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

Schedule and project info

- Three classes: April 12, April 16, April 18
  - Make up on week 16 or 18 if needed? Your availability?
- Project based on the material presented in these classes
  - Performance evaluation/comparison of a simple provisioning scenario
  - Groups of 2 students
  - Basic programming skills are required
  - Any programming language is OK (e.g., Matlab, Java, C++, etc.)
  - Project will be posted online by April 19, along with all detailed rules (Check also Course PM – KTH social)
  - Questions session, after one class, pls let me know?
  - Deadline for reporting on the group composition: April 12
  - Deadline: May 17

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 assignement
- Dynamic WDM network provisioning
  - heuristic methods used to solve both Routing (R) and Wavelength Assignment (WA) sub-problems

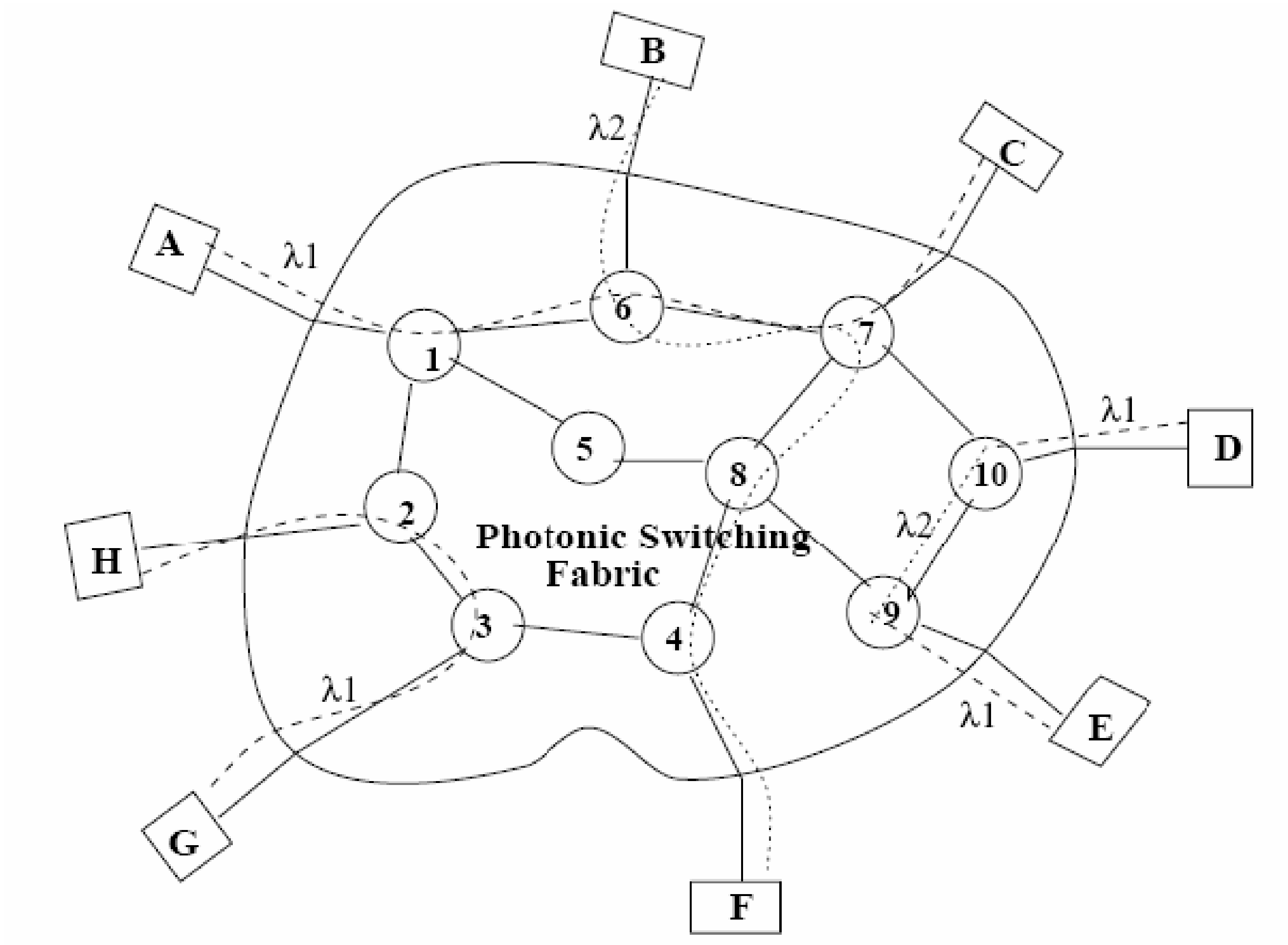
Wide-Area Optical Networks

- 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

