM networks
  - Progress on very short optical pulse technology enables optical TDM (OTDM) networks at 100 Gb/s and above
  - High-speed OTDM networks have to pay particular attention to transmission properties of optical fiber
  - In particular, dispersion significantly limits achievable bandwidth-distance product of OTDM networks due to intersymbol interference (ISI)
    - With ISI, optical power of adjacent bits interfere, leading to changed optical power levels & transmission errors
    - ISI is exacerbated for increasing data rates and fiber lengths => decreased bandwidth-distance product
  - OTDM networks well suited for short-range applications
  - Long-distance OTDM networks can be realized by using soliton propagation, where dispersion effects are cancelled out by nonlinear effects of optical fiber

Historical overview of optical networks

- Optical TDM networks
  - Optical TDM networks have two major disadvantages
    - Synchronization is required, which becomes more challenging for increasing data rates of >100 Gb/s
    - Lack of transparency since OTDM network clients have to match their traffic and protocols to underlying TDM frame structure
  - Using optical switching components with electronic control paves way to transparent OTDM networks
  - However, transparent OTDM networks are still in their infancy
  - Optical WDM networks are widely viewed as more mature solution to realize transparent optical networks
    - WDM networks do not require synchronization
    - Each wavelength may be operated separately, providing transparency against data rate, modulation & protocol

Historical overview of optical networks

- Optical WDM networks
  - Optical WDM networks are networks that deploy WDM fiber links with or without OEO conversion at intermediate nodes
  - Optical WDM networks can be categorized into
    - (a) Opaque WDM networks => OEO conversion
    - (b) Transparent WDM networks => optical bypassing
    - (a)+(b) Translucent WDM networks



Historical overview of optical networks

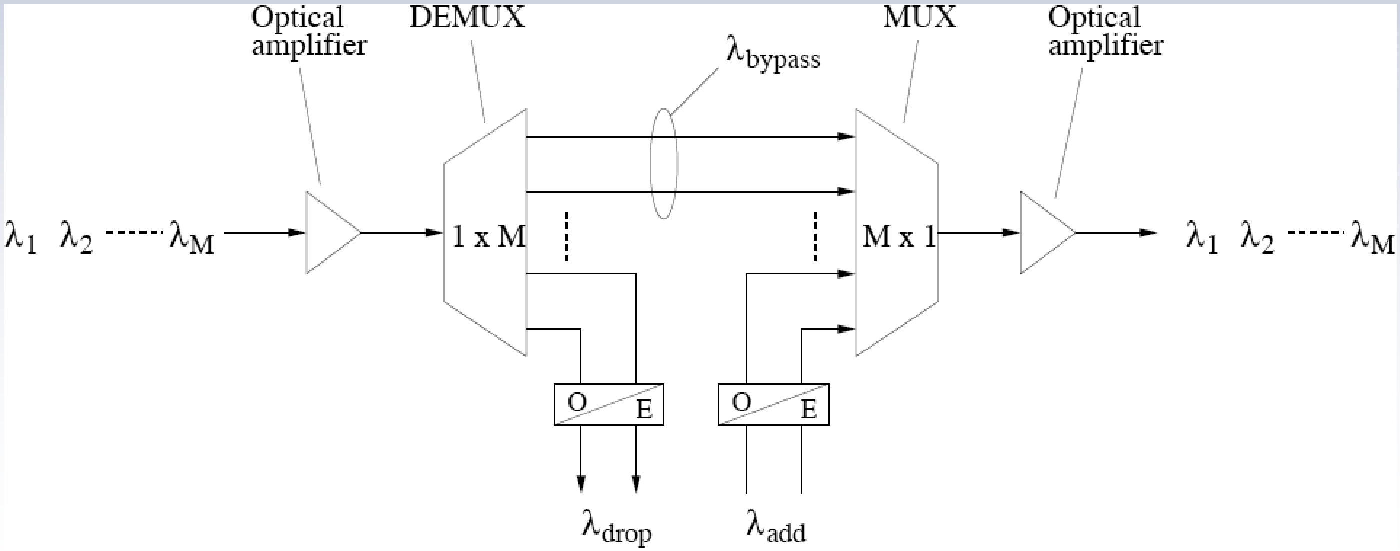
- All-optical networks (AONs)
  - AONs provide purely optical end-to-end paths between source and destination nodes by means of optically bypassing intermediate nodes => optical transparency
  - AONs are widely applicable and can be found at all network hierarchy levels
  - Typically, AONs are optical circuit-switched (OCS) networks
    - Optical circuits usually switched at wavelength granularity => wavelength-routing networks
  - AONs deploy all-optical (OOO) node structures which allow optical signals to stay partly in the optical domain
  - Unlike OEO nodes, OOO nodes do not perform OEO conversion of all wavelength channels => in-transit traffic makes us of optical bypassing

