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

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Outline

- Introduction
- Physical Layer Impairments
- Multicasting in Transparent Networks
- Multicast Protection
- Conclusions and Future Work

Introduction-
Optical Networks

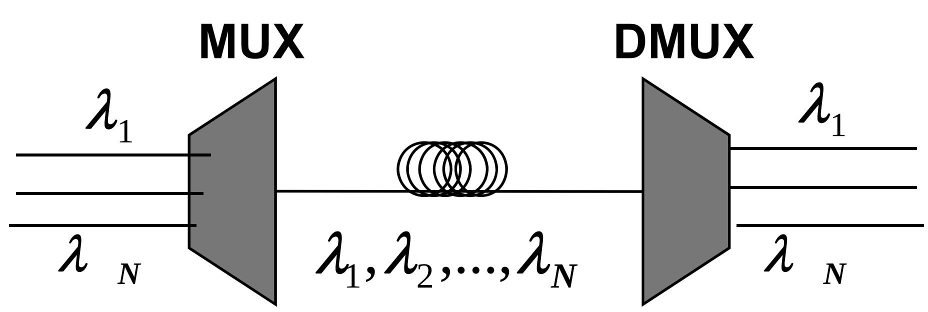
- Optical Network:
  - Telecommunications network with transmission links that are optical fibers, “intelligent” optical switching nodes, and with an architecture that is designed to exploit the unique features of fibers.

- 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.



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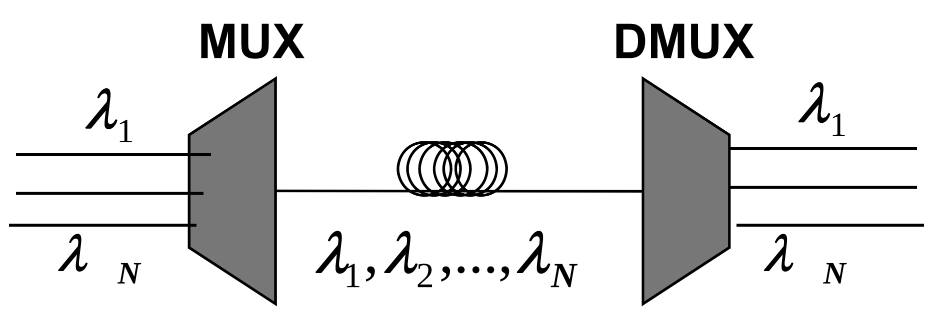


Introduction-
Evolution of Optical Networks

- **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:

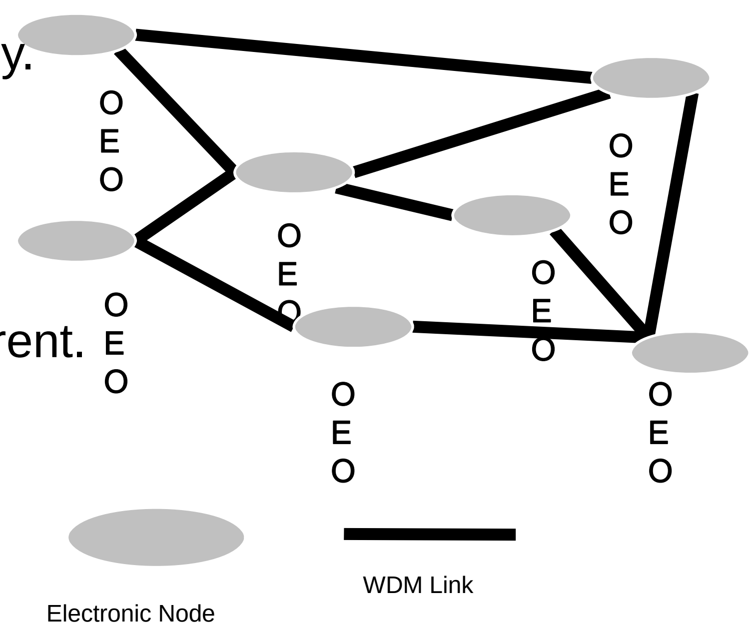
- All switching and processing of the data is handled by electronic switch fabrics.
- The optical signal carrying traffic undergoes an optical-electronic-optical (OEO) conversion at every switching node**.**

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.



