WDM Network Provisioning

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Some of the material is taken from the lecture slides of Prof. Biswanath Mukherjee, University of California, Davis, USA

The Aim of These Lectures

- More detailed insight of the provisioning concept in WDM networks
- Give an idea of the type of optimization problems and trade offs that are at play
- Knowledge of basic provisioning heuristics (Static + Dynamic)
- Solve simple provisioning problems in various network scenarios

WDM Network Provisioning

- Provisioning: general concept
- Routing and wavelength assignment (RWA) problem definition
  - constraints
  - traffic type (static vs. dynamic)
- Static WDM network provisioning
  - ILP formulation – routing
  - graph coloring – wavelength assignment
- Dynamic WDM network provisioning
  - heuristic methods used to solve both Routing (R) and Wavelength Assignment (WA) sub-problems

Wide-Area Optical Networks

- Wide-area (long-haul) optical networks (mesh topologies)
- Nodes employ optical cross-connects (OXCs)
- WDM channels called *lightpaths* are established between node pairs
- The terms *lightpath* and *connection* are interchangeable
- To establish a “connection” between a source destination pair, we need to set up a “lightpath” between them

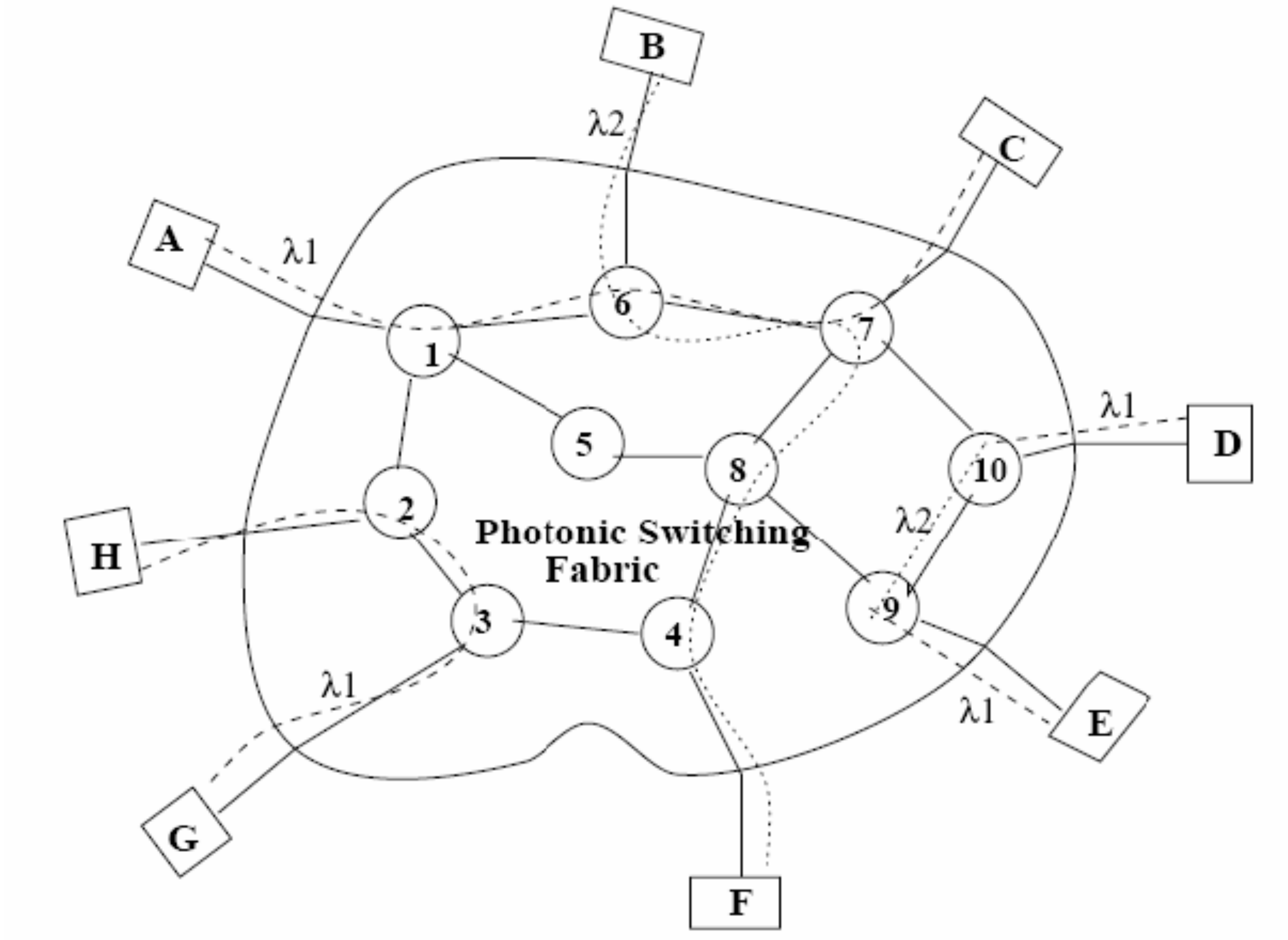
Which Type of Traffic?