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



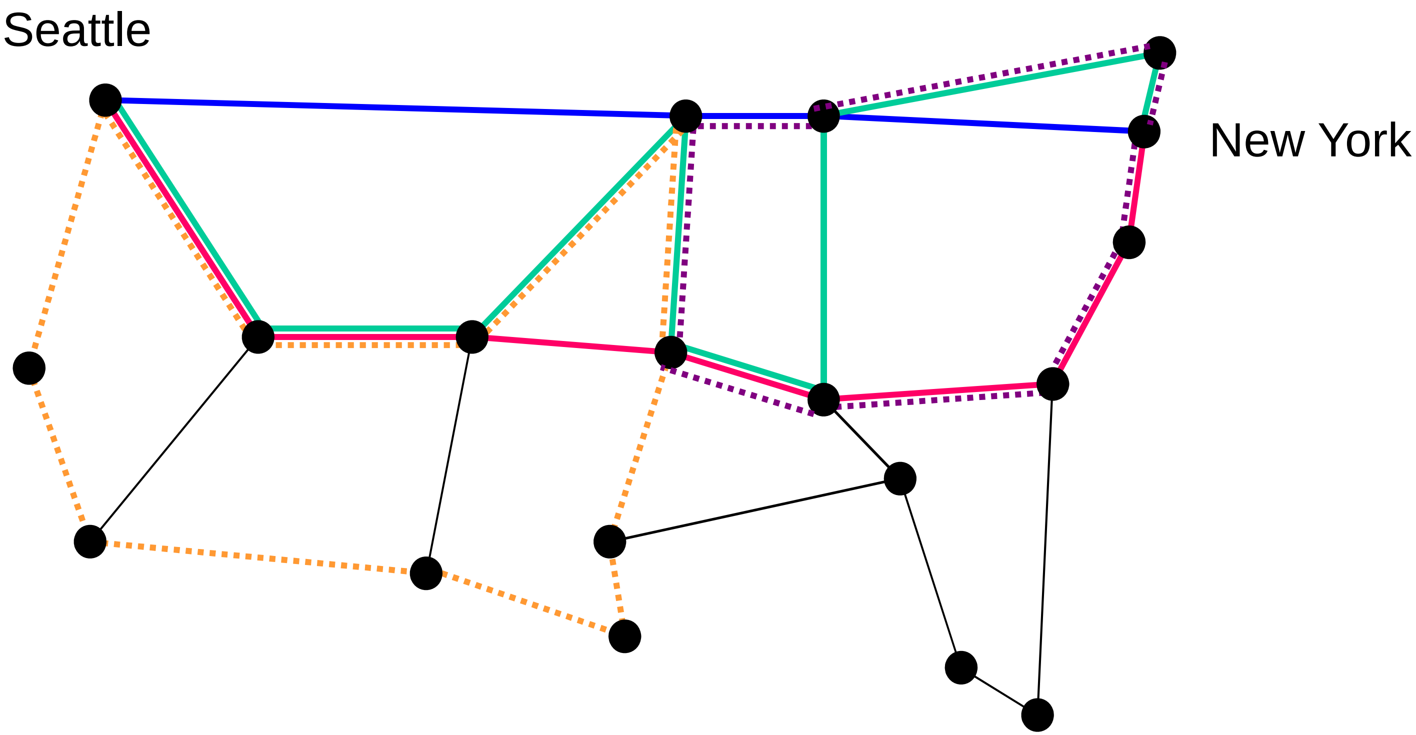
Output: 4 lightpaths

- 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

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

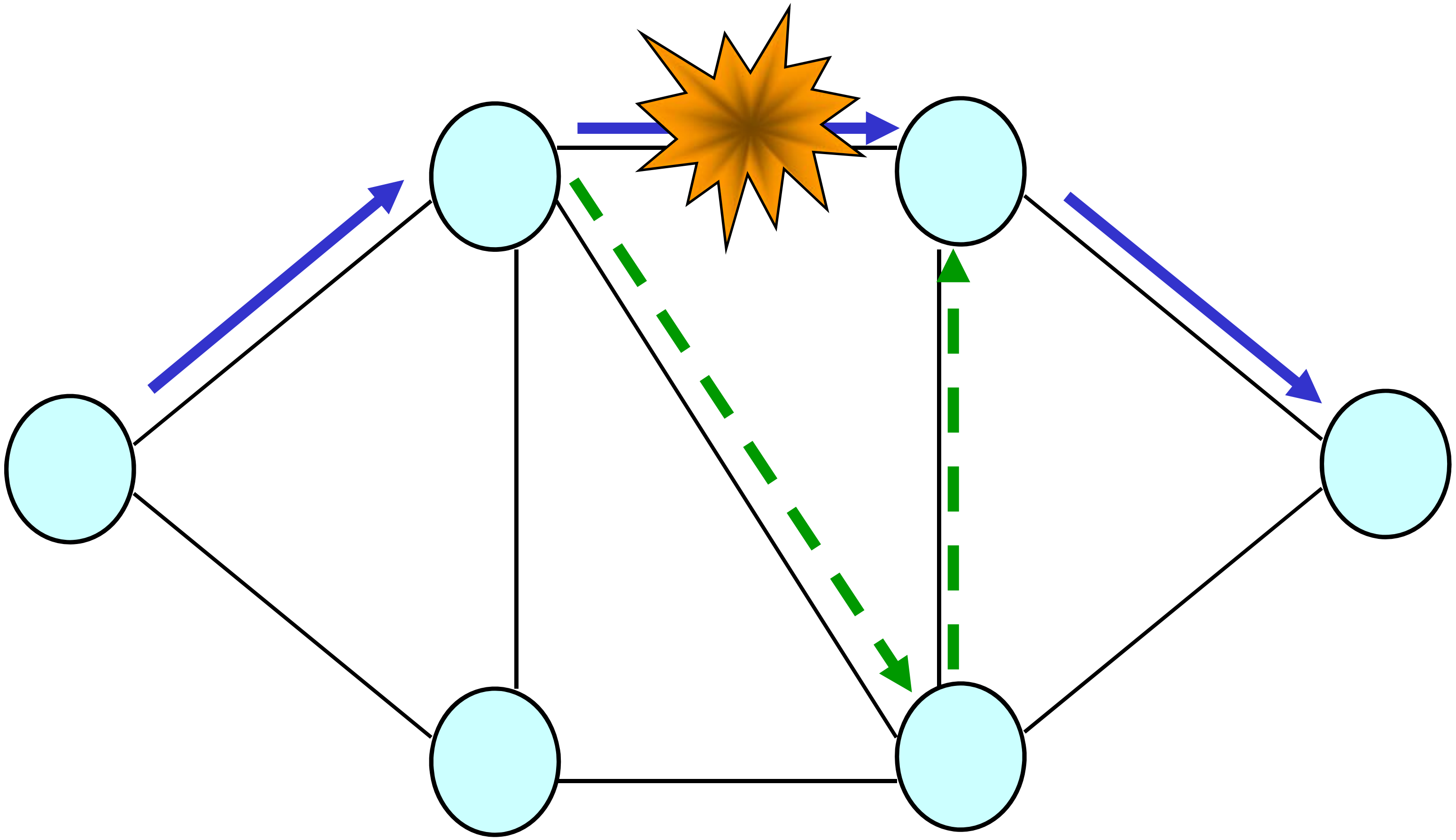
Physical Impairments Constraint

- 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 impariments can be mitigated by regenerating the signal
  - 3R regeneration: Reamplification, Reshaping and Retiming
- Trade-off: cost vs. performance