Introduction-

Evolution of Optical Networks

b. Transparent Network:

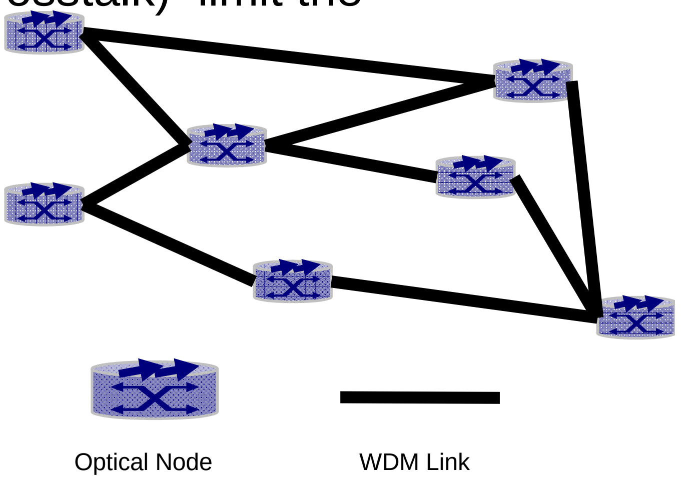
- Switching and processing of the data is moved to the optical part of the network

Ads

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

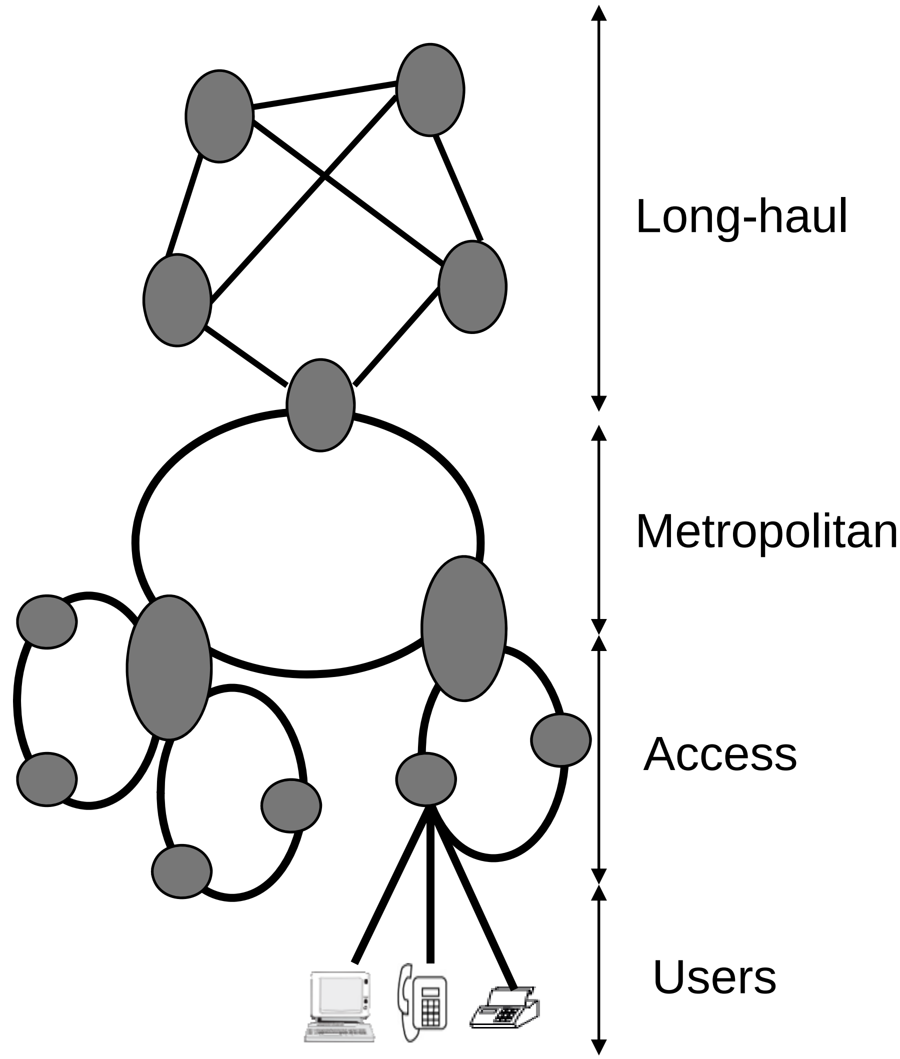
Cons

- 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.