- Unicast: point-to-point, from one (pre-defined) source to one (pre-defined) destination, e.g., NY to LA
- Multicast: point-to-multipoint, from one (pre-defined) source to a (pre-defined) set of destinations, e.g., CDN
- Anycast: point-to-point, from one (pre-defined) source to one destination (chosen among a set of potentials), e.g., grid/cloud services

Lightpath Concept

- A lightpath may span multiple fiber links
- It provides a "circuit switched" interconnection between two nodes that:
  - have a traffic flow between them and
  - are located "far" from each other in the physical fiber network topology
- Each intermediate node in the lightpath provides a circuit-switched *optical bypass* facility to support the lightpath

Optical Networks Provisioning: an Example



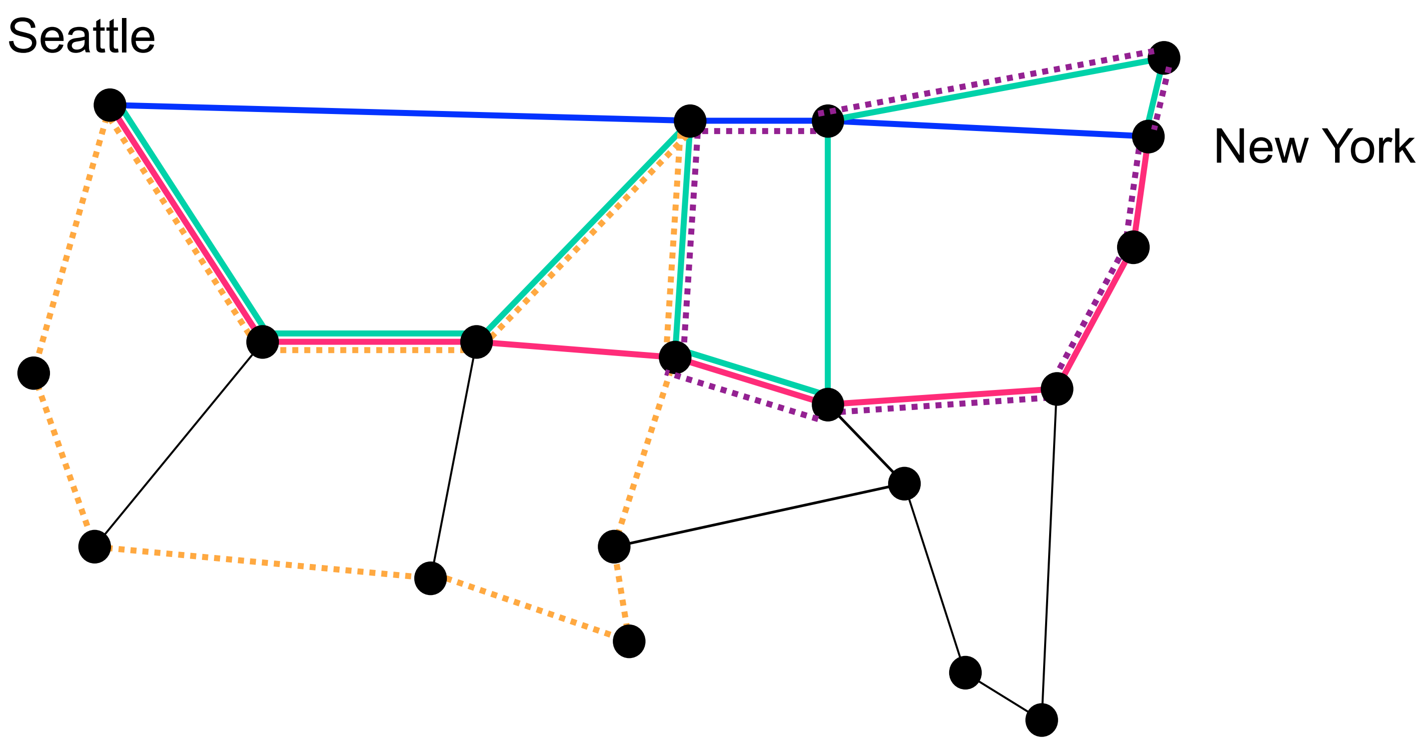
Output: 4 lightpaths

- L1: A-C (1)
- L2: B-F (2)
- L3: D-E (1)
- L4: G-H (1)

but

- Input: ?

Starting Point: Proper Network Design



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

  or/and

    - optimize the (existing) network

Network Design - Rules of the Game

- The offered traffic consists of a set of connections
- Each connection *may* or *may not* require the full bandwidth of a lightpath to be routed between source-destination pair
- Transceivers are expensive so that each node may be equipped with only a few of them
  - would like to have design result at minimum cost
- If network already existing (re-optimization) only a limited number of lightpaths may be set up on the network
  - would like to have design result at minimum blocking