Historical overview of optical networks

- AONs vs. SONET/SDH networks
  - Several similarities and analogies between AONs and SONET/SDH networks
    - Both networks are circuit-switched systems
    - TDM slot multiplexing, processing, and switching in SONET/SDH networks <=> WDM wavelength channel multiplexing, processing, and switching in AONs
    - Add-drop multiplexer (ADM) & digital cross-connect system (DCS) in SONET/SDH networks <=> All-optical replica of ADM & DCS in AONs
      - Optical add-drop multiplexer (OADM)/wavelength add-drop multiplexer (WADM)
      - Optical cross-connect (OXC)/wavelength-selective cross-connect (WSXC)

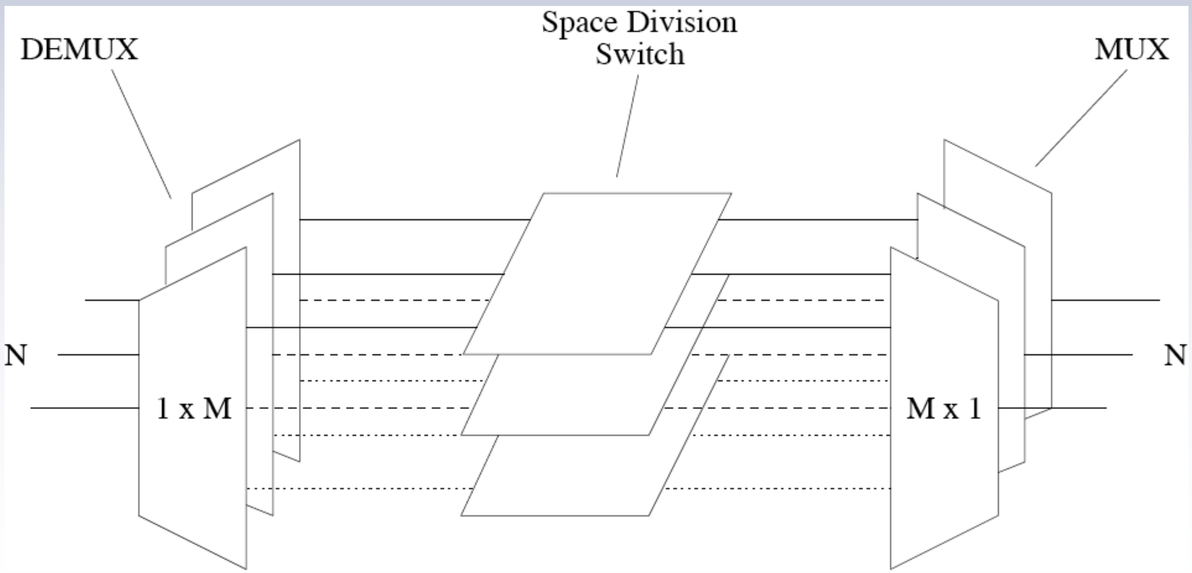
Historical overview of optical networks

- OADM
  - Incoming WDM comb signal optically amplified (e.g., EDFA) & demultiplexed (DEMUX) into separate wavelengths
  - Wavelengths λ_{bypass} remain in optical domain
  - Traffic on wavelengths λ_{drop} locally dropped
  - Local traffic inserted on freed wavelengths λ_{add}
  - Wavelengths multiplexed (MUX) & amplified on outgoing fiber



Historical overview of optical networks

- OXC
  - N x N x M component with N input fibers, N output fibers, and M wavelength channels on each fiber
  - Each input fiber deploys DEMUX & optical amplifier (optional)
  - Each wavelength layer uses separate space division switch
  - Each output fiber deploys DEMUX to collect light from all wavelength layers (plus optional optical amplifier)



Historical overview of optical networks

- Optical transport network (OTN)
  - An AON deploying OADMs and OXCs is referred to as optical transport network (OTN)
  - Benefits of OTN
    - Substantial cost savings due to optical bypass capability of OADMs & OXCs
    - Improved network flexibility and survivability by using reconfigurable OADMs (ROADMs) and reconfigurable OXCs (ROXCs)

