Multicasting with Physical Layer Constraints in Metropolitan Optical Networks with Mesh Topologies

Tania Panayiotou

KIOS Research Center for Intelligent Systems and Networks
Dept. Electrical and Computer Engineering
University of Cyprus

18th April 2011

Outline

- Introduction

- Physical Layer Impairments

- Multicasting in Transparent Networks

- Multicast Protection

- Conclusions and Future Work

Introduction-
Optical Networks

- Optical Network:
  - Telecommunications network with transmission links that are optical fibers, "intelligent" optical switching nodes, and with an architecture that is designed to exploit the unique features of fibers.

- Advantages of Optical fibers:
  - Huge bandwidth capability (e.g., 25 THz)
  - Low attenuation loss,
  - Extremely low bit-error rates,
  - Low cost,
  - Light weight,
  - Strength and flexibility,
  - Immunity to noise and electromagnetic interference
  - Security and privacy

Introduction-
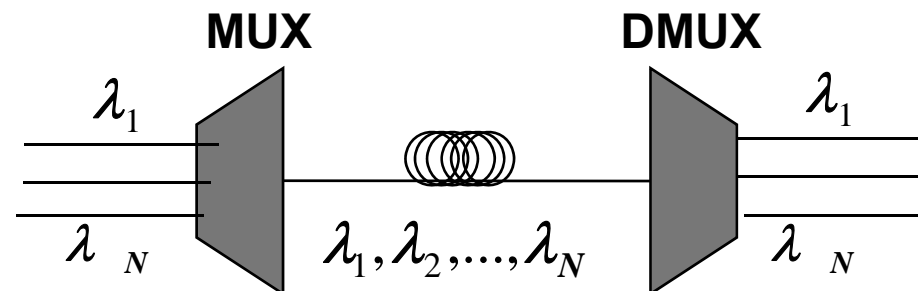## Evolution of Optical Networks

- **Point-to-point Networks:**
  - Fiber transmission links were used as a direct substitute for copper, with the fibers terminating on electronic equipment.
  - Due to electornic equipment only a small fraction of the potentially available bandwidth could be used.

- **WDM Networks:**
  - The capacity of a fiber link is dramatically increased.
 - A number of wavelengths is multiplexed for simultaneous transmission within the same fiber.

MUX   **DMUX**

λ_1 λ_1

λ_N $\lambda_1, \lambda_2, ..., \lambda_N$ λ_N

Introduction-
Optical Networks

- ## Optical Network:
  - Telecommunications network with transmission links that are optical fibers, "intelligent" optical switching nodes, and with an architecture that is designed to exploit the unique features of fibers.

- ## WDM Optical Network:
  - The capacity of a fiber link is dramatically increased.
  - A number of wavelengths is multiplexed for simultaneous transmission within the same fiber.

MUX **DMUX**

λ_1 λ_1

λ_N $\lambda_1, \lambda_2, ..., \lambda_N$ λ_N
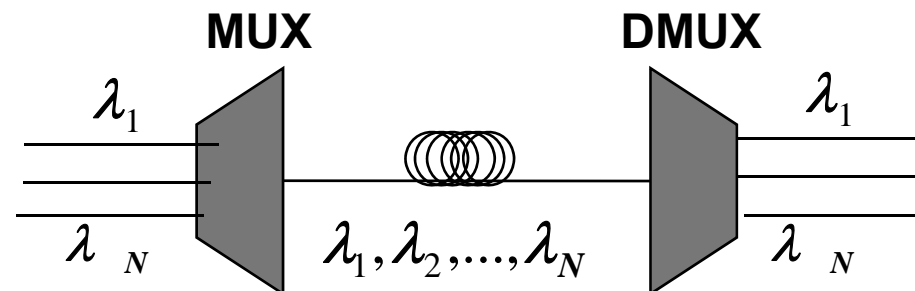
Introduction-
Evolution of Optical Networks

- **A typical WDM network cable contains:**
  - More than 100 fibers which are used as bidirectional pairs.
  - Each fiber can utilize 32 to 64 wavelengths of 0.8 nm spacing covering a range of 1260 - 1675 nm
  - Each wavelength transmits at rates of 10 Gbps.

- **A denser WDM network:**
  - 80 to 160 wavelengths per fiber
  - Each wavelength transmits at rates of 40 or 100 Gbps
  - Future DWDM networks expected to increase to 320 wavelengths per fiber.

Introduction-
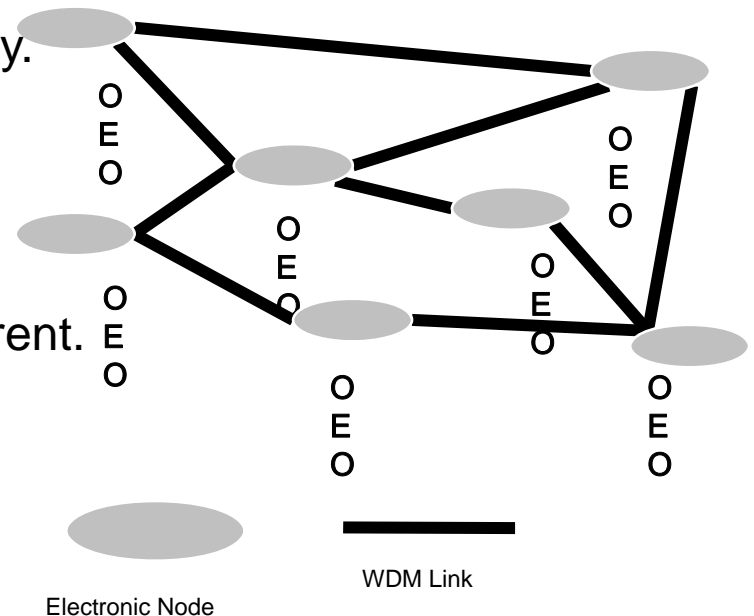## Evolution of Optical Networks

a. Opaque Network:

- All switching and processing of the data is handled by electronic switch fabrics.
- The optical signal carrying traffic undergoes an optical-electronic-optical (OEO) conversion at every switching node.

q Ads

- Offers full digital regeneration of the signal (re-shape, re-time, re-amplify).
- Any incoming stream can be switched to any available wavelength on any fiber.
- There is no need for end-to-end traffic engineering.
- The control and management of the network is easy.

q Cons

- Limitations in signal bit rate due to electronics.
- Costly network elements.
- Bit rate/protocol/modulation format are not transparent.

Electronic Node

WDM Link

Introduction-
Evolution of Optical Networks

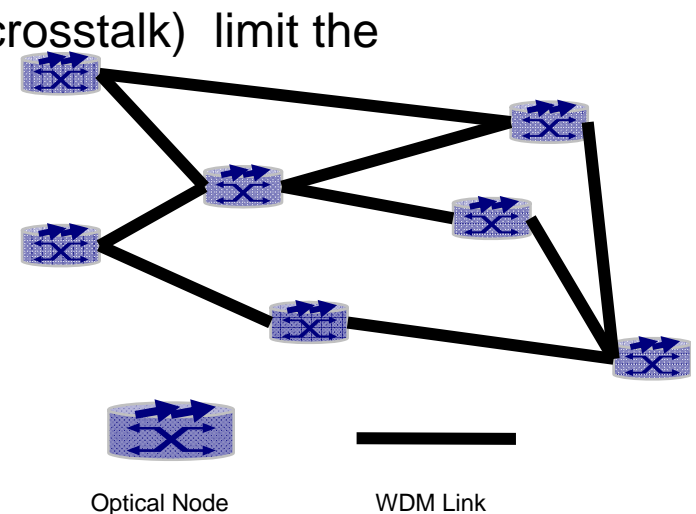**b.**   **Transparent Network:**

- Switching and processing of the data is moved to the optical part of the network

q   **Ads**

- Eliminates the expensive O-E-O conversions.
- Signal is transparent to bit rate, signal format, and protocols.
- Provides high bit rates.

q   **Cons**

- Physical layer impairments (e.g. noise, dispersion, crosstalk) limit the transmission reach of optical signals.
- End-to-end engineering of the traffic is required.
- Difficult control and management functions.