Solution: Split the Problem (LTD + RWA)

- 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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Routing and Wavelength Assignement

- Once a set of lightpaths has been chosen or determined we need to
  - route each lightpath in the network
  - assign a wavelength to it
- This is referred to as the *routing and wavelength assignment (RWA)* problem

RWA Problem Statement

- RWA problem can be stated as follows
- Given:
  - a set of lightpaths that need to be established on the network
  - a constraint on the number of wavelengths
- Determine:
  - the routes over which these lightpaths should be set up
  - the wavelengths which should be assigned to these lightpaths
- Lightpaths is blocked when can not be set up due to *constraints* on fiber and/or wavelengths
  - The corresponding network optimization problem is to minimize this blocking probability
- Cost optimization problem (design like)
  - Provision the set of lightpath using the minimum amount of resources

RWA Constraints

- Resources (fiber and/or wavelength)
- Wavelength continuity
- Physical impairments
- Survivability
- ...

Wavelength Continuity Constraint

- Normally, lightpaths operate on the same wavelength across all fiber links
- *Wavelength continuity constraint*
- If a switching/routing node is also equipped with a *wavelength converter* facility, then wavelength-continuity constraints disappear
- Lightpath may switch between different wavelengths on its route from its origin to its termination
- Trade off: cost vs. performance