Historical overview of optical networks

- AONs: Design Goals & Constraints
  - Two major design goals of AONs
    - Scalability
    - Modularity
  - Transparency enables cost-effective support of large number of applications, e.g.,
    - Voice, video, and data
    - Uncompressed HDTV
    - Medical imaging
    - Interconnection of supercomputers
  - Physical transmission impairments pose limitations on number of network nodes, used wavelengths, and distances => Large AONs must be partitioned into several subnetworks called islands of transparency

Historical overview of optical networks

- AONs: Design Goals & Constraints
  - AONs offer two types of optical paths
    - Lightpath: optical point-to-point path
    - Light-tree: optical point-to-multipoint path
  - Lightpath and light-tree may
    - be optically amplified
    - keep assigned wavelength unchanged => wavelength continuity constraint
    - have assigned wavelength altered along path => wavelength conversion
  - OXCs equipped with wavelength converters are called wavelength-interchanging cross-connects (WIXCs)
  - WIXCs improve flexibility of AONs and help decrease blocking probability in AONs since wavelength continuity constraint can be omitted

Historical overview of optical networks

- Wavelength conversion

Type	Definition
Fixed conversion	Static mapping between input wave-length λ_i and output wavelength λ_j
Limited-range conversion	Input wavelength λ_i can be mapped to a subset of available output wavelengths
Full-range conversion	Input wavelength λ_i can be mapped to all available output wavelengths
Sparse conversion	Wavelength conversion is supported only by a subset of network nodes

Historical overview of optical networks

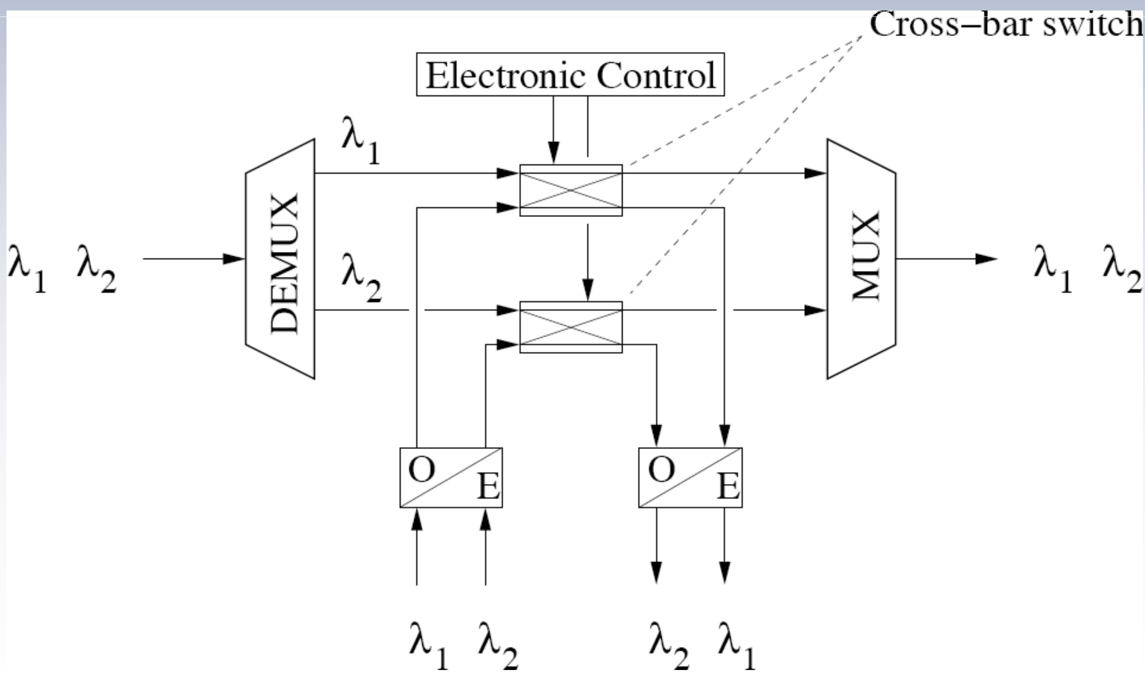
- Wavelength conversion
  - Wavelength converters may be realized
    - by OE converting optical signal arriving on wavelength λ_i and retransmitting it on wavelength λ_j (implying OEO conversion)
    - by exploiting fiber nonlinearities (avoiding OEO conversion)
  - Benefits of wavelength converters
    - Help resolve wavelength conflicts on output links => reduced blocking probability
    - Increase spatial wavelength reuse => improved bandwidth efficiency
  - At the downside, wavelength converters are rather expensive => solutions to cut costs
    - Sparse wavelength conversion
    - Converter sharing inside WIXC
      - Converter share-per-node approach
      - Converter share-per-link approach