Optical Node   WDM Link

Introduction-
Transparent MANs

- **Metropolitan Area Network (MAN)**
  - Spans a metropolitan area, typically tens to a few hundred kilometers.
  - Signal attenuation could be overcome using optical amplifiers, as needed.
  - The noise that these amplifiers introduce can be managed due to the relatively short distances, (short amplifier spans).
  - No dispersion issues due to short fiber lengths
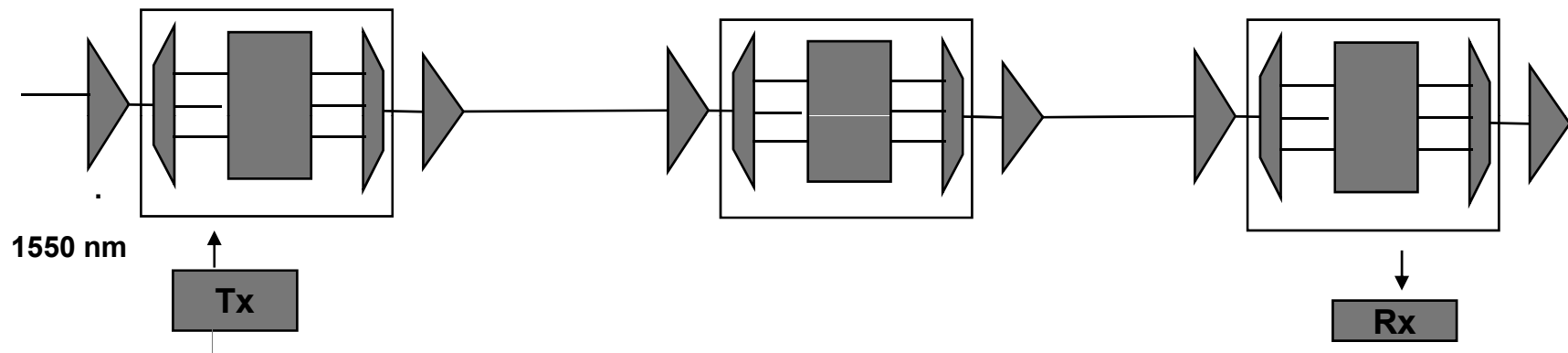 - High optical signal to noise ratio can be preserved.

Long-haul

Metropolitan

Access

Users
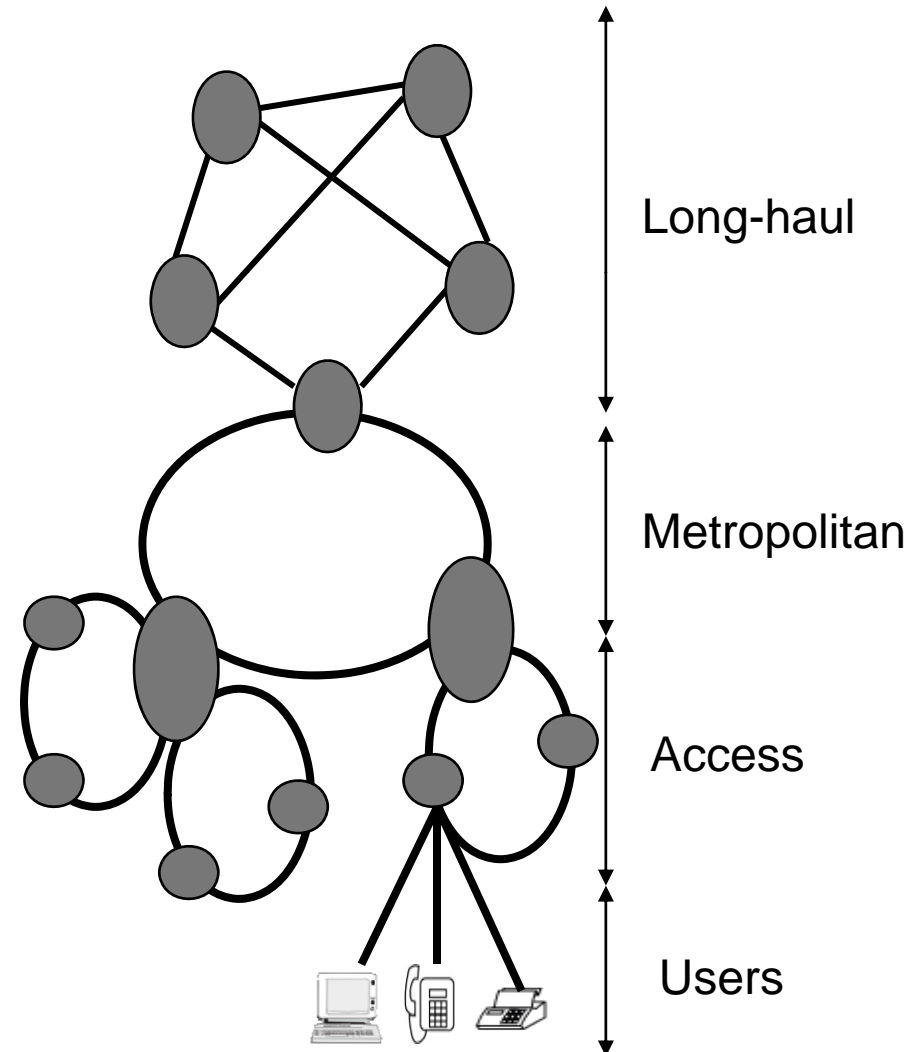
QoT-
Physical Layer Impairments

- **Quality of Transmition (QoT):**
  - The signal must be detectible to the receiver end

1550 nm

Tx

Rx

- **QoT is affected by:**
  - Amplifier Spontaneous Emission (ASE) Noise
  - Incoherent crosstalk
  - Fiber nonlinearities (FWM, SFM, XFM, ….)
  - Dispersion (CD, Intermodal dispersion, PMD)
  - Component Aging
  - Attenuation
  - PDL/PDG, etc

QoT-
Physical Layer System Modeling

•Physical Layer Impairments must be taken into account during the provisioning phase of request.

•Modeling of the physical layer is based on the physical path Q factor that is used to calculate the BER of the system.

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}, where$$

$$\sigma_i^2 = \sigma_{th}^2 + \sigma_{shot-i}^2 + \sigma_{ASE-ASE}^2 + \sigma_{s-ASE-i}^2 + \sigma_{RIN-i}^2 + \sigma_{ASE-shot}^2$$

•This approach assumes a baseline system with various receiver noise terms as well as ASE noise.

•A Q-budgeting approach is used to include:

- • Incoherent crosstalk channel penalty budgeted at 0.8dBQ.
- • Fiber nonlinearities factored at 1 dBQ.
- • PMD budgeted at 0.2 dBQ.
- •Optical filter narrowing penalty budgeted at 0.4 dBQ.
- • Safety margin of 1dBQ included for component aging

QoT-
Physical Layer System Modeling

• This approach enables a network designer to calculate the impact of physical layer effects, in the design of an optical network without the computationally complex time-domain approach.

• A Q threshold is set for a specified BER and the decision to provision a given multicast connection relies on whether we are above or below the threshold.

$$BER \ = \frac{1}{2} erfc \left(\frac{Q}{\sqrt{2}} \right) \approx \frac{e^{\frac{-Q}{2}}}{Q \sqrt{2\pi}}$$

• Q threshold set at 8.5 dBQ which corresponds to a BER of 10^{-12}

Multicasting-
Introduction

- **Multicast Applications:** interactive distance learning, video-conferencing, distributed games, movie broadcasts from studios, etc.