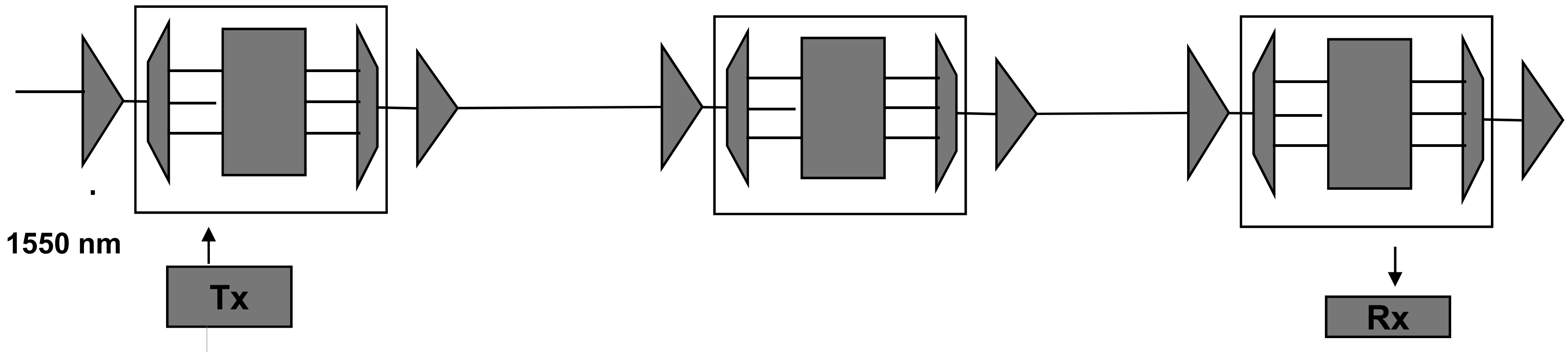
Introduction- Transparent MANs

- **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.



QoT-
Physical Layer Impairments

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



- **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.

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

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

- 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.

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

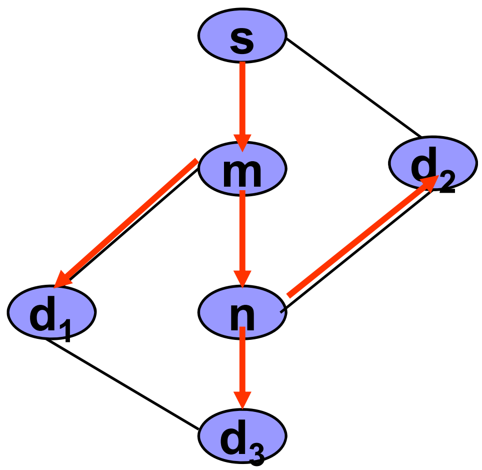
- Q threshold set at 8.5 dBQ which corresponds to a BER of 10^{-12}