Historical overview of optical networks

- Reconfigurability
  - Beneficial property of dynamically rerouting and load balancing of traffic in response to traffic load changes and/or network failures in order improve network flexibility & performance
  - Reconfigurable AONs may be realized by using
    - Tunable wavelength converters (TWCs)
    - Tunable transmitters & receivers
    - Multiwavelength transmitters & receivers
    - Reconfigurable OXCs (ROXCs)
    - Reconfigurable OADMs (ROADMs)

Historical overview of optical networks

- ROADM
  - Conventional OADM becomes reconfigurable by using optical 2 x 2 cross-bar switches on in-transit paths between DEMUX and MUX
  - Cross-bar switches are electronically controlled independently from each other to locally drop/add (cross state) or forward (bar state) traffic on separate wavelengths



Historical overview of optical networks

- Control & Management
  - Reconfigurable AONs allow to realize powerful telecommunications network infrastructures, but also give rise to some problems
    - Find optimal configuration for given traffic scenario
    - Provide best reconfiguration policies in presence of traffic load changes, network failures, and network upgrades
    - Guarantee proper and efficient operation
  - To solve these problems, control & management of reconfigurable AONs is key to make them commercially viable

Historical overview of optical networks

- Control
  - Adding control functions to AONs allows to
    - set up
    - modify and
    - tear down

    optical circuits such as lightpaths and light-trees by (re)configuring tunable transceivers, tunable wavelength converters, ROXCs, and ROADMs along the path
  - AONs typically use a separate wavelength channel called optical supervisory channel (OSC) to distribute control & management information among all network nodes

Historical overview of optical networks

- OSC
  - Unlike optically bypassing data wavelength channels, OSC is OEO converted at each network node (e.g., electronic controller of ROADM)
  - OSC enables both distributed and centralized control of tunable/reconfigurable network elements
    - Distributed control
      - Any node is able to send control information to network elements and thus remotely control their state
    - Centralized control
      - A single entity is authorized to control the state of network elements
      - Central control entity traditionally part of network management system (NMS)

Historical overview of optical networks

- NMS
  - NMS acquires and maintains global view of current network status by
    - issuing requests to network elements and
    - processing responses and update notifications sent by network elements
  - Each network element determines and continuously updates link connectivity & link characteristics to its adjacent nodes, stores this information in its adjacency table, and sends its content to NMS
  - NMS uses this information of all nodes in order to
    - construct & update view of current topology, node configuration, and link status of entire network
    - set up, modify, and tear down optical end-to-end connections
  - Telecommunications Management Network (TMN) framework plays major role in reconfigurable AONs

Historical overview of optical networks

- TMN
  - Jointly standardized by ITU-T and ISO
  - Incorporates wide range of standards that cover management issues of the so-called FCAPS model
    - Fault management
    - Configuration management
    - Accounting management
    - Performance management
    - Security management

Historical overview of optical networks

- FCAPS model
  - Fault management
    - Monitoring & detecting fault conditions
    - Correlating internal & external failure symptoms
    - Reporting alarms to NMS
    - Configuring restoration mechanisms
  - Configuration management
    - Provides connection set-up and tear-down capabilities
    - Paradigms for connection set-up and release
      - Management provisioning (initiated by network administrator via NMS interface)
      - End-user signaling (initiated by end user via signaling interface without intervention by NMS)

Historical overview of optical networks

- FCAPS model
  - Accounting management
    - Also known as billing management
    - Provides mechanisms to record resource usage & charge accounts for it
  - Performance management
    - Monitoring & maintaining quality of established optical circuits
  - Security management
    - Comprises set of functions that protect network from unauthorized access (e.g., cryptography)

