IO2654 Optical Networking

WDM network design

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KTH/ICT

1

The aim of these 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

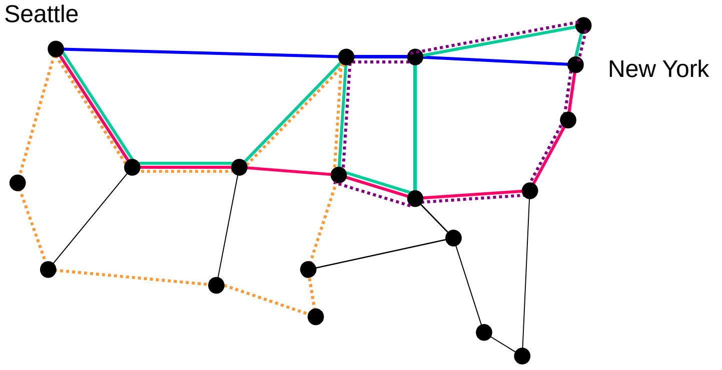
2

WDM Network design

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

3

Objective



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

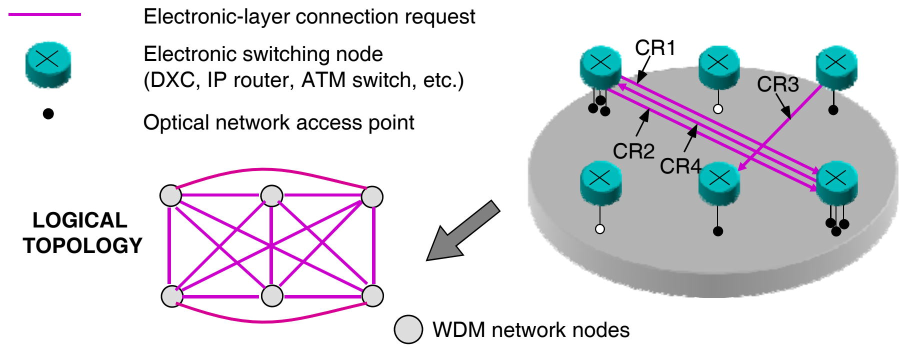
4

Definitions

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

5

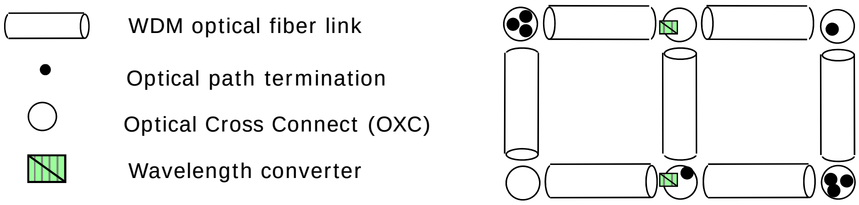
Logical topology



- Logical topology: each link represents a lightpath that could be (or has been) established to accommodate the traffic demand
- A lightpath is a "logical link" between two nodes
- Full mesh Logical topology: a lightpath is established between any node pair
- LT Design (LTD): choose, minimizing a cost function, the lightpaths to support a given traffic

6

Physical topology



WDM PHYSICAL TOPOLOGY

- Physical topology: set of WDM links and switching-nodes
- Some or all the nodes may be equipped with wavelength converters
- The capacity of each link is dimensioned in the design phase

7

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

8

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).

9

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10

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

11

LTD: mathematical formulation

- Assume n source and destination nodes
  - Up to $(n-1)n$ lightpaths ($\lambda^{ii} = 0, \forall i=j$)
  - 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

$$\min \lambda_{\max}, \lambda_{\max} = \max_{i,j} \sum_{s,d} a_{ij}^{sd} \lambda^{sd}, 0 \le a_{ij}^{sd} \le 1$$

12

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

13

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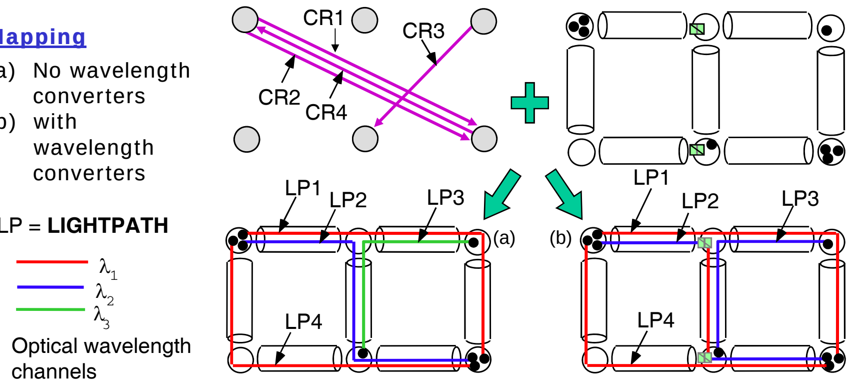
14

RWA: Mapping the logical topology over the physical topology

Mapping

(a) No wavelength converters
(b) with wavelength converters



- Solving the resource allocation problem is equivalent to mapping the logical topology over the physical topology

15

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

16

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)

17

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

18

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)

19

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

20

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

21

RWA approaches

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

22

RWA: ILP formulation

Minimize: $F_{\max}$

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

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

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

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

23

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

24

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

25

Physical Impairments Constraint

- Directly related to the nature of the optical physical medium and transparent 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

26

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 contraints for disjointness:
  - link disjoint
  - node disjoint
  - SRLG disjoint
  - ...

27

Routing & Wavelength Assignment

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

28

Routing sub-problem

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

29

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

30

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.

31

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 nods of G** such that no two adjacent nodes have the same color.

32

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.

33

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

34

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

36

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

37

RWA. Statistical dimensioning: Blocking model

Assume stochastic equilibrium

- Arrival rate strictly smaller than departure rate
- Determine maximum offered traffic
  - 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

38

Analysis problem vs. design problem

- For the statistical models the analysis problem is easier to solve than a design problem.
- **For a blocking model:**
  - Easier to calculate blocking probabilities on each link given link capacities and the traffic model than to determine link capacities given a blocking probability constraint.
- **For First-passage model:**
  - Easier to calculate the statistics of the time to first blocking given link capacities than to determine link capacities to achieve a pre-specified first-passage time.

39

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

40