IP over WDM Path Routing and Restoration

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Outline

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- Problem formulation
- Categories of solutions
- Discussion
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Introduction

- IP over WDM network
  - Optical-layer protection can provide fast recovery and high scalability
  - Higher-layer recovery provide finer granularity of recovery
- Routing and wavelength assignment (RWA) in WDM network contains
  - Route establishment
  - Wavelength assignment

Problem formulation

- IP over WDM network is modeled as
  - A graph G (V, E, W) where
    - V: set of all nodes
    - E: set of optical links
    - W: set of wavelengths per link
  - Given a request R(*s*, *d*, *b*) from ingress router *s* to egress router *d* requiring bandwidth *b*
    - Find a path and the wavelengths on the links along the path to meet the request requirement

Categories of solutions

- RWA problems can be solved in either
  - Two-stage: wavelength assignment after path routing
  - Joint RWA: consider both in the same time
- Routing problems can be divided into
  - Active/single path routing
  - Backup path routing
  - Disjoint paths routing
- Three generic approaches
  - Integer Linear Programming (ILP) optimization
  - Link-weight based Dijkstra's algorithm
  - Flooding based path searching

Active/single path routing

- Focus on maximizing network efficiency: to accommodate as many requests as possible
  - IWG [1]
  - MOCA [2]: based on MIRA
  - BI [3]
  - MCPS [4]

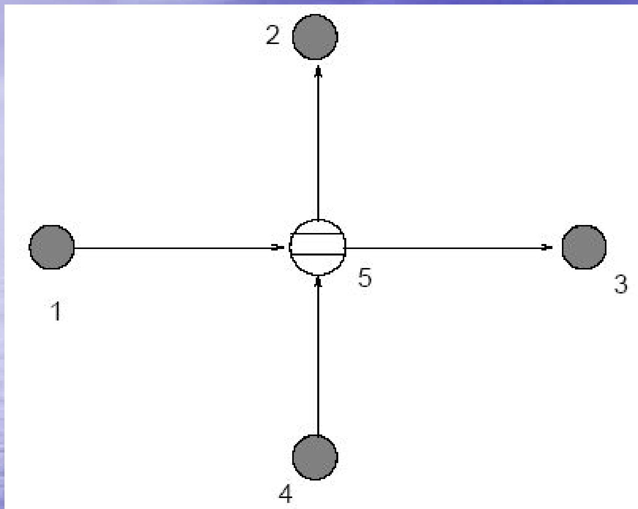
IWG

- IWG: IP over WDM Grooming
- Routing is based on cost function
  - Path_Cost = *N*_links + *P* * *N*_FA-LSP_Links + *Q* * *N*_hops, where
    - *N* links is the number of new optical links
    - *N*_FA-LSP_Links: number of optical links already active
    - *N*_hops: number of O/E/O conversions
    - *P* and *Q*: coefficients to adjust performance
      P<1 implies fostering reuse of established path
      Q>1 means paths with many O/E/O will be avoided

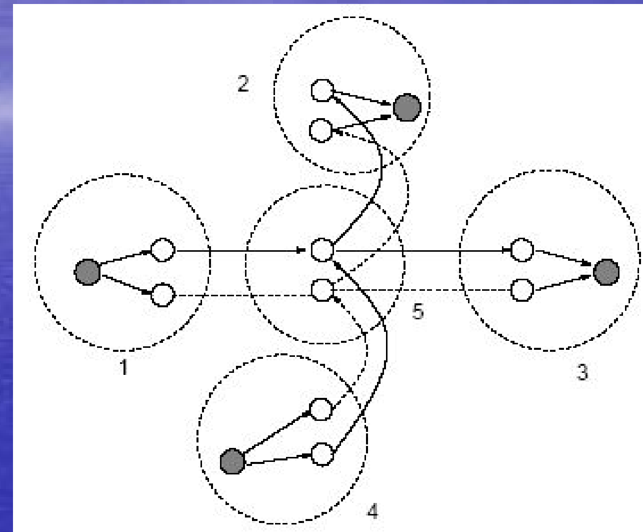
MOCA

- MOCA: Maximum Open Capacity Routing Algorithm
- Idea:
  - Model IP/WDM network with logical links
  - Find the shortest path in a modified network where the link weights are proportional to the criticality of the links
  - Define all links that belong to the minimum cut for an ingress-egress pair to be critical