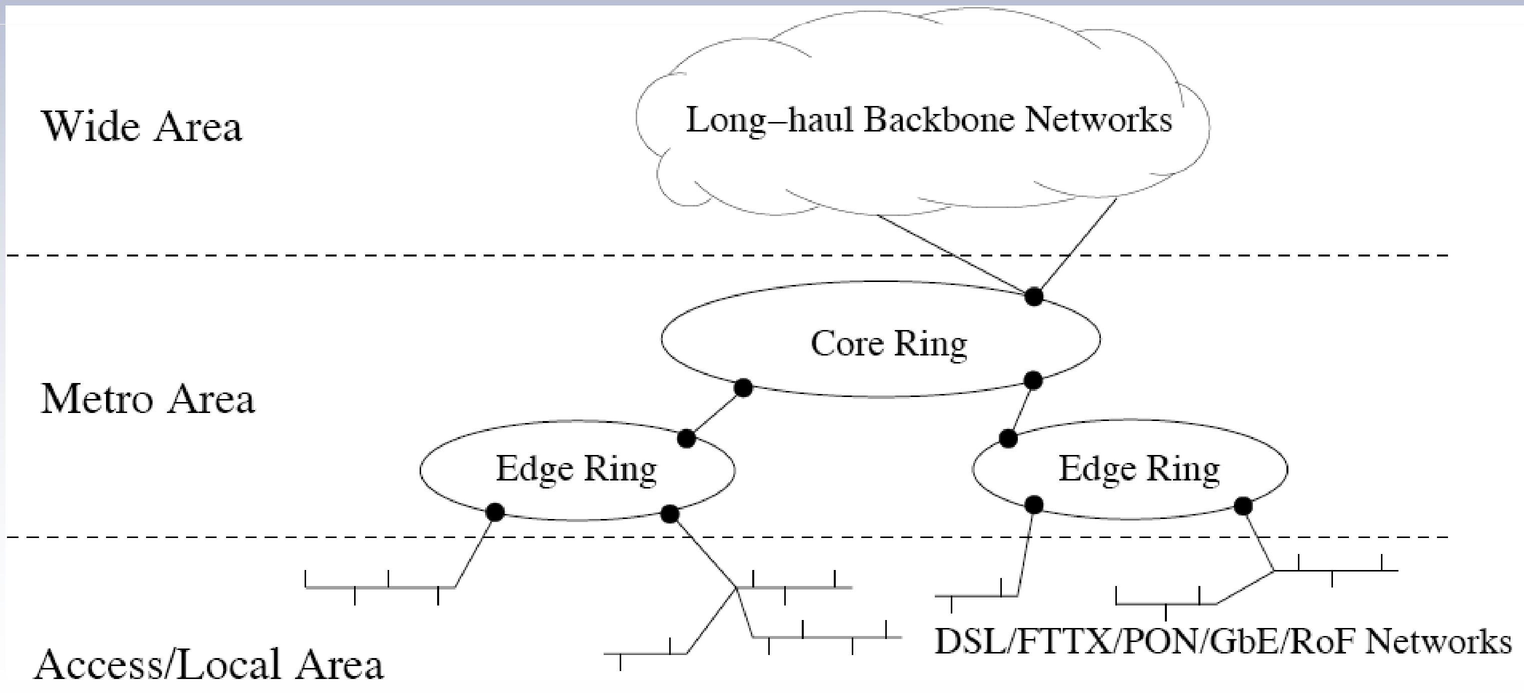
Optical switching networks

Optical switching networks

- Optical networks come in many flavors
  - Different topologies (star, ring, mesh, …)
  - Transparent, opaque, and translucent architectures
  - Different multiplexing approaches (TDM, SDM, WDM)
  - Tunable devices (transmitters, filters, wavelength converters)
  - Reconfigurable devices (ROADMs & ROXCs)
- Various multiplexing, tuning, and switching techniques enable single- or multichannel optical switching networks with
  - High flexibility
  - Dynamic (re)configuration capability in response to varying traffic loads and network failures

Optical switching networks

- End-to-end optical networks
  - Optical switching networks widely deployed in today's wide, metro(politan), access, and local area networks
  - Both telcos & cable providers steadily move fiber-to-copper discontinuity point toward end users



Optical switching networks

- First/last mile bottleneck
  - Typically, phone companies deploy digital subscriber line (DSL) based solutions while cable providers deploy cable modems in their access networks
  - Both approaches make use of copper-based final network segment to connect subscribers
  - Copper-based access segment forms bandwidth bottleneck between high-capacity optical backbone networks & increasingly higher-speed clients at network periphery
  - Bottleneck commonly referred to as first or last mile bottleneck

Optical switching networks

- FTTX
  - To mitigate or remove first/last mile bottleneck, fiber is brought close or all the way to business & residential subscribers
  - Depending on demarcation point X of fiber, this leads to so-called fiber to the X (FTTX) networks
  - Examples of FTTX networks
    - Fiber to the building (FTTB)
    - Fiber to the home (FTTH)
    - Fiber to the curb (FTTC)
    - Fiber to the neighborhood/node (FTTN)