Multicasting-
Introduction

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

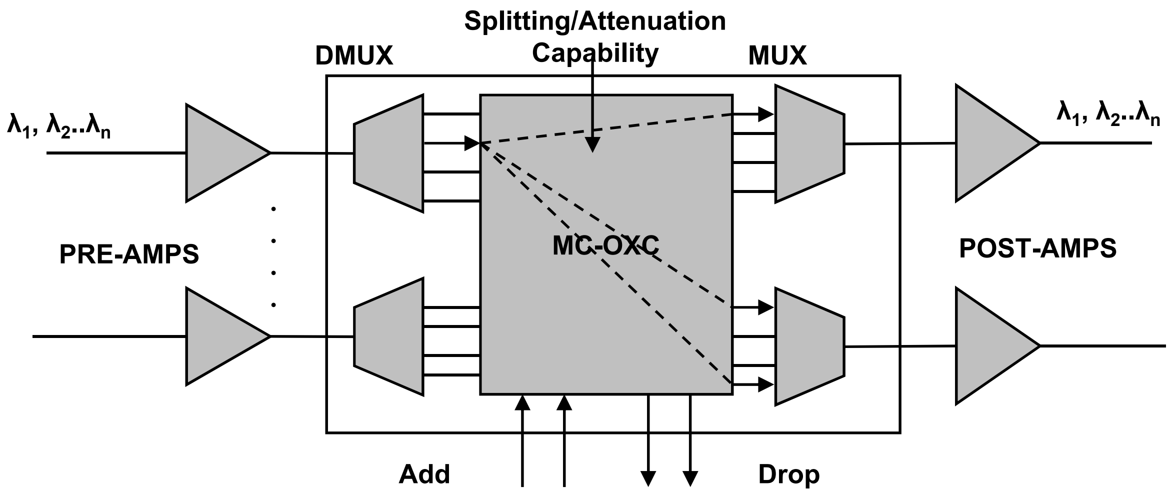
•**Multicast connection:**

- •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

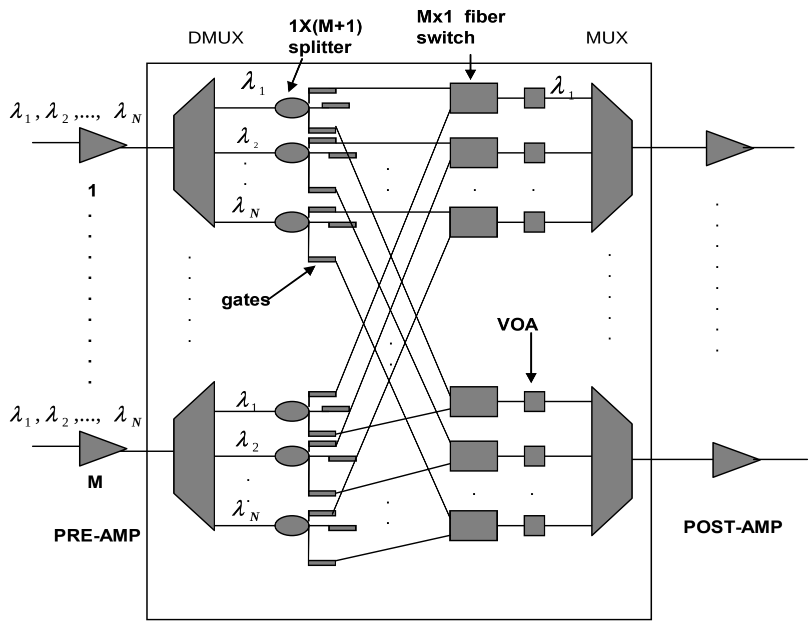
Multicast Capable Architectures



- (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

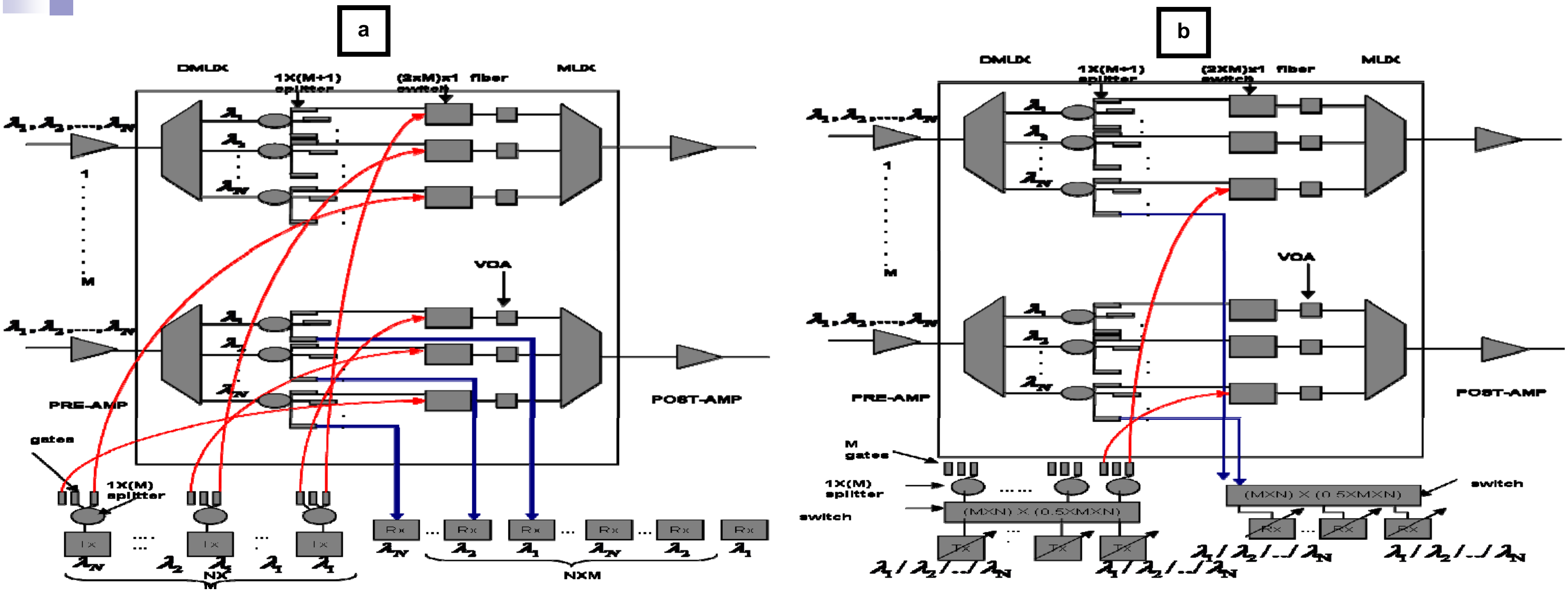
- **Worst case scenario :**
  - The maximum insertion loss a signal encounters passing through the maximum degree node.

- **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.