- **Multicast connection:**
    - One-to-many connectivity
    - Light from one source must reach many destinations.
    - In transparent optical networks optical splitters must be used inside the nodes to split the incoming signal to multiple output ports.
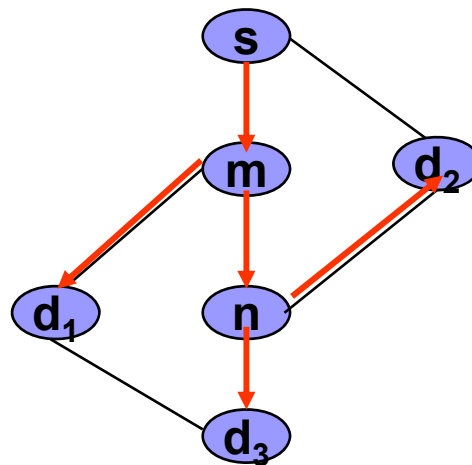
**Light-tree**

Multicast Capable Architectures
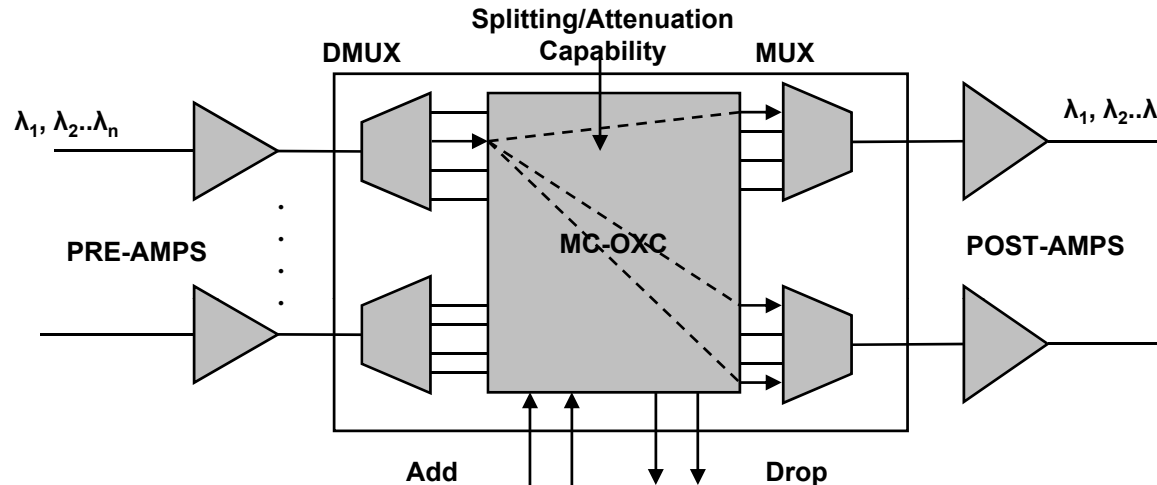
- (MxM) transparent node supporting n wavelengths:
  - The splitter equally splits the optical signal into M parts, where M is the number of outgoing (as well as incoming) ports.
  - $P_{Out} = 1/M\ P_{in}$.
  - Amplifiers are required to re-amplify the signal.
  - ASE noise is added to the signal
- These power considerations along with other physical layer impairments must be taken into account to:
  - The design and engineering of transparent optical nodes.
  - The multicast routing algorithms.

Multicast Capable Architectures

- **Several Multicast Capable Node architectures and Engineering Designs were investigated to determine the impact of the physical layer :**
    a. Fixed Txs/Rxs
    b. Tunable Txs/Rxs
    c. Tunable Txs/ Fixed Rxs
    d. Fixed Txs /Tunable Rxs
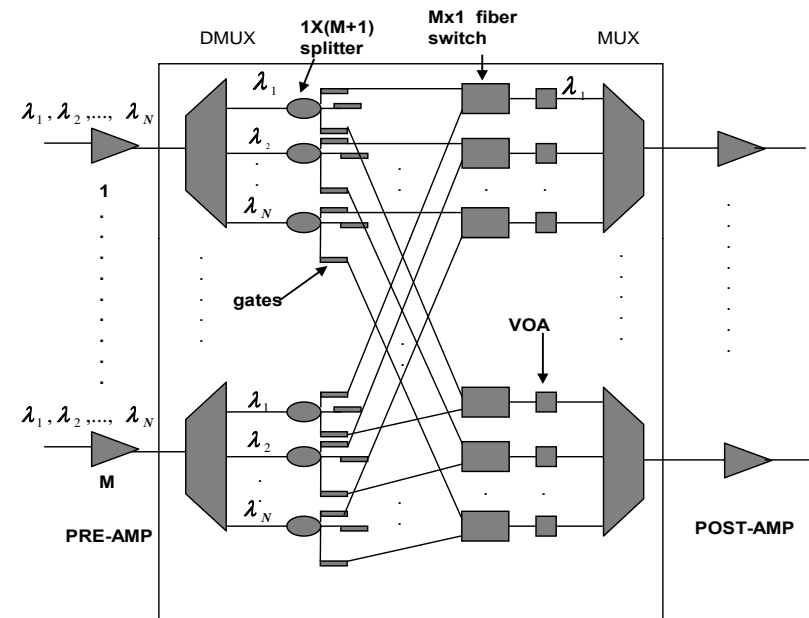
- **Component Insertion Loss**

| Component	Mux/Dmux	VOA	Splitter	SOA	Switch
Losses in dB	3	0.5	10*log(fan out)	0.6	1

Multicast Capable Architectures

- **Worst case scenario :**
  - The maximum insertion loss a signal encounters passing through the maximum degree node.

- **Components:**
  - **Amplifiers (EDFAs):**
    - Post-Amplifiers: Compensate for the node losses and their gain is set for the worst case scenario with an output power of +7dBm.
    - Pre-Amplifiers: Preceding the fiber span to compensate for the fiber losses that are set at 0.3dB/Km. Output power is +7dBm.
    - Noise Figures are based on realistic device specifications.

Gain in dB	NF
G<13	7
13<G<15	6.7
15<G<17	6.5
17<G<20	6
G>20	5.5

- **Variable Optical Attenuators (VOAs):** Required to equalize the individual total input powers to the post amplifiers and signals are attenuated for the worst case scenario.

Multicast Capable Architectures
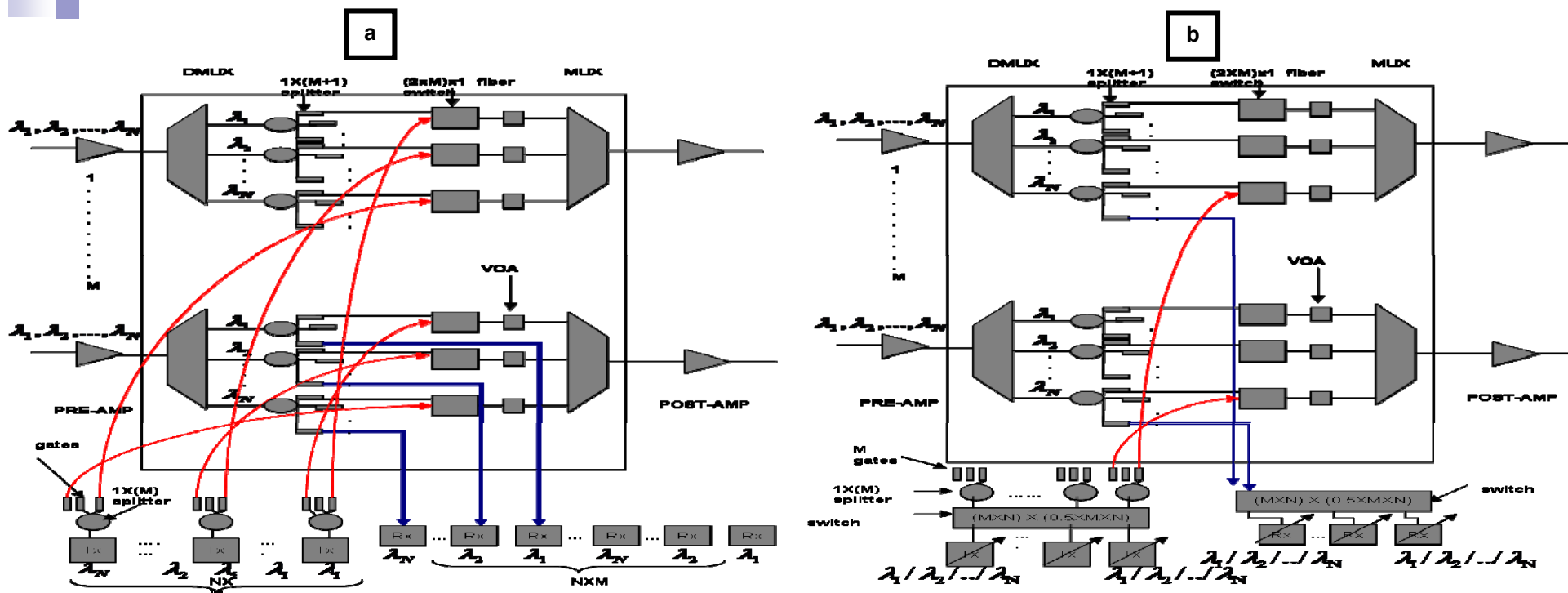
- **Node Architectures:**
  a. **Fixed Tx/Rx :** The number of transmitters/receivers for each source/destination node is equal to the number of wavelengths times the degree of the node.

  b. **Tunable Tx/Rx :** The number of transmitters/receivers for each source/destination node is equal to the number of wavelengths.