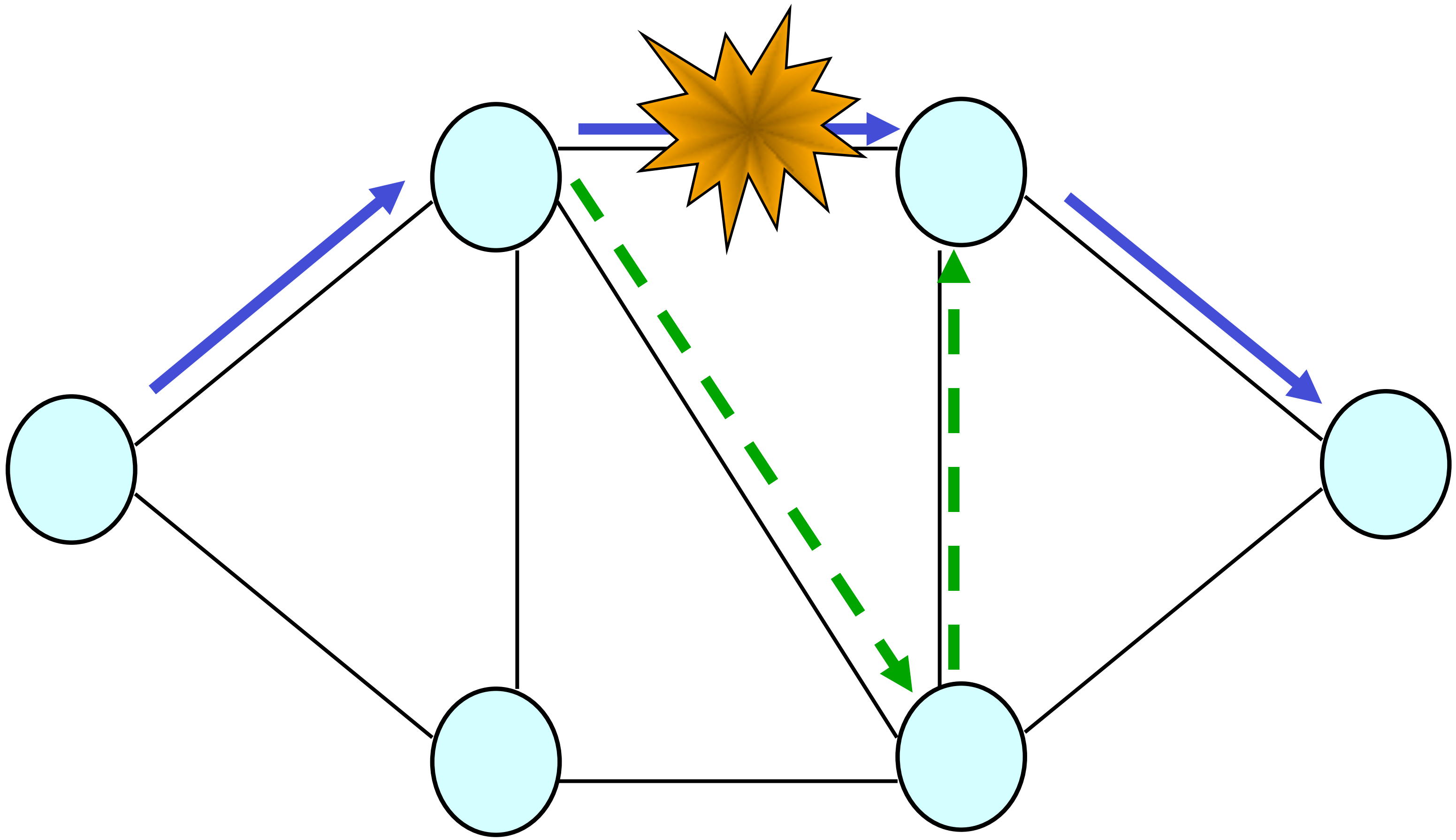
Physical Impairments Constraint

- Directly related to the nature of the optical physical medium and transparent transmission
- Optical physical impairments affect the quality of the lightpath signal
- Lightpaths have a *reduced reach*
- Physical imipariments can be mitigated by regenerating the signal
  - 3R regeneration: Reamplification, Reshaping and Retiming
- Trade-off: cost vs. performance