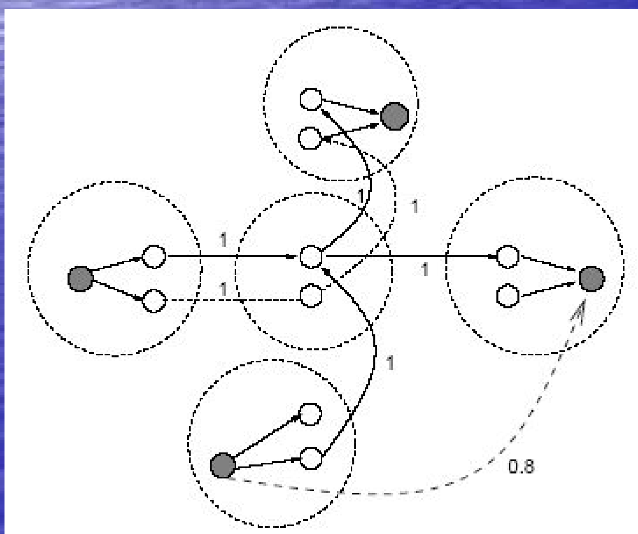
MOCA network model



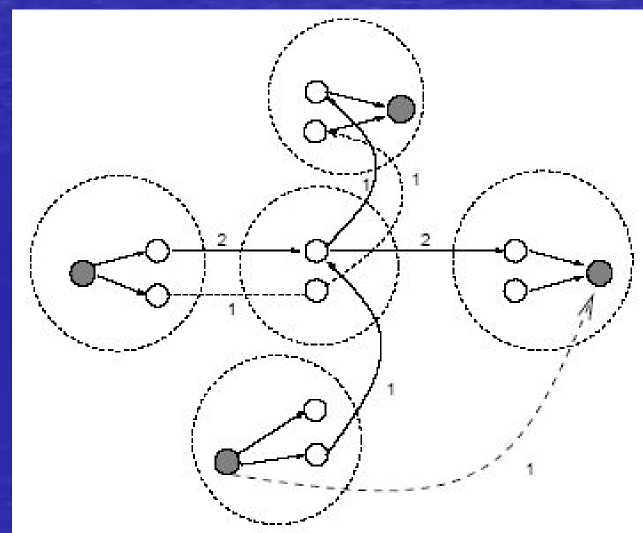
Two wavelength per link



After request (4,3,0.2)



Link weight after 4→3



BI

- BI: Blocking Island paradigm
- Routing is based on
  - Construction of BI hierarchy
  - Route existence check
  - K different weighted shortest routes using path cost function
    - Path_Cost = N_links + P * Active_Lightpaths
  - Pick the route with minimum splitting cost

MCPS

- MCPS: Multiple Constraints Path Selection
- Idea:
  - Each node maintains local network state info.
  - Routing is based on path information update by flooding
  - Select the best path at destination according to networks' operational criteria

Backup path routing

- Active path is assumed to be established first based on Dijkstra's algorithm
- Focus on minimizing reserved bandwidth for all backup paths
  - SPR (Shortest Path Restoration)
  - PIR [6]
  - FIR [5]: enhance PIR
  - DLB [7]

Backup path routing

- PIR: Partial Information Restoration
  - Idea: weight each link using an estimate of additional bandwidth that needs to be reserved if a particular restoration path is selected
  - After service path *Ps* is selected, the source node calculate maximum service bandwidth *M* over all links along the service path
  - Assign a weight to each link in the network

$$w[i] = \begin{cases} \min(b, M+b-R[i]) \cdot W[i], & \text{if } M+b-R[i] > 0 \text{ and } i \notin Ps \\ \varepsilon, & \text{if } M+b-R[i] \leq 0 \text{ and } i \notin Ps \\ \infty, & \text{if } i \in Ps \end{cases}$$