Multicast Capable Architectures

- **Tunable Tx/Rx case:**
  - Switches added at the Tx/Rx can add/drop 50% of the total number of wavelengths in the network.
  - The size of the switches is proportional to the number of wavelengths and the fan-out of the node.
  - Insertion loss of switches depends on their size.

Size	Switches Losses in dB
X<25	1
25<X<36	1.5
36<X<56	2.2
56<X<68	3
68<X<80	3.7
80<X<100	4.5
X>100	5

Multicast Routing Algorithms

❑ Several multicast routing algorithms are used for the simulations.

1. **Minimum Steiner tree heuristic (MST):**
   - Finds the minimum cost tree.
   - The Steiner tree problem is NP-complete when the multicast group has more than two members.
   - Several heuristics have been developed for the Steiner tree problem.

2. **Optimized Shortest Paths Tree (OSPT):**
   - Aims at decreasing the number of the links utilized by the tree.

Step 1	For every destination node of the multicast session, repeat Steps 2 and 3
Step 2	Find the minimum-cost path from source to the destination node.
Step 3	Update cost = 0 for all the links included in the already-found path.
Step 4	Merge all the minimum-cost paths together and construct a multicast tree.

Multicast Routing Algorithms

3. **Balanced Light-Tree (BLT):**

   - Takes power budget constraints into consideration.
   - Aims at minimizing the average splitting losses of the tree.
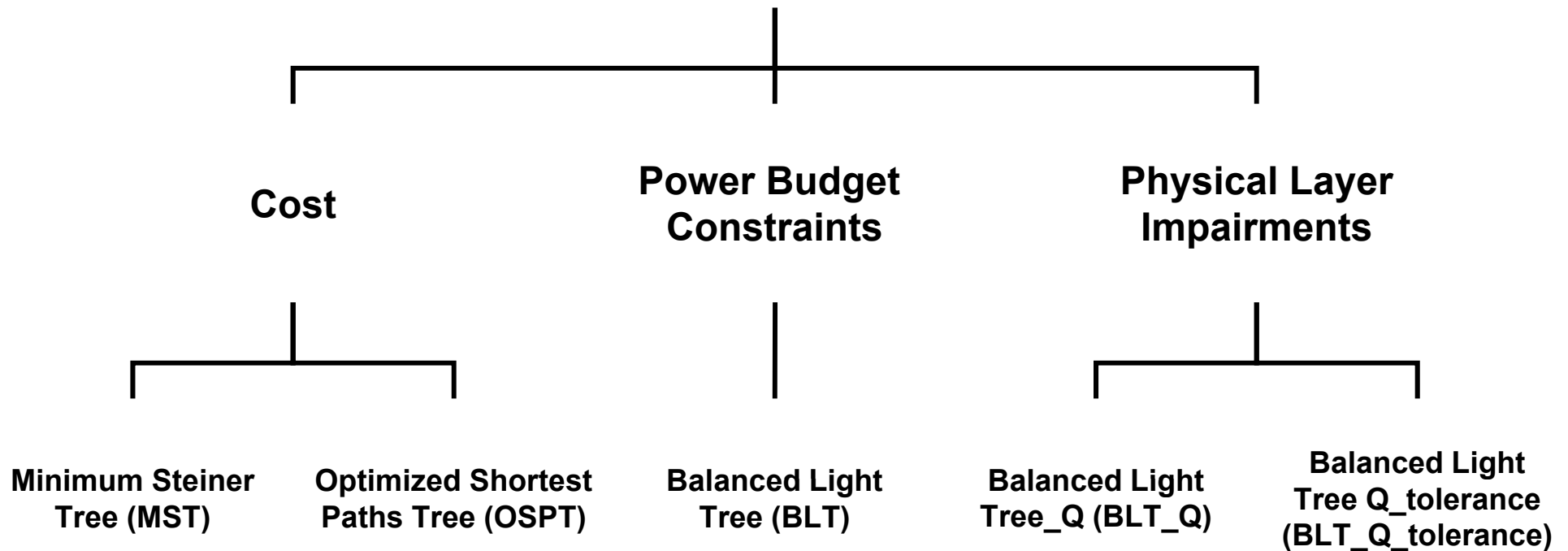   - Balancing procedure:
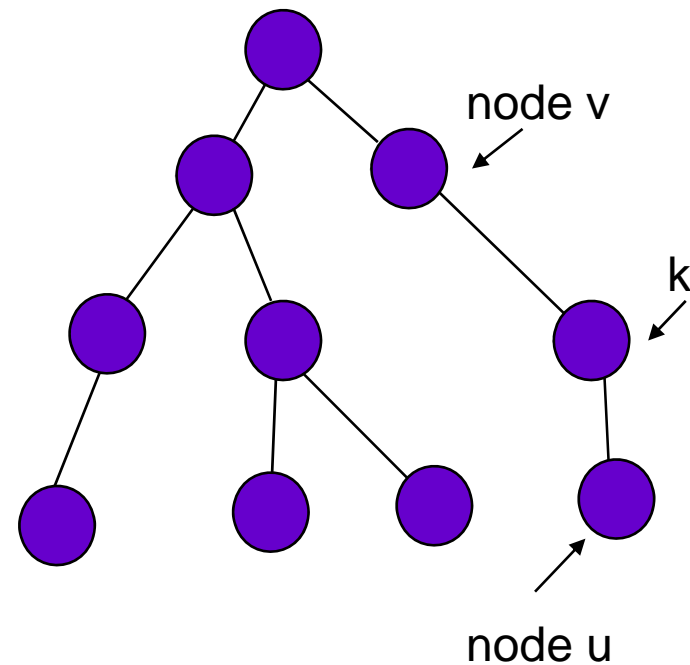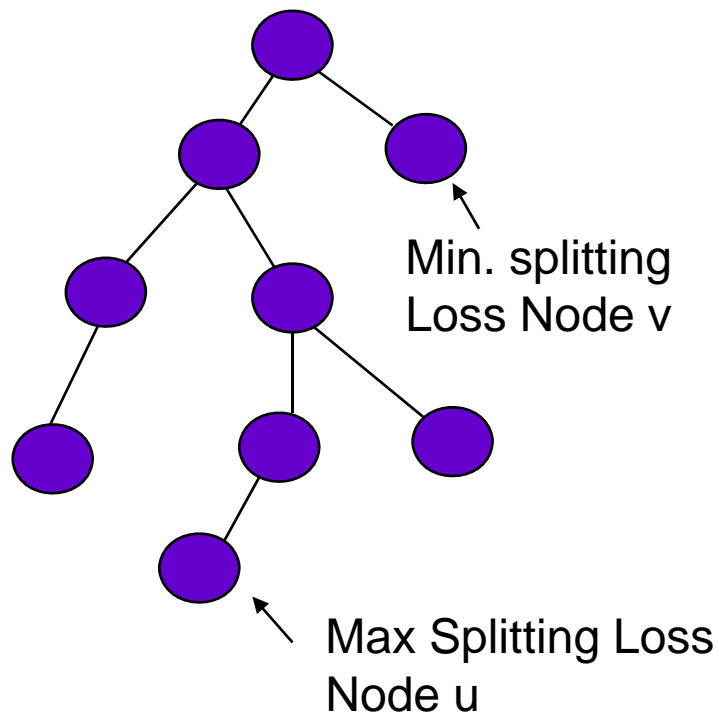
Min. splitting Loss Node v

Max Splitting Loss Node u

node v

k

node u

Multicast Routing Algorithms

❑ Several multicast routing algorithms are used for the simulations
.

**Multicast Routing
Algorithms**

Cost

**Power Budget
Constraints**

**Physical Layer
Impairments**

**Minimum Steiner
Tree (MST)**

**Optimized Shortest
Paths Tree (OSPT)**

**Balanced Light
Tree (BLT)**

**Balanced Light
Tree_Q (BLT_Q)**

**Balanced Light
Tree Q_tolerance
(BLT_Q_tolerance)**

Multicast Routing Algorithms

❑ **BLT_Q :** Aims at maximizing the average Q-value of the tree.

   ❑ Balancing procedure:

Max Q
node v

Min Q
node u

node v

k

node u

❑ **BLT_Qtolerance:** improves on the BLT_Q by maximizing the Q-factor only at those destination nodes that the Q value below the Qtolerance value.

Multicast Routing Algorithms

- The balancing part of the algorithm terminates when two successive iterations fail to increase the minimum Q-factor.