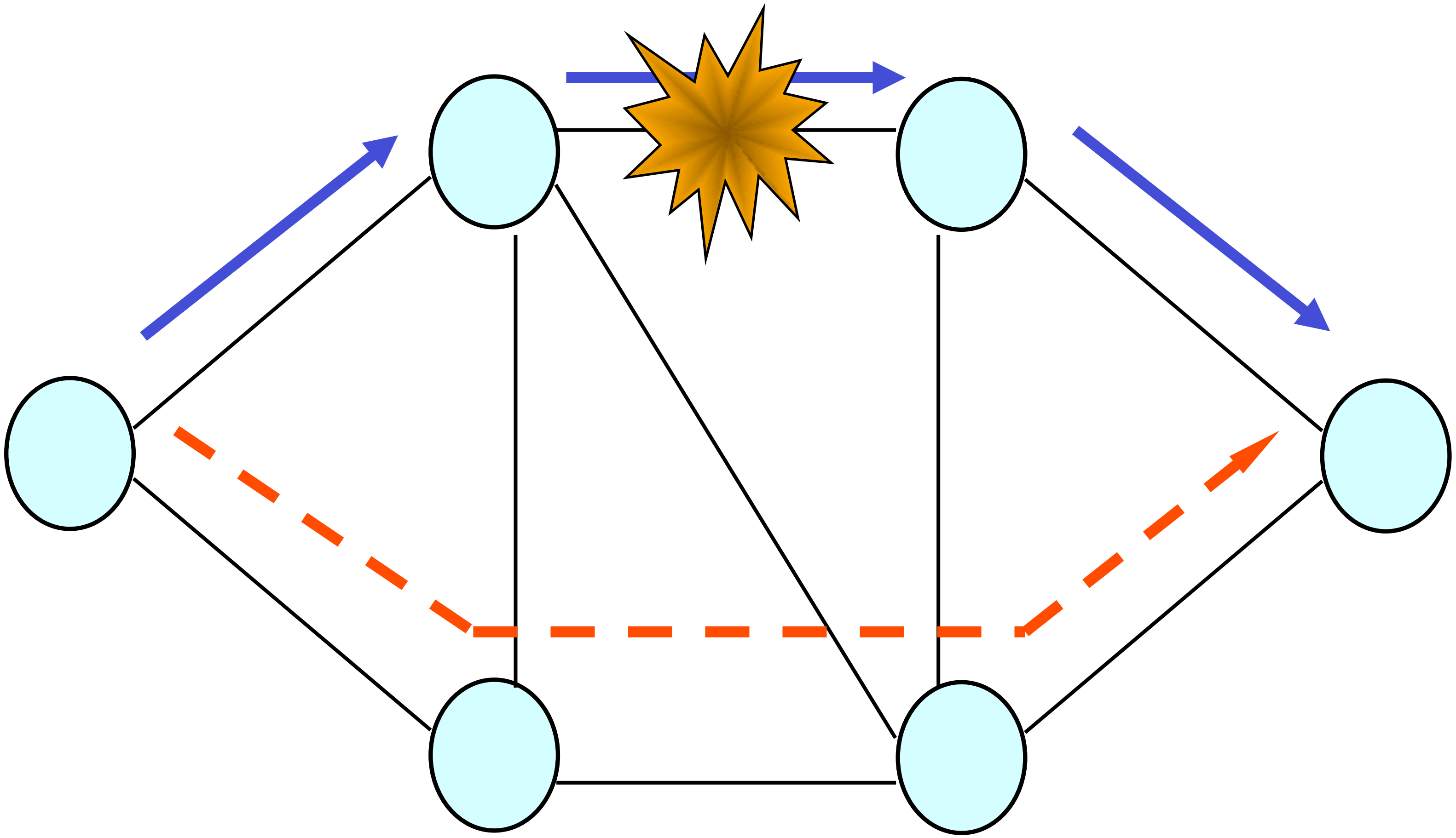
Survivability Constraint

- 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 to a link or node failure
- Impact on the RWA solution due to the extra contraints for disjointness:
  - link disjoint
  - node disjoint
  - SRLG disjoint
  - …

Link Protection



Path Protection



Connection Requests

- Connection requests may be of three types:
  - static:
    - the entire set of connections is known in advance
    - set up lightpaths for the connections in a global fashion while minimizing network resources
    - known as *static lightpath establishment* problem
  - incremental:
    - connection requests arrive sequentially, are established as they arrive, and remains in the network indefinitely
  - dynamic:
    - a lightpath is set up for each connection request as it arrives, and it is released after some amount of time
    - known as *dynamic lightpath establishment* problem

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Solving the Static RWA

- Physical and logical topology (i.e., lightpath requests) are known
- Offline RWA
- The objective is to *minimize* the *number of wavelengths*
- Offline RWA can be formulated as an integer linear program (ILP)
  - objective: minimize the flow in each link, i.e., minimizing the number of lightpaths passing through a link (congestion)
- The general problem is NP-complete

Linear programming (LP)

