

WDM network design

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The aim of the next two lectures

- To introduce some new definitions
- To make you aware about the trade-offs for WDM network design
- To give you insight into the dimensioning and optimization problems

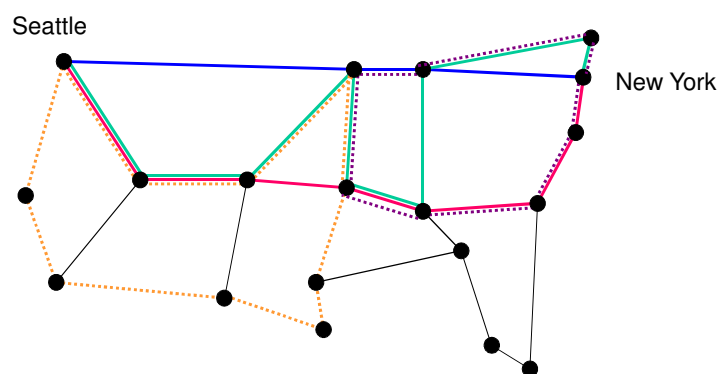
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WDM Network design

- Introduction
- Definitions
- Trade-offs
- Problem definition
- Lightpath topology design (LTD)
- Routing and wavelength assignment (RWA)
- Summary
- Examples

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Objective



Given a traffic matrix (a forecast) and a fiber (physical) topology:
design the network that supports the traffic forecast

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Definitions

- Lightpath topology:
 - Logical (virtual) topology
- Physical topology:
 - Fiber topology
- Grooming:
 - Kind of time multiplexing: packing a low speed channels into higher speed channels.

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Problem definition

- The WDM network transports data traffic from the client layer
- The WDM network is to establish lightpaths to support the client traffic demands
 - Given the fiber (physical) topology and traffic demand (forecast)
 - Determine the lightpath (virtual or logical) topology (Lightpath topology design: LTD)
 - Routing and wavelength assignment (RWA)
- Traffic demands are expressed in a traffic matrix $T=[\lambda^{sd}]$
 - λ^{sd} is the demand in packets/second between source node s and destination node d
 - The traffic matrix is obtained by forecasting

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Heuristic solution

- Hard to determine the lightpath topology jointly with the routing and wavelength assignment
- Split into separate LTD and RWA problems
 - Solve the LTD problem and then realize the obtained LTD within the optical layer (i.e. for the obtained LTD solve RWA problem).

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Lightpath Topology Design (LTD) problem

- Given
 - The traffic demands
 - The maximum number of ports per client node, Δ
 - Lightpaths interconnect client nodes bidirectionally
- Determine the topology and routing of packets
 - Objective: Minimize the maximum load that any lightpath must carry

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LTD: mathematical formulation

- Assume n source and destination nodes
 - Up to $(n-1)n$ lightpaths ($\lambda^{ij} = 0, \forall i=j$)
 - Traffic between s and d might use several lightpaths
 - Conservation of flow $s-d$: rate λ^{sd} at source, $-\lambda^{sd}$ at the destination, and 0 at all intermediate nodes
 - Each lightpath starts and terminates at ports in client nodes
 - $b_{ij} = 1$ if nodes i and j are interconnected by a lightpath, 0 otherwise
- Goal: Find the b_{ij} under the objective
$$\min \lambda_{\max}, \lambda_{\max} = \max_{i,j} \sum_{s,d} a_{ij}^{sd} \lambda^{sd}, 0 \leq a_{ij}^{sd} \leq 1$$

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LTD computation

- This is a mathematical program
 - Linear if unconstrained (LP)
 - Mixed integer linear program (MILP) when
 - λ 's are real, positive, and
 - b_{ij} are integer $\{0, 1\}$
 - Computational complexity an issue

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How to map the LT to the fiber topology

- Undirected or directed edges
 - Can one wavelength channel be used in both directions?
- **Lightpaths cannot share wavelength channels on a shared fiber link**
- Wavelength conversion
 - Allows the lightpath to use different wavelengths
 - No conversion: One wavelength for the entire path
 - Limited conversion
 - From a limited input set to a limited output set
 - In some but not all nodes
- Other limitations
 - Signal quality (regeneration)
 - Survivability
 - etc