- Tends to create shallower trees increasing the Q-value at the destination nodes and increasing the total number of the links in the tree.

❑ **BLT_Q$_{tolerance}$**:

- Aims at maximizing the average Q-value of the tree but keeping the total number of the links in the tree as low as possible.

- Considering that the tolerance Q-factor is k, this algorithm maximizes the Q-factor only at those destination nodes that the Q-factor is below k.

- Terminates if the Q-value of all destination nodes in the tree is above k, or if two successive iterations fail to increase the minimum Q-factor.

Simulation Parameters

❑**Network :**

• 50 nodes, 196 bidirectional links, average node degree of 3.92 ,maximum node degree of 6, an average distance between the links of 60 Km.

❑ **Dynamic System:**

• Poisson arrivals

•Exponentially distributed holding times with a unit mean.

•100 Erlangs load.

•For each run 5.000 requests were generated for each multicast group size.

•The results for each simulation point were obtained as the average of 5 runs .

❑In the **MC-RWA algorithm:** Multicast request is **accepted** if

•A route and wavelength assignment can be found.

•The Q-factor for each path on the tree is above the predetermined Q threshold.

•There are available Txs and Rxs for that connection,

Otherwise **blocked.**

Simulation Parameters

- To determine the Q-value for each multicast call, a baseline system Q-value is first calculated based on the signal and noise terms, assuming:
  - 10 Gbps bit rate
  - a pre-amplified photodiode
  - 32 wavelengths in each fiber spaced at 100 GHz.
  - +5dBm power launched into the system .

- To include other common physical layer impairments a Q-budgeting approach is used that starts from the Q-value for the baseline system and budgets Q-penalties for the various physical layer impairments present.

- Each Q-penalty is calculated as the Q (in dB) without the impairment in place minus the Q (in dB) with the impairment present.

Impairment Aware - MC-RWA Algorithm

- For each multicast connection request, the algorithm first solves the multicast routing problem and then assigns a wavelength for that tree (first-fit algorithm).

    - **Blocked:** There is no available wavelength for the entire tree.
    - **Accepted:**
        - A route and wavelength assignment can be found.
        - The Q-factor for each path on the tree is above the predetermined Q threshold.
        - There are available Txs and Rxs for that connection
    - If the physical impairments constraints are not met, a new wavelength assignment is implemented and the heuristic is repeated until no new wavelength assignment is possible.

Simulation Results


Fixed Txs/Rxs
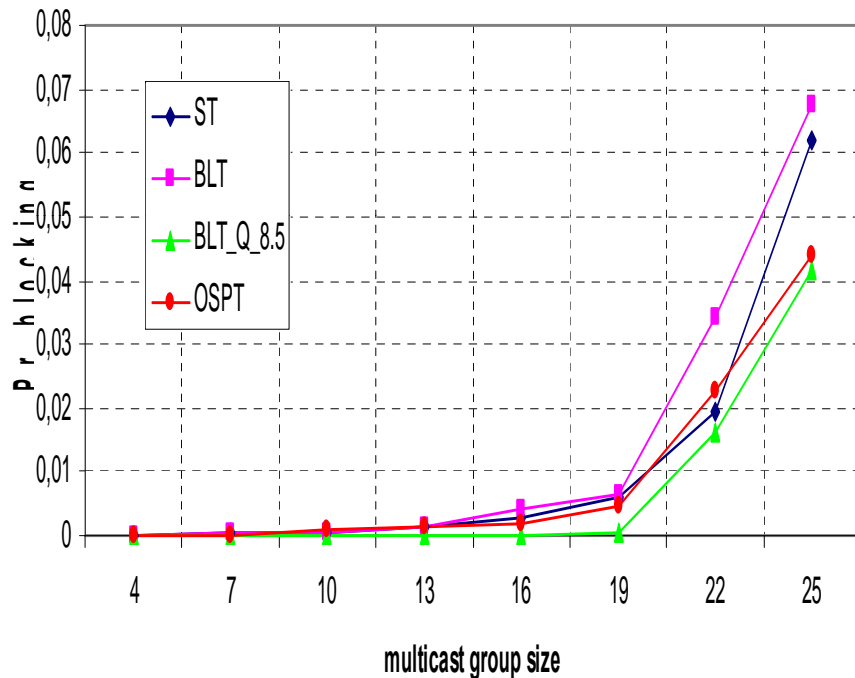
Tunable Txs/Rxs
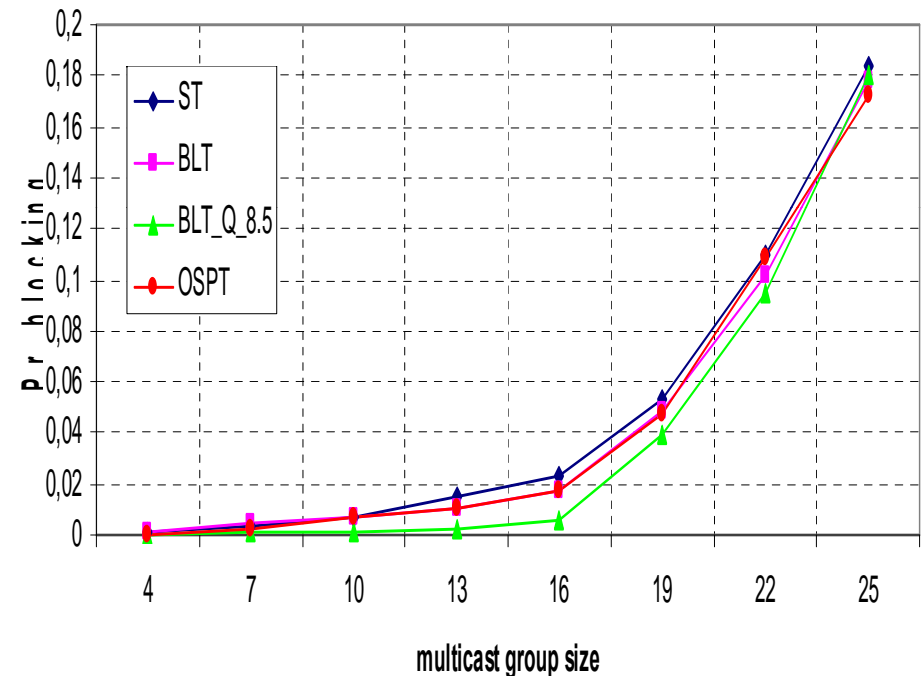
- **BLT_Q$_{8.5}$** that takes the PLIs into account performs the best compared to the other multicast routing algorithms for both cases,
- **Pr. Blocking** in tunable case is increased compared to the fixed case, since in fixed Txs/Rxs case a larger number of Txs/Rxs is used.

Multicast Protection

- It is important that the multicast traffic is not only routed efficiently through the optical network but it is protected against any possible failures in the network.

- Fiber cuts occur often and are the predominant form of failure.

Backup path

source

d1

d2

d3
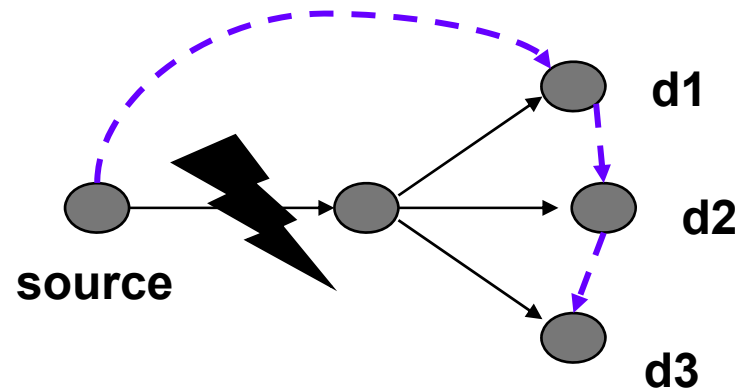
- A fiber cut (link failure) may jeopardize the entire multicast session

Multicast Protection

- **Objective:** Ensure that every affected destination can receive the information from the source via the backup path(s) after the failure.