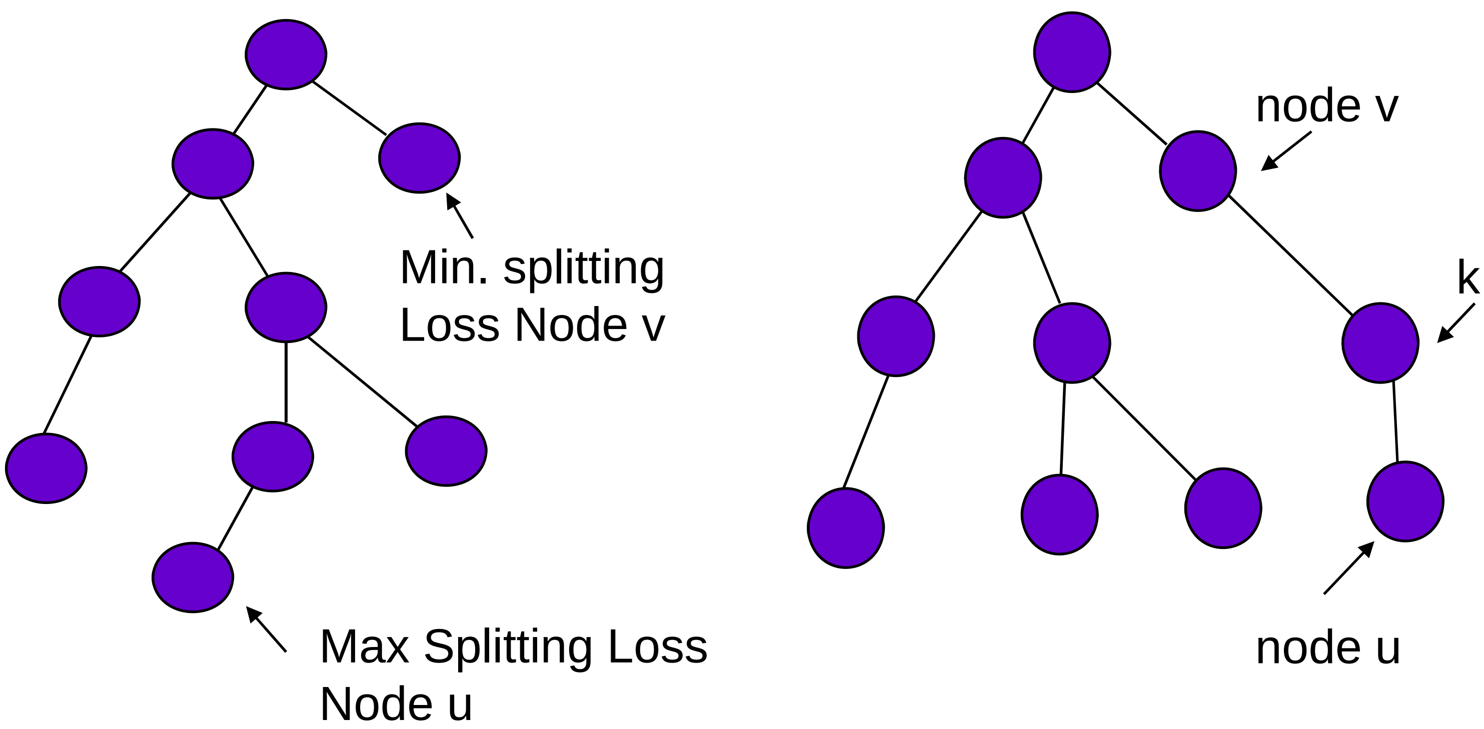
1. **Minimum Steiner tree heuristic (MST):**
   - Finds the minimum cost tree.
   - The Steiner tree problem is NP-complete when the multicast group has more than two members.
   - Several heuristics have been developed for the Steiner tree problem.

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:



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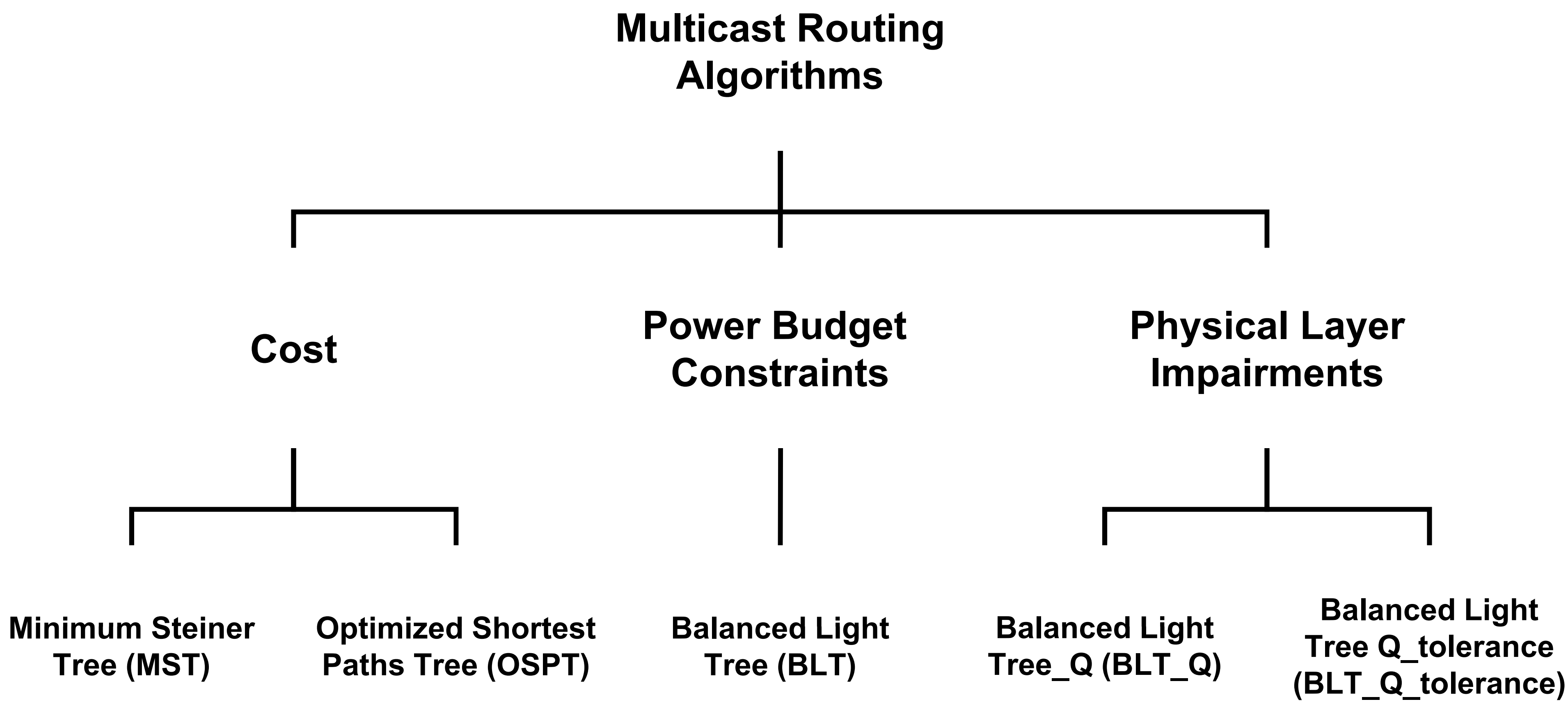
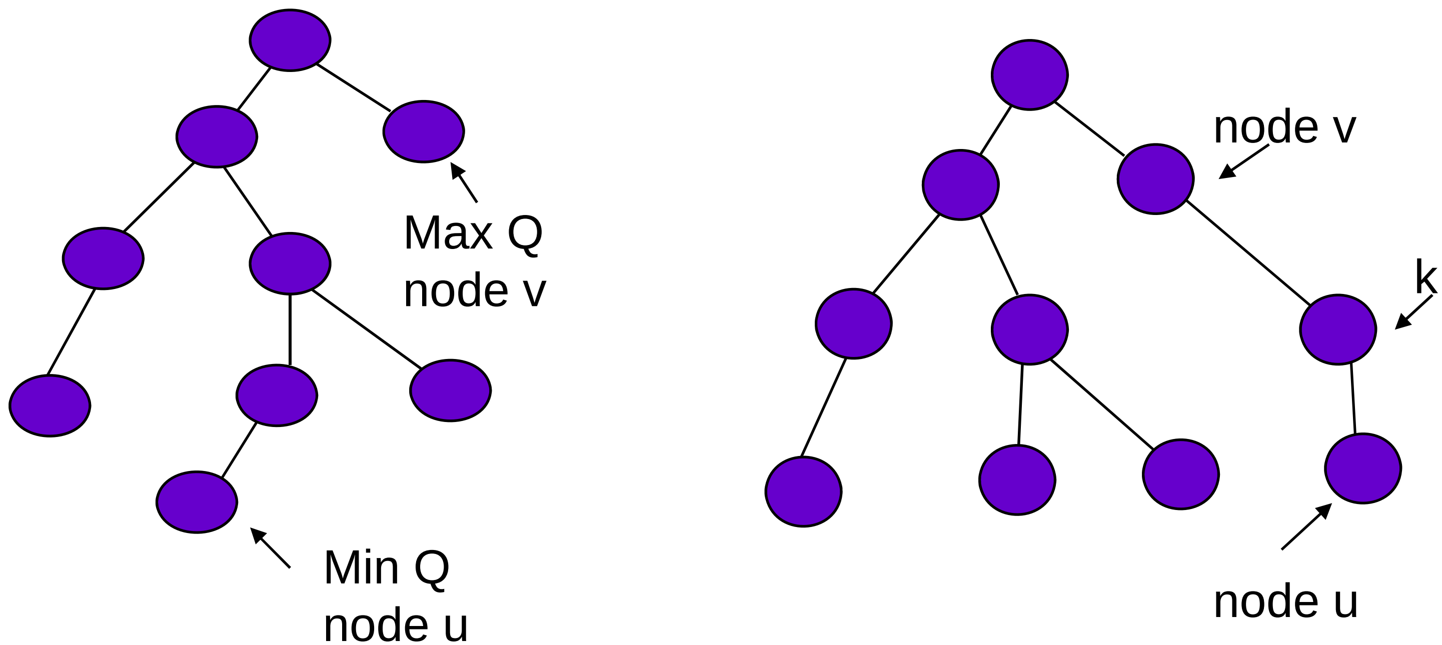