- A mathematical method for determining a way to achieve the best outcome (such as maximum profit or lowest cost) in a given mathematical model with a list of requirements represented as linear relationships
- More formally, linear programming is a technique for the optimization of a *linear objective function*, subject to linear *equality* and linear *inequality constraints*

Solution of the Static RWA

- Approximation algorithms to solve RWA problem for large network sizes
- RWA problem can be decomposed into different sub-problems, where each can be solved independently
  - a linear program (LP) relaxation (using the idea of *multi-commodity flow* in a network) and a general-purpose LP solver to derive solutions to routing problem
  - graph coloring algorithms to assign wavelengths to the lightpaths
- Sub-dividing in sub-problems allows practical solutions of the RWA problem for networks with a *large number of nodes*

Routing solution as m-c flow problem

- The RWA problem, <u>without</u> the wavelength-continuity constraint, can be formulated as a *multi-commodity flow problem* with integer flows in each link
- Let λ_{sd} denote the traffic (in terms of a lightpath) from any source *s* to any destination *d*
  - at <u>most one lightpath</u> from any source to any destination
  - $\lambda_{sd} = 1$ if there is a lightpath from *s* to *d*
  - otherwise $\lambda_{sd} = 0$
- Let F_{ij}^{sd} denote the *traffic (*in terms of number of lightpaths) flowing from source *s to* destination *d* on link *ij*

ILP formulation

Minimize: $F_{\max}$ (1)

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Such that:

$$F_{\max} \geq \sum_{s,d} F_{ij}^{sd} \quad \forall ij \quad (2)$$

$$\sum_i F_{ij}^{sd} - \sum_k F_{jk}^{sd} = \begin{cases} -\lambda_{sd} & if \quad s = j \\ \lambda_{sd} & if \quad d = j \\ 0 & otherwise \end{cases} \quad (3)$$

$$\lambda_{sd} = 0,1 \quad (4)$$

$$F_{ij}^{sd} = 0,1 \quad (5)$$

Formulation Complexity

- If we consider the general multi-commodity formulation, the *number of equations* and the *number of variables* in the formulation *grow rapidly* with the size of the network
- For example, assume that there are:
  - 10 nodes
  - 30 physical links (*i,j pairs)*
  - an average of 4 connections originating at each node, 40 connections (*s,d pairs)*
- In the general formulation,
  - number of λ_{sd} *variables: 10 × 9 = 90*
  - number of F_{ij}^{sd} *variables: 90 s,d pairs × 30 i,j pairs = 2,700*
  - number of equations will be 3,721
- Even for a small problem, the number of variables and equations are very large
- These numbers grow proportionally with the square of the number of nodes

Problem Size Reduction Options

- A smarter solution can be obtained by only considering the λ_{sd} variables that are 1
- Assume that a particular lightpath will not pass through all of the *i,j* links
  - determine the links which have a good probability of being in the path through which a lightpath may pass

Wavelength Assignment

- Once path has been chosen for each connection, need to *assign wavelengths* to each lightpath
  - any two lightpaths that pass through the same physical link are assigned different wavelengths
- If intermediate switches *do not have* wavelength *conversion*, lightpath has to operate on the *same wavelength* throughout its path
- *Assigning wavelength* colors to different lightpaths, with obj minimize the number of wavelengths with the *wavelength-continuity constraint*
  - equivalent to the *graph coloring* problem

Graph Coloring

- Construct a graph *G(V,E)*
  - each lightpath in the system is represented by a node in graph *G*
  - there is an undirected edge between two nodes if the corresponding lightpaths pass through a common physical fiber link
- Color the nodes of the graph *G* such that no two adjacent nodes have the same color
- This problem has been shown to be NP-complete
- The minimum number of colors (*chromatic number*) needed to color a graph *G is difficult to determine*
- However, there are efficient *sequential graph coloring* heuristics

Graph Coloring Heuristics

- Greedy heuristics: build a coloring by repeatedly extending a partial coloring of the graph
- A graph is said to be *partially colored* if a subset of its vertices is validly colored
- Greedy coloring heuristics carefully picks the next vertex to color and the color for that vertex
- In these heuristics, once a vertex is colored, its *color never changes*