Optical switching networks

- PON
  - FTTX networks typically realized as so-called passive optical networks (PONs)
  - PONs consist of passive optical components without using amplifiers or any other powered devices
  - Benefits of PONs
    - Provide low capital expenditures (CAPEX) and operational expenditures (OPEX)
    - Simplify network operation, administration, and maintenance (OAM)
    - Simplify network management
  - PONs come in different flavors
    - ATM-based PON (APON) Broadband PON (BPON) Gigabit PON (GPON)
    - Ethernet PON (EPON)

Optical switching networks

- ATM vs. Ethernet PONs
  - At present, access networks are fastest growing sector of communications networks
  - Optical access networks play key role in providing broadband access
  - Cost reduction currently more important than capacity and speed increase
  - EPON appears to be in advantageous position over ATM based PONs due to
    - Low cost & simplicity of Ethernet
    - Wide deployment of Ethernet LAN technology & products

Optical switching networks

- 10GbE LAN
  - Ethernet is predominant technology in today's local area networks (LANs)
  - Line rate and transmission range of Ethernet LANs steadily increased over last few years
  - State-of-the-art 10 Gigabit Ethernet (10GbE) provides maximum transmission range of 40 km over optical fiber
  - Besides LAN applications, 10GbE considered a promising low-cost solution for optical high-speed MANs & WANs
    - 10GbE equipment costs about 80% lower than that of SONET equipment
    - 10GbE services expected to be priced 30-60% lower than other managed network services
  - Ethernet technology has potential to build end-to-end Ethernet optical networks

Optical switching networks

- Optical-wireless access networks
  - Current access networks are either optical or wireless
  - Pros & cons of optical access networks
    - Provide practically unlimited bandwidth
    - Require fiber cabling & do not go everywhere
  - Pros & cons of wireless access networks
    - Enable mobility & reachability of users
    - Provide rather limited bandwidth
  - Future access networks likely to be bimodal combining merits of optical & wireless technologies => radio-over-fiber (RoF) networks
  - RoF networks may be viewed as final frontier of optical networks interfacing with their wireless counterparts

Optical switching networks

- Applications
  - Many of today's applications can be categorized into
    - Latency-critical applications
      - Small- to medium-size file transfers with low-latency requirements
      - Examples: Broadcast television, interactive video, video conferencing, security video monitoring, interactive games, telemedicine, and telecommuting
    - Throughput-critical applications
      - Large-size file transfers requiring much bandwidth with relaxed latency constraints
      - Examples: Video on demand (VoD), video & still-image email attachments, backup of files, program & file sharing, and file downloading (e.g., books)

Optical switching networks

- Applications: Impact
  - Applications have significant impact on throughput-delay performance requirements & traffic loads of optical networks
  - Examples
    - Web browsing
      - Based on client-server paradigm
      - Clients send short request messages to server for downloading data files of larger size => asymmetric traffic loads
    - P2P applications
      - Steadily growing P2P traffic
      - P2P traffic already represents major traffic load in some existing access networks
      - Each client also acts as server => more symmetric traffic loads
    - HDTV, Grid computing, …