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WDM network planning: Input

- Input parameters, given *a priori*
 - Physical topology (OXC nodes and WDM spans)
 - Forecast of traffic demand (virtual topology = lightpath topology)
 - Connections can be unidirectional or bidirectional
 - Each connection corresponds to one lightpath to be setup between the nodes
 - Each connection requires the full capacity of a wavelength channel (no traffic grooming)

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WDM network planning: Resources

- Network resources: two cases
 - Fiber-constrained: the number of fibers per link is a pre-assigned global parameter while the number of wavelengths per fiber required to setup all the lightpaths is to be defined
 - Wavelength-constrained: the number of wavelengths per fiber is a pre-assigned global parameter and the number of fibers per link required to setup all the lightpaths is to be defined

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Static WDM network planning: Physical constraints

- Wavelength conversion capability
 - Absent (wavelength path, WP)
 - Full (virtual wavelength path, VWP)
 - Partial (partial virtual wavelength path, PVWP)
- Propagation impairments
 - The length of lightpaths and #of nodes are limited by physical impairments (physical-length constraint)

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WDM network optimization

- **Routing:**
 - Constrained: only some possible paths between source and destination (e.g. the K shortest paths) are admissible
 - Great problem simplification
 - Unconstrained: all the possible paths are admissible
 - Higher efficiency in network resource utilization
- Cost function to be optimized (**optimization objectives**)
 - Route all the lightpaths using the **minimum number of wavelengths**
 - Route all the lightpaths using the **minimum number of fibers**
 - Route all the lightpaths minimizing **the total network cost**, taking into account also switching systems

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Objective

Realize the lightpath topology, meet all constraints

- **Minimize the number of wavelengths used per link**
 - Offline: For all lightpaths determined by the LTD
- **Minimize blocking and number of wavelengths used per link**
 - Online: For demands coming during operation

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RWA approaches

- ILP formulation
- Heuristic
 - Routing sub-problem
 - Wavelength assignment sub-problem

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RWA: ILP formulation

Minimize: F_{\max}

Such that: $F_{\max} \geq \sum_{s,d} F_{ij}^{sd} \forall ij$

$$\sum_i F_{ij}^{sd} - \sum_k F_{jk}^{sd} = \begin{cases} \lambda_{sd} & \text{if } s = j \\ -\lambda_{sd} & \text{if } d = j \\ 0 & \text{otherwise} \end{cases}$$

λ_{sd} : # of lightpaths between s and d .

F_{ij}^{sd} : # of lightpaths on link ij that are following from s to d .

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RWA (provisioning) Problem Statement

- **Given:**
 - a set of lightpaths that need to be established in the network
 - physical topology
 - number of fibers and number of wavelengths on fiber
 - other constraints: e.g., wavelength continuity, physical impairments, survivability, etc
- **Determine:**
 - the routes over which these lightpaths should be set up
 - the wavelengths which should be assigned to these lightpaths
 - meet all constraints
- Lightpath is blocked when it cannot be set up due to lack of resources (routes and/or wavelengths) or due to other constraints
- The corresponding network optimization problem is to minimize the blocking probability

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Wavelength Continuity Constraint

- No wavelength conversion functionality in the network → lightpaths operate on the same wavelength across all fiber links
- Wavelength continuity constraint can be alleviated by *wavelength converter* functionality at all or some selected nodes
 - Lightpath may switch between different wavelengths on its route from its origin to its termination
 - **Tradeoff:** cost vs. performance

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Physical Impairments Constraint

- Directly related to the nature of the physical medium (fiber) and transparent optical transmission
- Optical signal impairments affect the quality of the lightpaths → Limiting reach of the lightpaths
- Physical impairments can be mitigated by signal regeneration
 - 3R regeneration: Re-amplification, Re-shaping and Re-timing
- **Tradeoff**: cost vs. performance

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Survivability Constraint

- Related to the network ability to ensure service provisioning in the presence of failures
- Link and path protection
- Each working lightpath is assigned spare wavelength resources to survive in case of a link or node failure
- Impact on the RWA solution due to the extra constraints for disjointness:
 - link disjoint
 - node disjoint
 - SRLG disjoint
 - ...