Protection tree:
- Protection
  - Dedicated
    - Tree-Based
    - Path-Based
    - Segment-Based
  - Cross-Shared
    - Tree-Based
    - Path-Based
    - Segment-Based
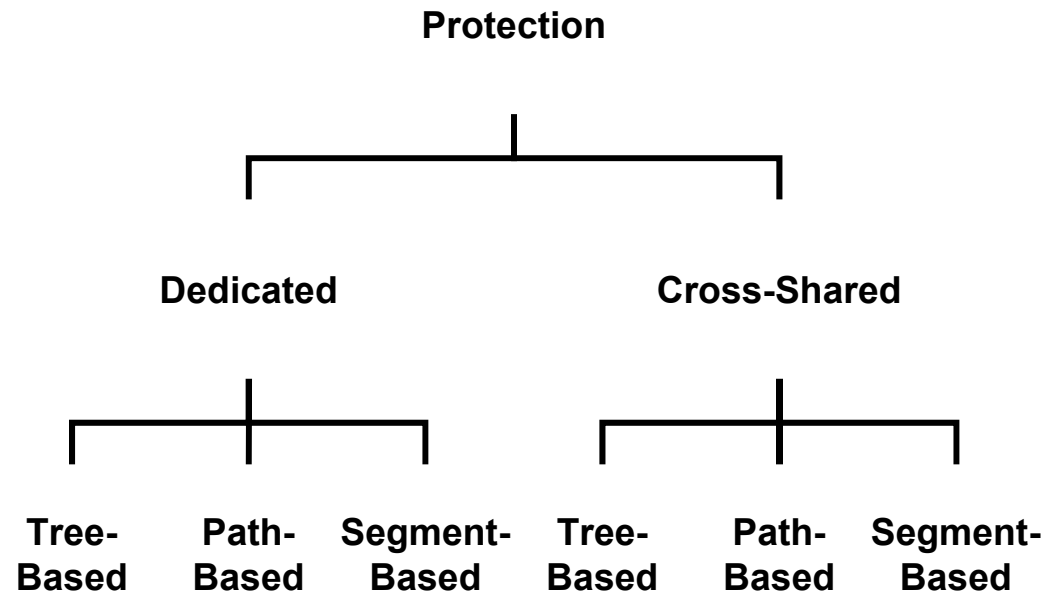
Dedicated: Resources along the backup path(s) are dedicated for only one connection and are not shared with the backup paths for other connections.

Cross-Shared: Resources along a backup path may be shared with other backup paths for other connections.
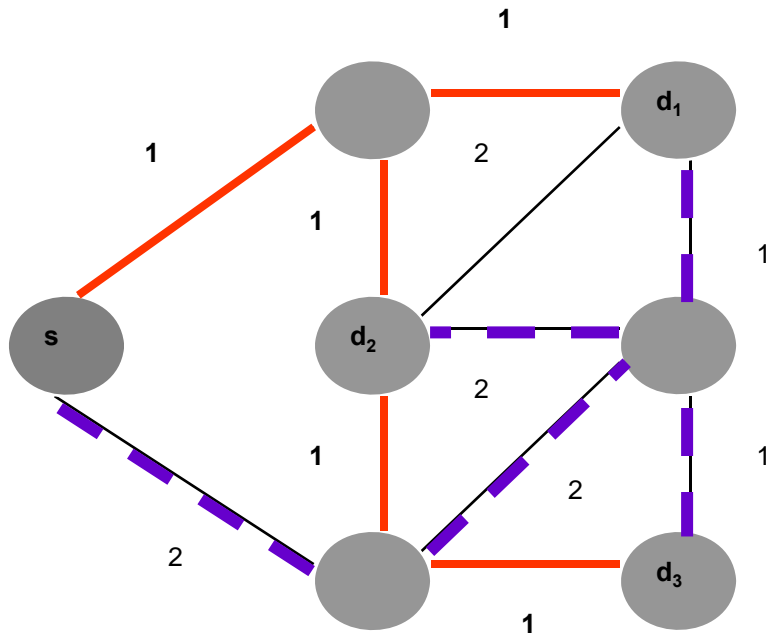
Multicast Protection-
Tree-based

Link-Disjoint:

1. A primary tree.

2. A link-disjoint backup tree.

Arc-Disjoint:

1. A directed primary tree.

2. A directed arc-disjoint backup tree

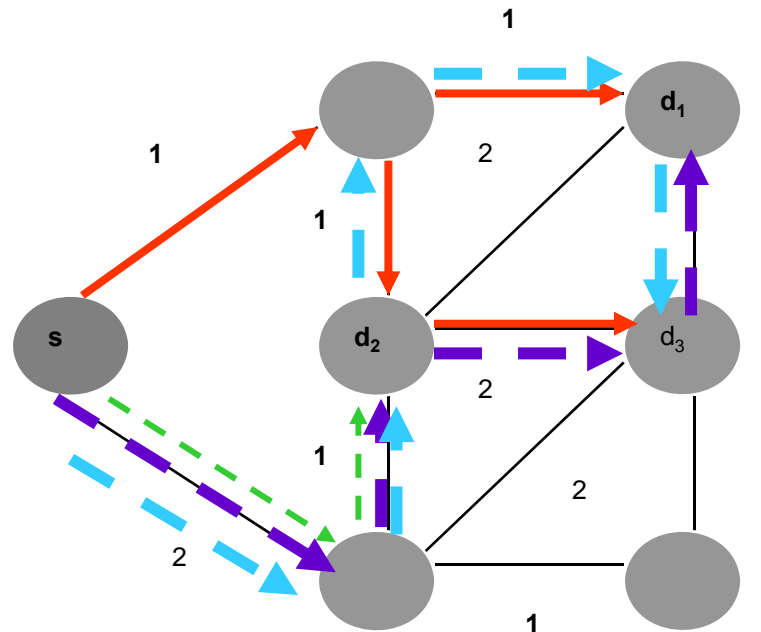**Redundant capacity reaches the 100 %.**
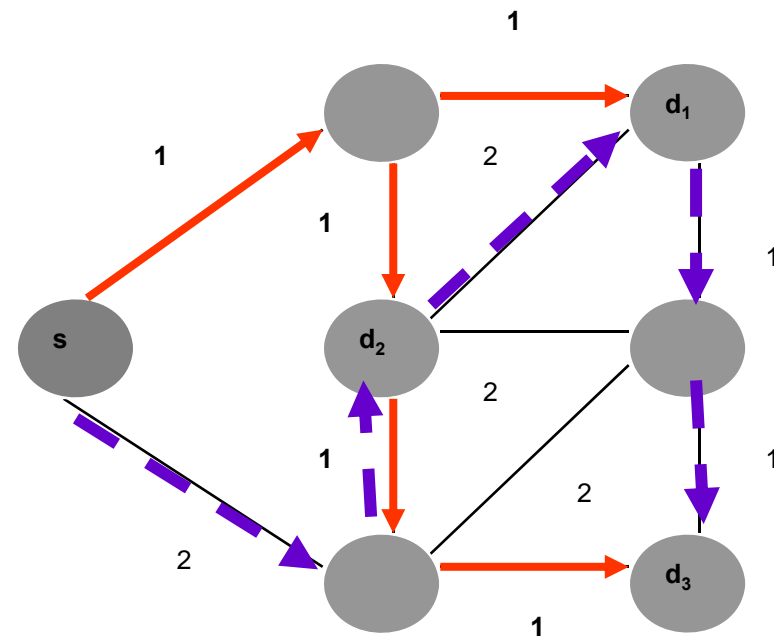
Multicast Protection-
Path-based

1. Find primary Light-tree.

2. Divides primary tree into several paths according to the destination nodes.

3. For each path a minimum cost path from the source to the destination node is computed, that is arc-disjoint from its primary path.