Optical switching networks

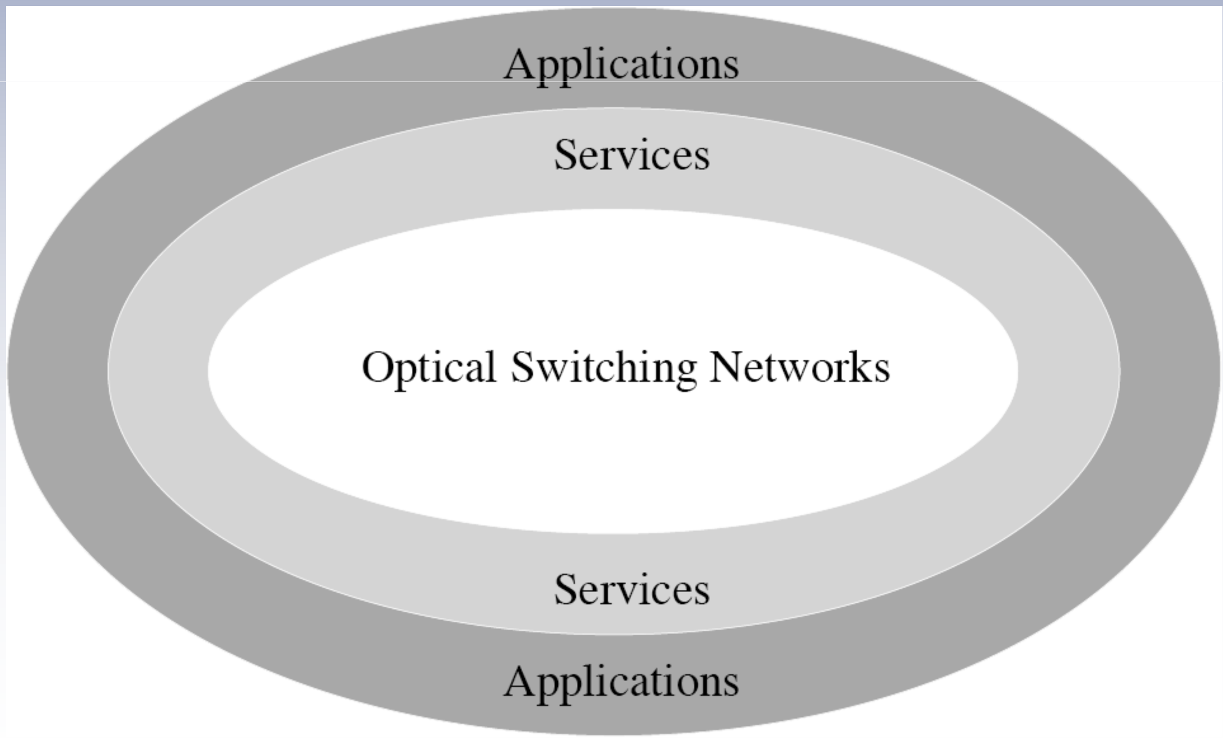
- Services
  - To support wide range of applications, optical networks provide connection-oriented & connectionless services
    - Connection-oriented services
      - Handshake procedure between source & destination required to establish connection before data transmission
      - Sender & destination (e.g., TCP) and possibly also intermediate nodes (e.g., ATM, MPLS) need to maintain state information for established connection
      - State information enables recover from data loss and QoS support for applications with different SLAs
    - Connectionless services
      - No connection establishment needed to send data
      - Connectionless services (e.g., UDP) well suited for transfer of best-effort traffic

Optical switching networks

- Services
  - Examples
    - Triple-play
      - Bidirectional voice, bidirectional data, and unidirectional video services delivered to residential & business users by cable companies
    - Virtual private network (VPN)
      - Closed community of authorized users to access various network-related services & resources
      - Similar to leased private lines, VPNs provide privacy by isolating traffic of different VPNs from each other
      - Virtual topology on physical network infrastructure whose resources may be shared by multiple VPNs
        => more cost-effective solution than leased private lines
      - VPNs used for telecommuting, remote access, and LAN interconnection
      - Realized at link layer (L2VPN) or network layer (L3VPN)

Optical switching networks

- Services
  - Services are offered to applications by underlying optical switching networks through dynamic connections of different switching granularity



Optical switching networks

- Switching granularity
  - Connections in optical switching networks can be categorized according to their switching granularity
  - Switching granularities range from
    - coarse granularity (fiber switching) to
    - fine granularity (OPS)

Fiber switching
Waveband switching
Wavelength switching
Subwavelength switching
Optical circuit switching (OCS)
Optical burst switching (OBS)
Optical packet switching (OPS)

Optical switching networks

- Switching granularities
  - Fiber switching
    - All data arriving on an incoming fiber is switched to another outgoing fiber
  - Waveband switching
    - Set of wavelength channels carried on fiber is divided into multiple adjacent wavebands, each containing two or more contiguous wavelength channels
    - Wavebands arriving on the same incoming fiber are switched independently from each other
  - Wavelength switching
    - Special case of waveband switching
    - Incoming WDM comb signal is first demultiplexed into its individual wavelength channels
    - Each wavelength channel is then switched independently

Optical switching networks

- Switching granularities
  - Subwavelength switching
    - Wavelength channel interleaved by means of TDM => optical TDM (OTDM)
    - In OTDM networks, each time slot carries data of different client and may be switched independently at subwavelength granularity
  - Optical circuit switching (OCS)
    - All aforementioned switching techniques are OCS techniques
    - In OCS networks, circuits (fibers, wavebands, wavelengths, time slots) are dedicated to source-destination node pairs & cannot be claimed by other nodes if unused
    - OCS networks suffer from wasted bandwidth under bursty traffic

Optical switching networks

- Switching granularities
  - Optical packet switching (OPS)
    - Unlike OCS, OPS allows for statistical multiplexing
    - Efficient support of bursty traffic
    - Technological challenges
      - Optical RAM not feasible
      - Instead, fiber delay lines (FDLs) used to realize optical buffers as recirculating fiber loops
      - FDLs have several shortcomings
        - » Restricted reading/writing
        - » Increased delay for small-size packets => OPS networks favor (fixed-size) cell switching