Multicast Routing Algorithms

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



- **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.

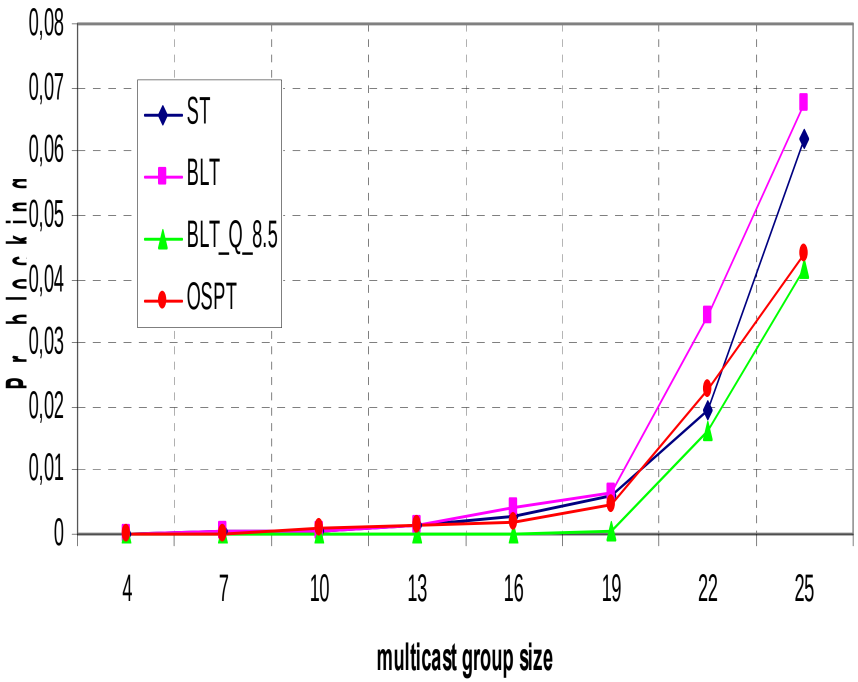
Impairment Aware - MC-RWA Algorithm

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

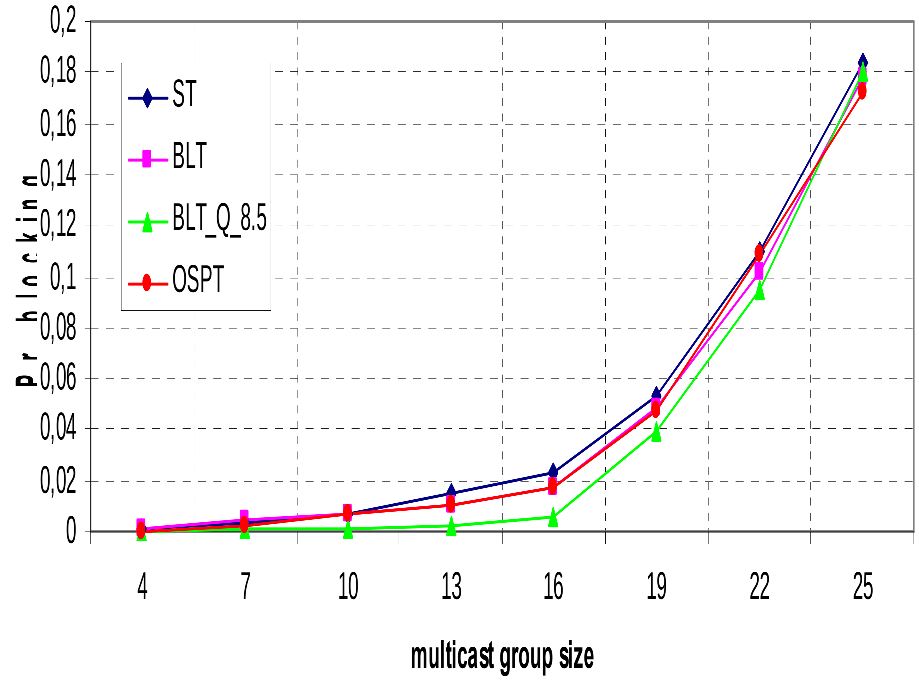
  - **Blocked:** There is no available wavelength for the entire tree.
  - **Accepted:**
    - A route and wavelength assignment can be found.
    - The Q-factor for each path on the tree is above the predetermined Q threshold.
    - There are available Txs and Rxs for that connection
  - If the physical 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