First Fit

- First Fit is the easiest and fastest of all greedy coloring heuristics
- The First Fit coloring algorithm is fed the set of vertices in some *arbitrary order*
- The algorithm sequentially assigns each vertex the *lowest legal color*
- First Fit has the advantage of being very *simple* and *very fast*

First Fit – Pseudo Code

- Suppose to have *n* nodes to colour in graph G (given)
- Pseudo code of First Fit:

$FirstFit(G)$
begin
    for $i = 1$ to n do
        assign smallest legal color to v_i
    end-for
end

Degree Based Ordering Approaches

- A better strategy is
  - use a certain *selection criterion* for choosing the vertex to be colored among the currently uncolored vertices
- Has potentials for providing a better coloring than First Fit

Degree Based Ordering – Pseudo Code

- Suppose to have all the nodes in set *U* to colour in graph G (given)
- Pseudo code:

$Greedy(G)$
begin
  $U = V$
  while $U \neq \emptyset$ do
    choose a vertex $v_i \in U$ according to a selection criterion
    assign smallest legal color to v_i
    $U = U - \{v_i\}$
  end-while
end

Largest Degree Ordering (LDO)

- Ordering the vertices by *decreasing degree* was one of the earliest ordering strategies
- This ordering works as follows:
  - Suppose the vertices $\{v_1, v_2, \ldots, v_{i-1}\}$ have been chosen and colored
  - Vertex v_i is chosen to be the vertex with the *maximum degree* among the set of uncolored vertices

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Solving the Dynamic RWA

- In case of dynamic traffic, LP is not an option
- Heuristic methods are used to solve the dynamic (on-line) RWA problem
- The general RWA is divided into
  - routing sub-problem
  - wavelength assignment sub-problem
- Basic routing heuristics are
  - fixed routing
  - fixed-alternate routing
  - adaptive routing
- Trade off in terms of number of blocked requests versus complexity

Fixed Routing

- The most straightforward approach
- Always choose the same fixed route for a given *s*,*d* pair
- Example: fixed shortest path routing
  - the shortest paths are calculated in advance for each source-destination pair
  - any connection between a specified node pair is established using a pre-determined route
- Pros: no network updates required
- Cons: *no flexibility*, if wavelengths along a fixed route are busy, connection is blocked

Fixed Alternate Routing

- Each node maintains a routing table that contains a list of fixed routes to each destination
  - Example: shortest path, second shortest path, third shortest path
- When a connection request arrives:
  - The source node attempts to establish the lightpath on alternate path 1
  - If no wavelength on the route is available, then the second alternate path is tried
  - … and so on
- Connection is blocked if a lightpath cannot be established on any of the alternate routes

Adaptive Routing

- The route between two nodes are calculated dynamically (i.e., *on the fly*)
- Ongoing connections are taken into account
- *Network state* must be *represented* in some form
- Each time a connection request arrives, a route must be determined according to the free wavelengths on the physical links
- Pros: better blocking performance
- Cons: high signalling cost, prone to inaccurancies

Algorithmic solutions

- They are mostly based on the notion of *shortest path routing*
- Fixed routing -> shortest path
  - Dijkstra Algorithm
  - Bellman-Ford
- Fixed alternate routing-> k-shortest path
  - Yen’s algorithm
- Adaptive -> shortest path
  - Dijkstra Algorithm

Dijkstra Algorithm

- Greedy procedure to compute a set of paths at minimum cost originating at a given node
- Assumption: cost associated with each link has to be positive
- Given
  - a graph G(N,V) and a source node (root) *s*
- Output
  - Minimum cost tree from node *s* to all the other nodes in the network

Dijkstra Algorithm in a nutshell

- Starting from the one *closest to the root* each node is visited once
- Once node is visited, algorithm guarantees that cost to reach that node is the *minimum*
- While visiting a node, algorithm checks all unvisited neighbors to see if cheaper routes are available
- Algorithm stops when all nodes are visited