1. {s − d₁}
2. {s − d₂}
3. {s − d₃}

Self-Sharing: Backup paths can share the primary arcs on the primary tree, as long as there are path arc-disjoint.
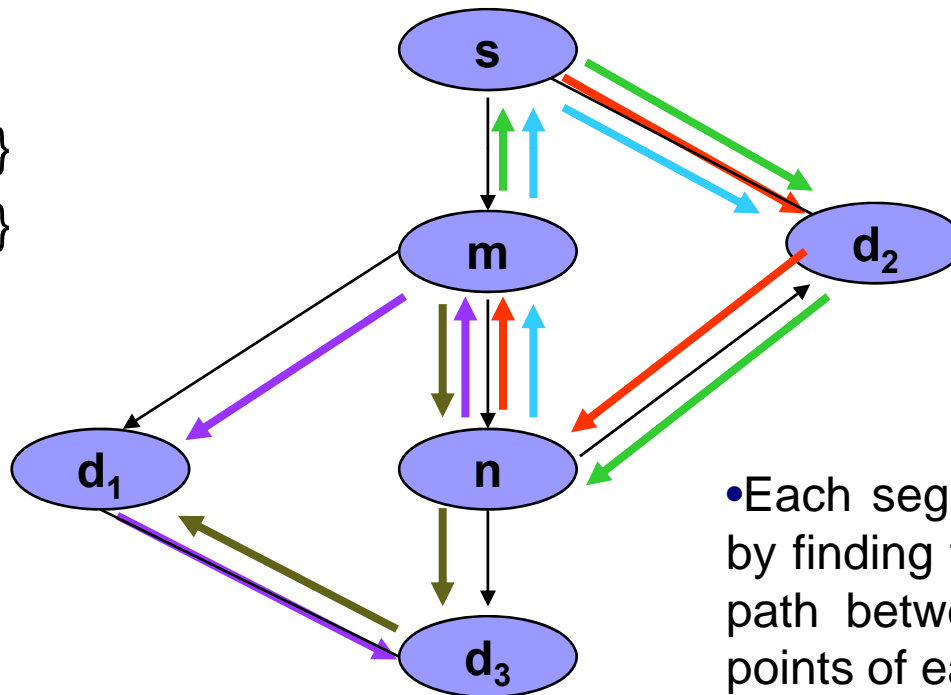
Multicast Protection- Segment-based

1. Find primary light-tree.

2. Divide primary light-tree to un-overlapped segments according to the segment points of the tree.

3. Find the backup paths for each segment .

- **Definitions:**
  - **Segment :** A path between two segment points.
  - **Segment points :** Splitting nodes, source and destination nodes.

Multicast routing and protection algorithms

□ {s ->m}

□ {m ->n}

□ {n ->d3}

□ {n -> d2}

□ {m ->d1}

•Each segment is protected by finding the minimum cost path between the segment points of each segment.

• The backup paths must be arc-disjoint from their primary segments.
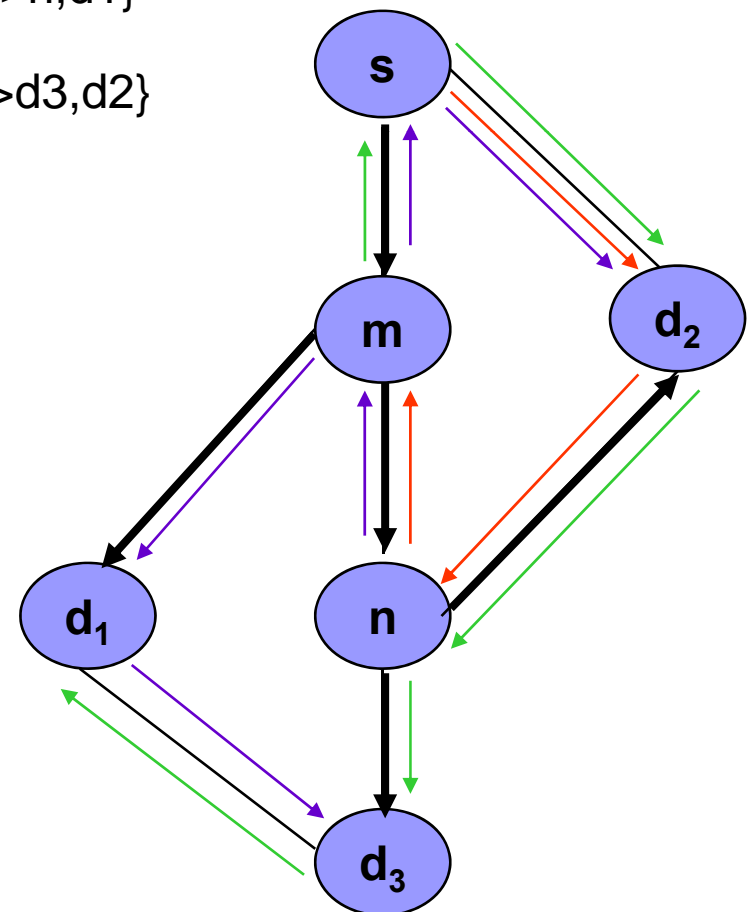
Multicast Protection-
Segment-based

- ❑ Sister Node First Algorithm (SSNF)
  - • Differs from the conventional SP in the way the segments are identified
  - • **Definitions:**
    - • **Sister Nodes:** Nodes with a common parent in the tree.
    - • **segment points** and **segments** are as previously defined.

- • The first segment is protected as in the conventional case.
- • The next segments are protected by computing the minimum cost trees that start from the splitting nodes of each segment and span the sister nodes in the sets.

❑ {s ->m}

❑ {m ->n,d1}

❑ {n ->d3,d2}

Multicast Protection-
Segment-based

❑ Level Protection Algorithm (LPA)
- Differs from other segment based schemes in the way the segments are identified

■ Divides the primary light-tree into un-overlapped segments based on the levels of the tree and finds backup paths for each Level segment.

- **Definitions:**
  - **Segment:** a path between two segmentation nodes in the tree.
  - **Segmentation node**: source node and destination nodes.
  - **Level(i) of a segmentation node:** the number of the segments between that segmentation node and the source.
  - **Level (i-1, i) segment:** is the set of all the segments of the tree that are between level (i-1) and level (i) segmentation nodes.

Multicast Protection- Segment-based (LPA)

Level 0

Level 1

Level 2
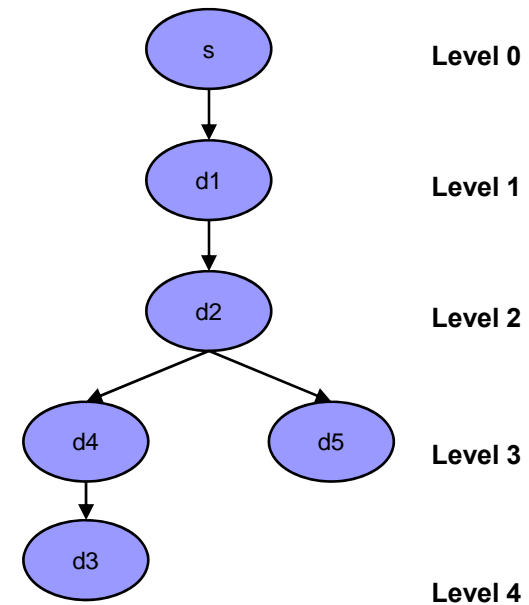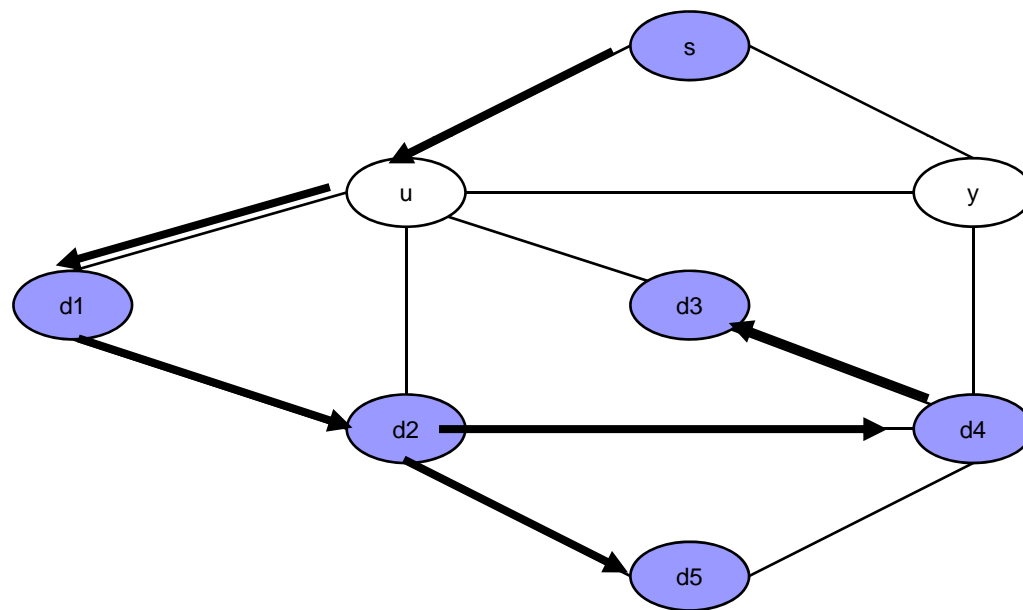
Level 3