Backup path routing

- FIR: Full Information Restoration
  - Idea: after selecting service path *Ps*, the source node collects the array *T[i]*, the maximum bandwidth needed on link *i* if any of the links along *Ps* fails
  - Assign a weight to each link in the network

$$w[i] = \begin{cases} \min(b, T[i]+b-R[i]) \cdot W[i] & \text{if } T[i]+b-R[i]>0 \\ & \text{and } i \notin Ps \\ \varepsilon & \text{if } T[i]+b-R[i] \leq 0 \\ & \text{and } i \notin Ps \\ \infty & \text{if } i \in Ps. \end{cases}$$

Backup path routing

- DLB: Decentralized Local Backup LSP calculation
  - Given the primary path P={N_{x0},N_{x1},…,N_{xn}}
  - For each node along the primary path, each link is assigned a cost K_{ij}

if we protect against node failure

$$K_{ij} = \begin{cases} Inc_{ij}(F,bw) & \text{if } i \neq F \wedge j \neq F \\ & \wedge Inc_{ij}(F,bw) \neq 0 \\ \varepsilon & \text{if } i \neq F \wedge j \neq F \\ & \wedge Inc_{ij}(F,bw) = 0 \\ \infty & \text{if } i = F \vee j = F \end{cases}$$

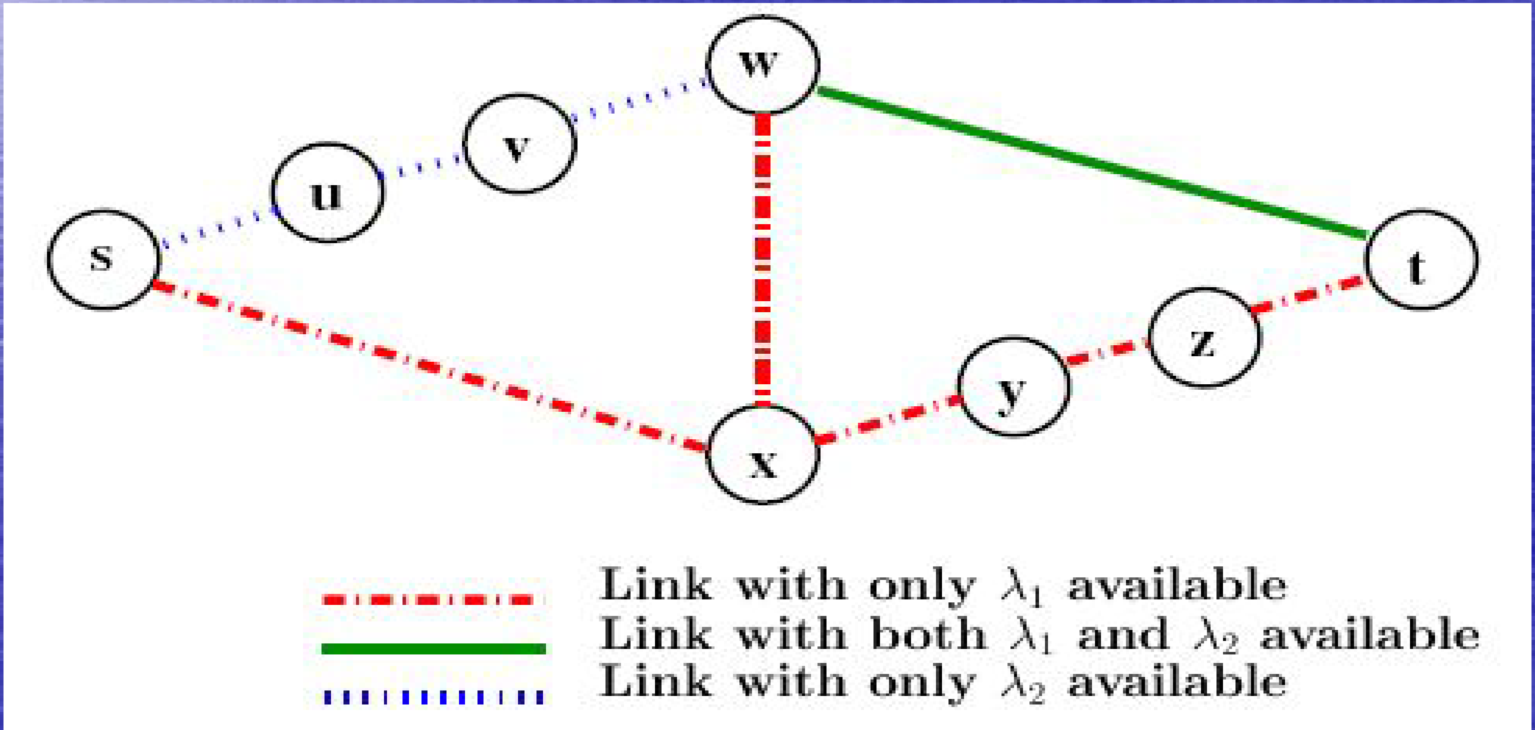
- if we protect against link failure

$$K_{ij} = \begin{cases} Inc_{ij}(F,bw) & \text{if } (i \neq N_{x_k} \vee j \neq F \\ & \wedge Inc_{ij}(F,bw) \neq 0 \\ \varepsilon & \text{if } (i \neq N_{x_k} \vee j \neq F \\ & \wedge Inc_{ij}(F,bw) = 0 \\ \infty & \text{if } i = N_{x_k} \wedge j = F \end{cases}$$

  - $Inc_{ij}(F,bw) = R_{ij}' - R_{ij}$, increased reserved bandwidth

Trap problem

- Active path first (APF) heuristic may lead to the so-called "trap problem"
  - Fail to find link-disjoint paths when such a pair exists



Disjoint path routing

- Find link/node-disjoint paths
  - SPP [8]: min-weight disjoint path
  - MIRR [9]: based on MIRA
  - APFE [10]: enhanced APF
  - COLE [11]

MIRR

- MIRR: Minimum Interference Restorable Routing algorithm
- Idea
  - Compute the maximum 2-route flows
  - Compute the 2-critical link sets C_{sd}
  - Compute the criticality indices *w(l)* as link weight of link *l*
  - Use SPP to find shortest disjoint paths based on link weight *w(l)*
  - Choose one as active path, the other as backup path

APFE

- APFE: enhanced Active Path First
- Idea:
  - Find AP (Active Path) using minimum number of links