Dijkstra Pseudo Code

```
Algorithm Dijkstra (G (V,E), s){
   for (each vertex v in V) do {                        // initialization
          dist[v] = infinity ;                          // distance vector from the source node
          previous[v] = NULL ;                          // pointer to the previous node in sh-path
   endfor}

   dist[s] = 0 ;                                        // distance from root to itself
   U = V ;                                              // all nodes are set to not visited

   while (U is not empty) do {
          u = vertex in U with min dist[] ;             // node with min dist from the root

          if (dist[u] = infinity) do{                   // the node is disconnected
                 break ;
          endif}

          remove u from U                               // mark node u as visited
          for (each neighbor v in U of u) do {          // where v belongs to U,
                 temp = dist[u] + distance(u, v) ;
                 if (temp < dist[v]) do {               //update the distances
                        dist[v] = temp ;
                        previous[v] = u ;
                 endif}
          endfor}
   end while}
endDijkstra}
```

Dijkstra Example

- One Dijkstra interactive example available at:
  - http://www-b2.is.tokushima-u.ac.jp/~ikeda/suuri/dijkstra/DijkstraApp.shtml?demo1

Dijkstra Algorithm Applications

- It is very general, distance is just one of the possible application of Djikstra algorithm
  - Path minimum delay
  - Path minimum power consumption
  - .....

Wavelength Assignment for Dynamic Provisioning

- Path is given: result of the “Routing” sub problem
- Objective: minimize connection blocking
- Several heuristics can be used:
  - Random
  - First-fit
  - Least used / SPREAD
  - Most used / PACK
  - …

Random Wavelength Assignment

- Determine the set of all available wavelengths on the required path
- Choose one randomly (usually with uniform probability)

First-fit WA

- All wavelengths are numbered
- A lower-numbered wavelength is considered before a higher-numbered one
- The first available wavelength is then selected
- Compared to random WA lower computation cost
- Main idea: pack all of the in-use wavelengths toward the lower end of wavelength space
  - Continuous longer paths toward the higher-numbered end will have a good chance of being available

Least Used (SPREAD)

- Select the wavelength that is least used in the network
- Attempts to balance the load, among all the wavelengths
- Breaks the long wavelength paths quickly
- The performance is worse than random WA

Most Used (PACK)

- Attempts to select the most used wavelength in the network
- Outperforms LU significantly, and slightly better than FF
- Packs connections into fewer wavelengths
- Conserves spare capacity for less used wavelengths

One final comment on R + WA heuristics

- Heuristics explained so far can be also applied to a static provisioning problem
- Objective is different: minimize the number of resources used
- How?
  - First, all the lightpaths are ordered
  - Then, routes and wavelengths are sequentially assigned using one of the R and WA heuristics

List of papers for the oral exam

- All PDF are available for download at: http://web.it.kth.se/~pmonti/publications.html
  - J. Ahmed, C. Cavdar, P. Monti, L. Wosinska, "Hybrid Survivability Schemes Achieving High Connection Availability with Reduced Amount of Backup Resources," IEEE/OSA Journal of Optical Communication and Networking (JOCN), Vol. 5, No. 10, pp. 152-161, October 2013.
  - P. Wiatr, P. Monti, L. Wosinska, "Power savings versus network performance in dynamically provisioned WDM networks," IEEE Communication Magazine - Optical Communication Series, Vol. 50, No. 5, pp. 48-55, May 2012.
  - A. Jirattigalachote, P. Monti, L. Wosinska, K. Katrinis, A. Tzanakaki, "ICBR-Diff: an Impairment Constraint Based Routing Strategy with Quality of Signal Differentiation," Journal of Networks, special Issue on All-Optically Routed Networks, 2010, Vol. 5, No. 11, pp. 1279-1289, November 2010.
  - M. S. Savasini, P. Monti, M. Tacca, A. Fumagalli, H. Waldman, "Regenerator Placement with Guaranteed Connectivity in Optical Networks," in Proc. of International Conference on Optical Networking Design and Modeling (ONDM), (Invited Paper), May 29-31, Athens, Greece, 2007.
  - P. Monti, M. Tacca, A. Fumagalli, "Resource-Efficient Path-Protection Schemes and Online Selection of Routes in Reliable WDM Networks," Journal of Optical Networking, special issue on Next-Generation WDM Network Design and Routing, Vol. 3, No. 4, pp. 188-203, April 2004.