Level 4

Segmentation nodes, levels and level segments are identified

Multicast Protection-
Segment-based (LPA)
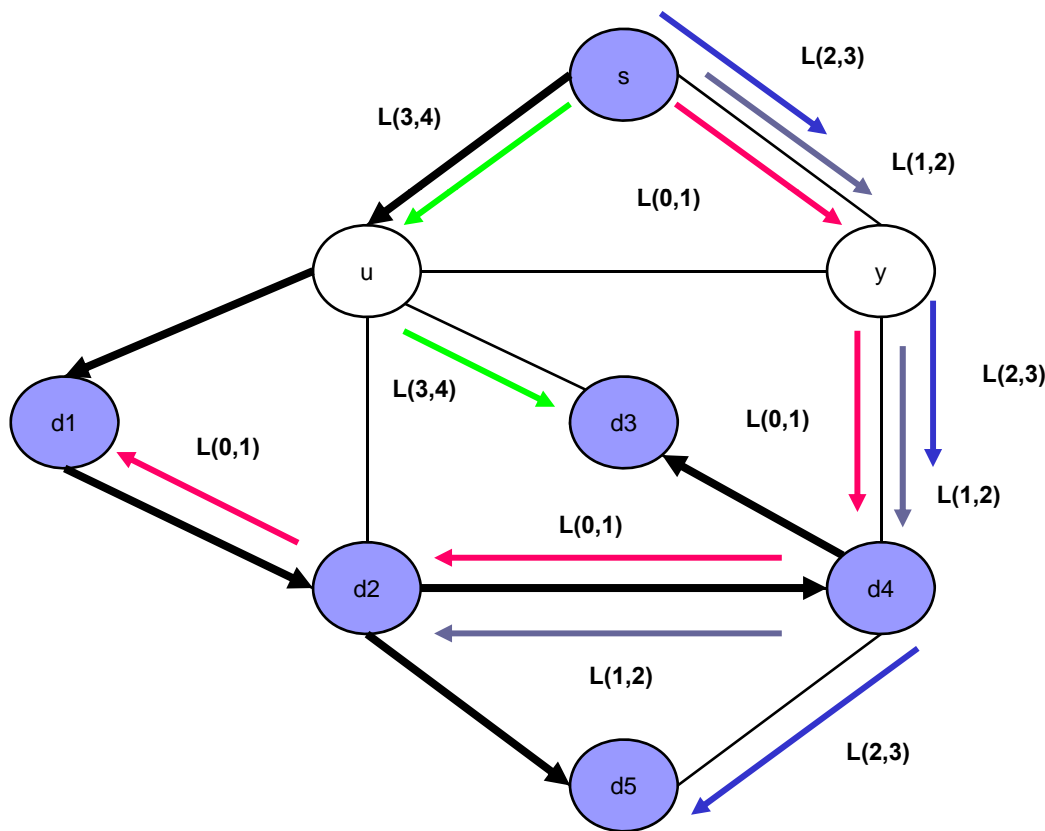
- **Backup path:** A minimum cost tree that starts from any segmentation node in lower levels, and spans every segmentation node in the current level.

- **Example:** if we want to protect the segmentation nodes in level 2, a minimum cost tree is computed that starts from any segmentation node in levels 0 or 1, and spans every segmentation node in level 2.

- **Constrain:** The backup tree, must be arc disjoint from its primary level segment and from every level segment that lies between higher levels.

Simulation Parameters

❑ **Network :**
- 50 nodes
- 196 bidirectional links
- 64 wavelengths

❑ **Dynamic System:**
- Poisson arrivals
- Exponentially distributed holding times with a unit mean.
- 100 Erlangs load.
- For each run 5.000 requests were generated for each multicast group size.
- The results for each simulation point were obtained as the average of 5 runs .
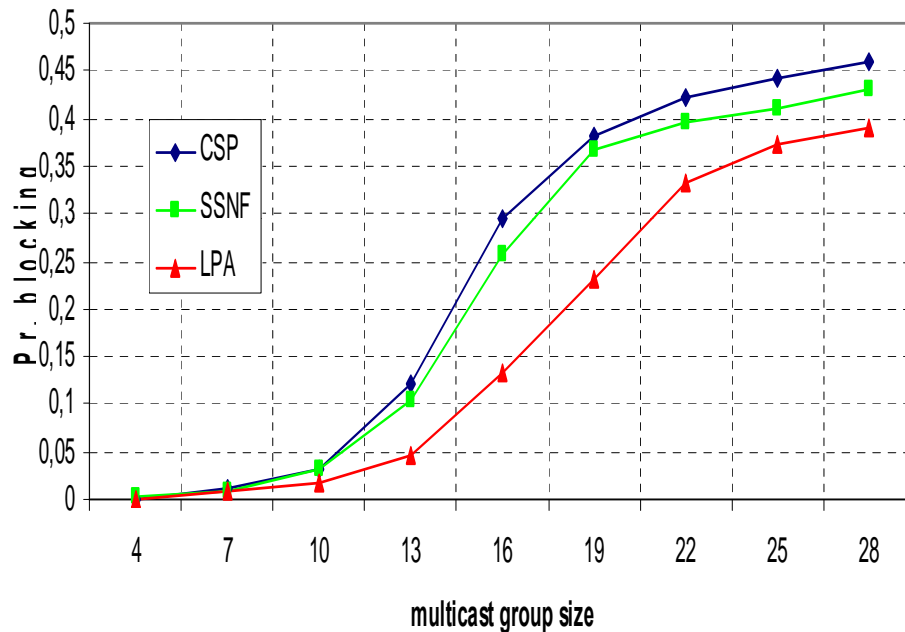
❑ **MC-RWA algorithm:**
Accepted:
- A route and wavelength assignment can be found for both the primary and the backup trees,
    - The Q-factor for each path on both trees is above the predetermined Q threshold.
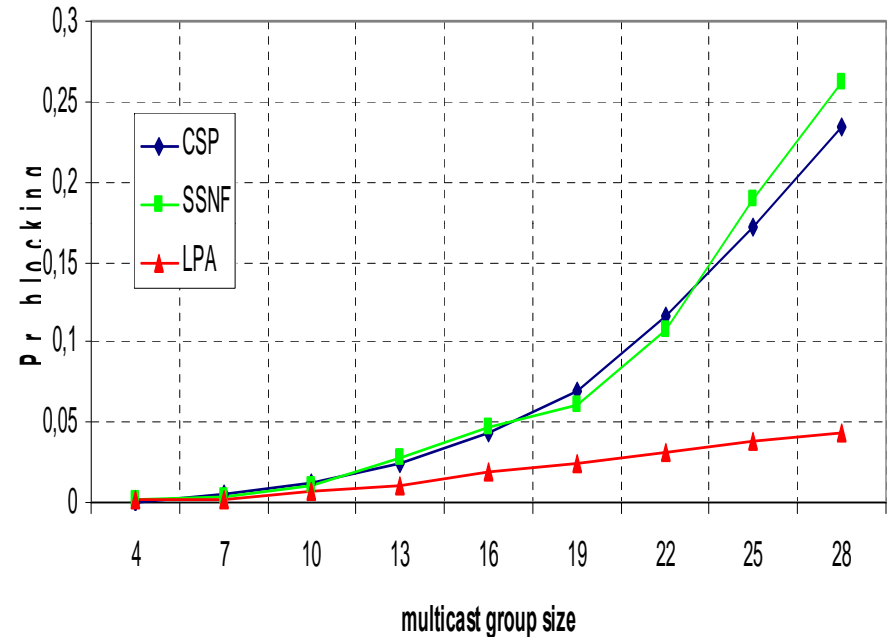   - There are available Txs and Rxs for that connection.

Simulation Results

Dedicated

Cross-sharing

- **Assumptions**: Fixed Txs/Rxs, Q threshold = 8.5 dBQ
- **LPA** performs the best in both cases compared to the other segment based protection algorithms.
- **Cross-Sharing** significantly improves the network performance.

Conclusions and Future Work

❑**Conclusions:**
- Different node architectures and engineering designs produce different multicast group blocking, a strong indicator that a better interaction between physical and logical layers is needed for multicast connection provisioning.

❑**Future Work:**
- Our current work focuses on further accounting and determining the impact of PDG and PDL on the algorithms and the system performance.
- Future work focuses to the provisioning and protection of groupcast requests when PLIs are taken into account.
- Additional work has been done on unicast connections taking into account the PLIs.
- Additional work has been done on grooming subrate connections for multicast applications (grooming for groupcast applications is scheduled as future work).