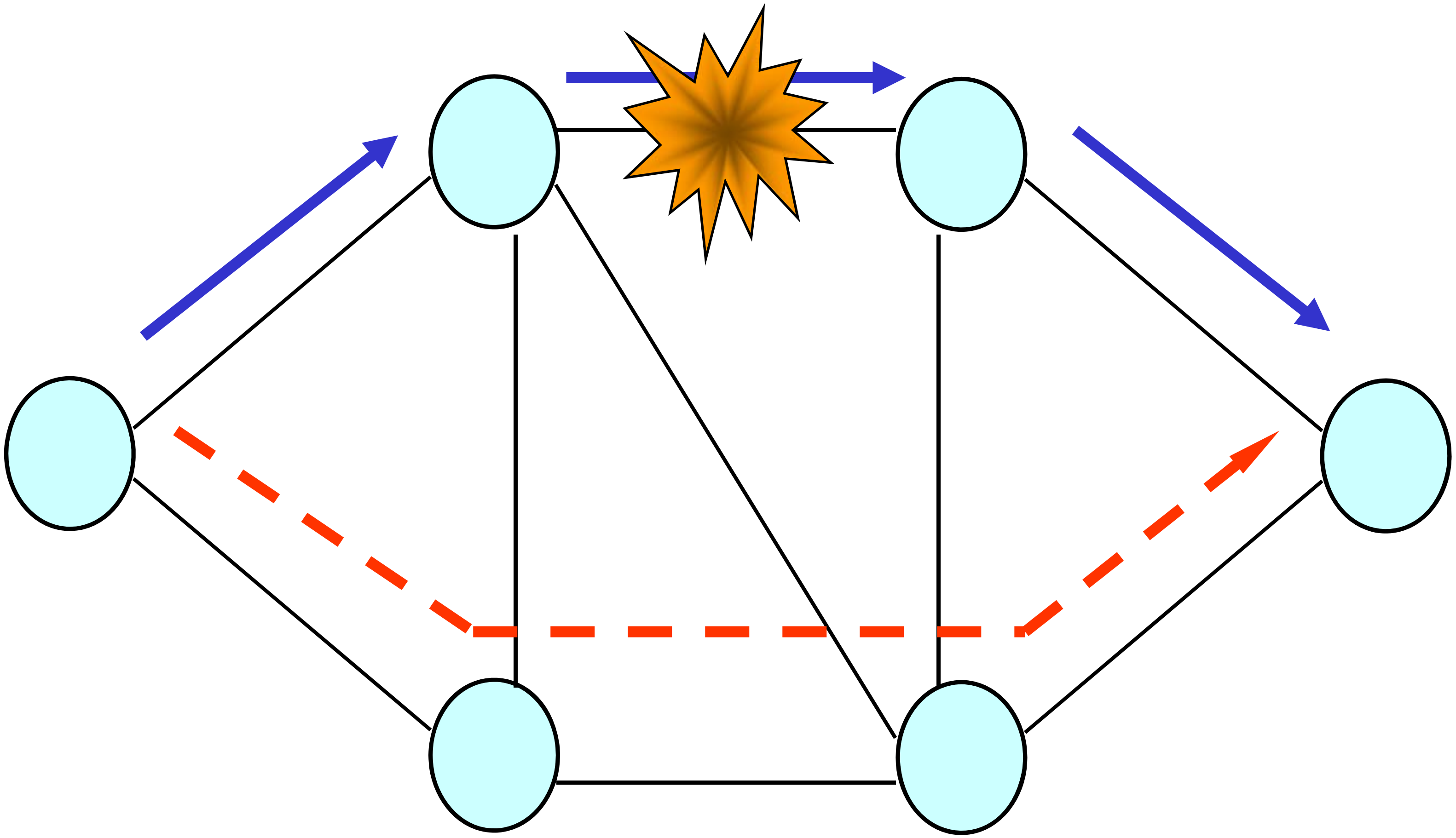
Survivability Constraint

- 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 topology and 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
  - means 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 for some 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, 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 this problem
  - graph coloring algorithms to assign wavelengths to the lightpaths
- Subdividing in sub-problems allows practical solutions of the RWA problem for networks with a *large number of nodes*

ILP Formulation - Definition

- 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 most one lightpath from any source to any destination
  - λ_{sd} = *1* if there is a lightpath from *s* to *d*
  - otherwise λ_{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)

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
- Relax the integrality constraints

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* algorithms

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 {*v1,v2,...,vi-1*} have been chosen and colored
  - Vertex *vi* is chosen to be the vertex with the *maximum degree* among the set of uncolored vertices