Optical switching networks

- Switching granularities
  - Optical burst switching (OBS)
    - OBS aims at combining strengths of OCS & OPS while avoiding their drawbacks
    - Operation of OBS networks
      - Network ingress nodes aggregate client data into bursts
      - Prior to sending burst, a reservation control packet is sent on dedicated control wavelength channel to configure intermediate nodes
      - Burst is sent after prespecified offset time such that it can be all-optically switched at intermediate nodes in cut-through fashion
    - OBS allows for statistical multiplexing & QoS
    - Unlike OPS, OBS avoids need for optical RAM & FDL
    - Unlike OCS, OBS deploys one-way reservation

Optical switching networks

- Interlayer networking
  - Aforementioned switching paradigms work at data plane of optical switching networks
  - Control plane needed for coordinating various switching techniques efficiently
  - Two approaches to realize control plane
    - Design of new control protocols taking properties of optical switching networks into account
    - Extension of existing control protocols used in electronic data networks
  - Following the latter approach, adoption of IP signaling & routing protocols has been receiving much attention from both industry & academia
  - IP-centric control plane enables IP clients to dynamically set up, modify, and tear down lightpaths in AONs
    => flexible & resilient IP/WDM networks with interlayer networking between AONs & IP clients

Optical switching networks

- Interconnection models
  - IP & optical networks interwork according to inter-connection models
    - Peer model
      - Integrated IP & optical networks with unified control plane
      - IP routers & OXCs/OADMs act as peers => exchange of full routing information, giving rise to security issues
    - Overlay model
      - IP & optical networks operate completely independently, running different sets of control protocols
      - Interfaces between both networks must be standardized
    - Interdomain (augmented) model
      - IP & optical networks have their own routing instances
      - Optical networks provide reachability information of IP routers to IP clients

Optical switching networks

- Optical control plane standardization
  - ITU-T ASTN/ASON
    - Automatic switched transport/optical network (ASTN/ASON) framework for control plane
    - Deals with network functions (e.g., autodiscovery of network topology & resources) and interfaces [e.g., optical user-network interface (O-UNI)]
  - IETF GMPLS
    - Generalized multiprotocol label switching (GMPLS) routing & signaling protocols to set up & tear down connections through O-UNI
  - OIF O-UNI functionality
    - O-UNI functionality assessed in Optical Internetworking Forum (OIF)
  - T1X1 O-UNI requirements
    - O-UNI requirements determined in T1X1 together with ITU-T

Optical switching networks

- Customer-controlled networks
  - ASON concepts & GMPLS protocols well suited for conventional centrally managed optical networks
  - Customer-managed & customer-controlled optical networks are interesting alternative
    - Customers acquire, control, and manage own dark fibers and optical network equipment independent from any carrier => "condominium" networks
    - Potential cost savings by replacing monthly expenditures with one-time initial expenditure shared by customers
    - Customers can freely select network control & management systems without giving visibility to any carrier
    - Well suited to support data-intensive applications (e.g., Grid computing)
    - Increasingly common among large enterprise networks, research networks, and government departments

Optical switching networks

- Security
  - Many security mechanisms used in electronic networks can also be applied at higher electronic protocol layers of optical switching networks (e.g., AAA, encryption)
  - Specific security issues in optical switching networks
    - Malicious signals harder to detect due to transparency
    - Susceptible to QoS degrade or even service disruption due to technological limitations of current optical components & devices, e.g.,
      - Gain competition in EDFA lets malicious high-power optical signals use more upper-state photons => reduced gain of other user signals
      - Limited crosstalk of optical devices (OADM, OXC) may reduce QoS on one or more wavelength channels
    - Attacks can be easily launched from remote sites due to small propagation loss

Optical switching networks

- Grooming
  - Most previous work was done in SONET/SDH ring networks to bypass intermediate ADMs & reduce number of ADMs
  - Traffic grooming can be extended to optical mesh networks
    - Assigning low-rate circuits & data flows to optically bypassing wavelength channels
    - Reducing number of wavelength channels & nodal processing
    - Cost savings
    - Performance improvements (e.g., decreased blocking probability)
  - Future challenges
    - Degree of required opacity (number of dropped wavelengths)
    - Exploitation of topological properties (e.g., star, tree)
    - Study of more realistic traffic patterns (e.g., hot-spot, multicast)