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Routing & Wavelength Assignment

- **Routing sub-problem**
- **Wavelength assignment sub-problem**

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Routing sub-problem

- Fixed routing
- Fixed-alternate routing
- Adaptive routing
- Fault-tolerant routing

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Routing algorithms

- Shortest Path → selects the shortest source-destination path (# of links/nodes)
- Least Loaded Routing → avoids the busiest links
- Least Loaded Node → avoids the busiest nodes

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Wavelength assignment sub-problem

- Static (offline) WA sub-problem
 - Graph coloring
 - Dynamic/static (on/offline) WA sub-problem
 - Random (**R**) Wavelength Assignment
 - First-Fit (**FF**)
 - Least-Used (**LU**)/SPREAD
 - Max-Used (**MU**)/PACK
 - Least Loaded (**LL**)
- etc.

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Static (offline) WA: Graph coloring

- **NC** → Wavelength continuity constraint
- **Given:** all connections and routes
- **Objective:** assign wavelengths (colors) to each lightpath so as to minimize the number of wavelengths used under the wavelength continuity constraint
- **Construct a graph G** so that each lightpath in the system is represented by a node. Undirected edge between nodes in the G if the corresponding lightpaths share a physical link
- **Color the nodes of G** such that no two adjacent nodes have the same color.

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Dynamic (online) WA algorithms

- **Random (R)**
 - Determine the set of wavelengths that are available at a given route
 - Pick one with uniform probability
- **First-Fit (FF)**
 - All wavelengths are numbered
 - Assign the first available wavelength
- **Least-Used (LU)/SPREAD**
 - Select the wavelength that is the least used in the network
- **Max-Used (MU)/PACKED**
 - Select the most used wavelength in the network
- **Least-Loaded (LL)** designed for multi-fiber networks
 - Select the wavelength with largest residual capacity on the most loaded link along the connection.

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WA: Alternate routing lowers blocking

- **Random-1:** (no alternative routes)
 - Choose at random one of the available wavelengths on a fixed shortest path between s-d
- **Random-2:**
 - Fix two shortest paths between every s-d
 - Choose at random one of the available wavelengths on the first shortest path
 - If no such wavelength is available choose a random one on the second shortest path
- **Max-used-1:**
 - On a fixed shortest path between s-d choose the available wavelength that is used most in the network at that time
- **Max-used-2:**
 - Use the wavelength for first path that is used most in network
 - Try second path when first path is full

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Dimensioning
wavelength routing (WR) networks

common practice

Deterministic vs. Statistical dimensioning

Deterministic network dimensioning:

- Forecast traffic demands
- Solve the LTD
- Solve the RWA (network dimensioning problem)
- Iterate every 6 to 12 months
 - Upgrade the network to meet all demands
 - Constrain RWA not to disturb established lightpaths
- Deterministic setting

Alternatively:

Statistical dimensioning using statistical models

- First-passage model
- Blocking model

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RWA Statistical dimensioning: First-passage model

Transient network state

- Network starts without any lightpaths
- Demands arrive randomly and lightpaths are set up one by one
 - Lightpaths might be terminated
 - Rate of termination strictly less than rate of arrivals of demands
 - Number of lightpaths increases
 - Eventually, a demand cannot be met

Dimensioning of WDM network

- Blocking should not occur before a given time
- Time chosen to be long enough for network upgrade
- Goal is probabilistic
- Problem with tractability

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RWA. Statistical dimensioning: Blocking model

Assume stochastic equilibrium

- Arrival rate strictly smaller than departure rate
- Determine maximum offered traffic (offered load)
 - Given an upper bound on blocking probability
 - Usually assumes arrival as Poisson process, lightpaths with exponentially distributed durations and uniform traffic distribution
- Reuse factor: offered load per wavelength at given blocking probability. Depends on
 - network topology
 - traffic distribution
 - actual RWA algorithm
 - number of wavelengths available
- Usually evaluated by simulation

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Summary

- The WDM network should meet client layer demands
 - Demands arrive one by one
 - Demands forecasted
- The lightpath topology is designed to meet limits in port counts while minimize the highest load
- Routing and wavelength assignment
 - Maps the lightpath topology to the fiber topology
 - Provides dimensioning of WDM network
- General problems of computability
 - Optimization problems with complex constraints

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