  - Assign a cost of infinity for every active or reserved channel, assign a cost of M (very big number) for every free channel on a link of AP, assign a cost of 1 for every other free channel
  - Find a minimum cost BP (Backup Path)
  - If AP and BP are not link-disjoint, use the BP as active path and repeat until AP and BP are link disjoint

COLE

- COLE: Conflicting Link Exclusion
- Idea
  - Minimize the cost of AP (Active Path)
  - Find the shortest AP in the network
  - Identify the conflicting link set T
  - Divide the problem P into sub-problems in the form of P(I, O) based on T; the sub-problem without link-disjoint path pairs is further divided
  - Compare link-disjoint path pairs found in each sub-problem, choose the one with shortest AP

Discussion

<table>
<tr><td>Problems</td><td>Single cost</td><td colspan="4">Dual cost</td></tr>
<tr><td>Min-Max</td><td>NPC [9], [10]</td><td colspan="4">NPC [9], [10]</td></tr>
<tr><td>Min-Min</td><td>NPC</td><td colspan="4">NPC</td></tr>
<tr><td rowspan="4">Min-Sum</td><td rowspan="4">Polynomial (SPP [4], [5])</td><td colspan="3">Ordered (MSOD)</td><td>Arbitrary</td></tr>
<tr><td colspan="2">Uniform (MSOD-U)</td><td>Non-uniform</td><td rowspan="3">NPC [8]</td></tr>
<tr><td>Directed</td><td>NPC [7]</td><td rowspan="2">NPC [6]</td></tr>
<tr><td>Undirected</td><td>NPC</td></tr>
</table>

Ref [11]

- Active/single path routing considers WDM wavelengths and logical network thus better utilize network resource, but doesn’t consider backup path simultaneously
- Backup path routing after active path minimizes reserved bandwidth but may encounter trap problem
- Disjoint path routing considers optimized disjoint path for restoration, but doesn’t consider WDM layer multi-wavelength effect

Discussion

- Design goal of IP/WDM routing
  - WDM physical path disjointness
  - With minimum interference to maximize the acceptable requests
  - Consider both dedicated and shared bandwidth among all backup paths
- Bandwidth sharing may not be allowed
  - Link-state information for backup paths not available
  - 1+1 redundancy
  - After failure is fixed, traffic will not switched back to the primary path

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