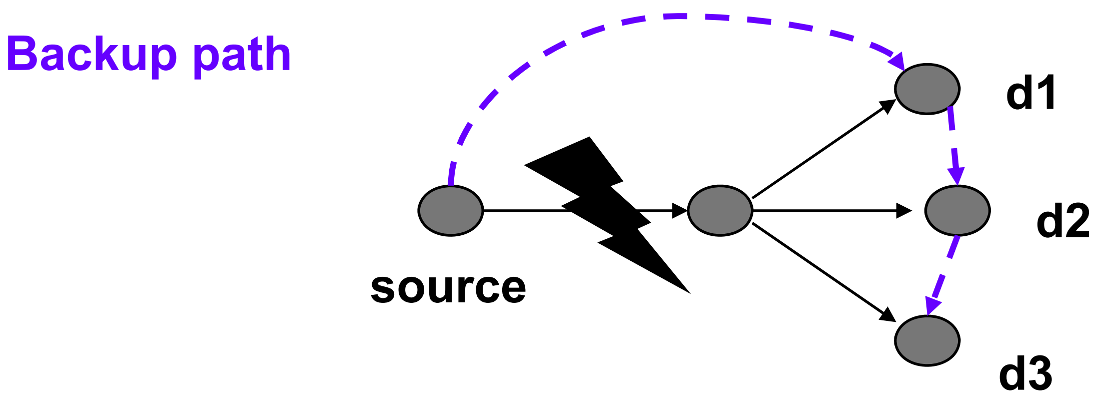


- **BLT_Q$_{8.5}$** that takes the PLIs into account performs the best compared to the other multicast routing algorithms for both cases,
- **Pr. Blocking** in tunable case is increased compared to the fixed case, since in fixed Txs/Rxs case a larger number of Txs/Rxs is used.

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.

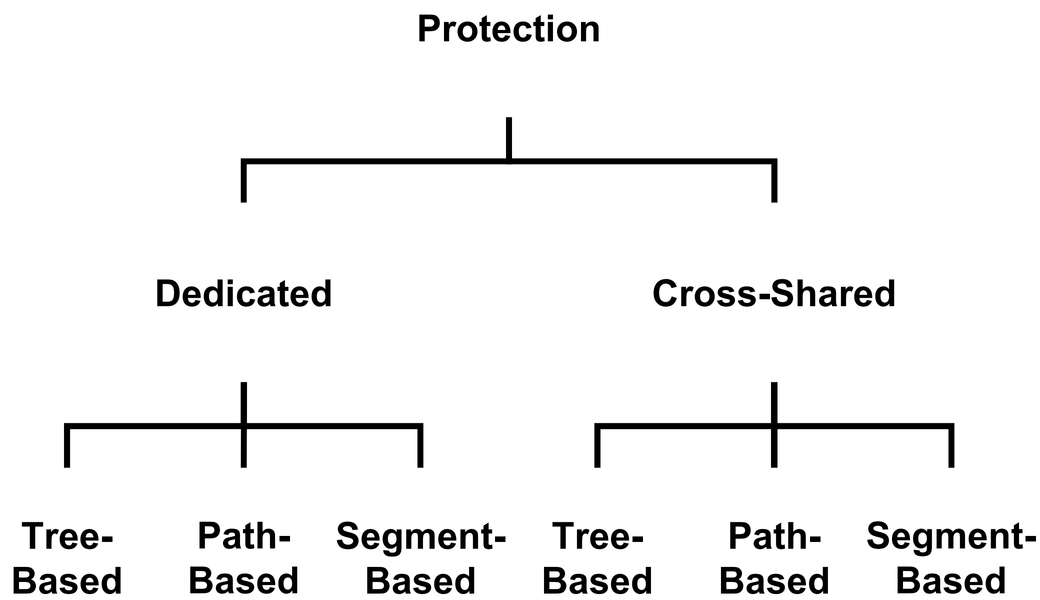
- Fiber cuts occur often and are the predominant form of failure.



- 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.



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

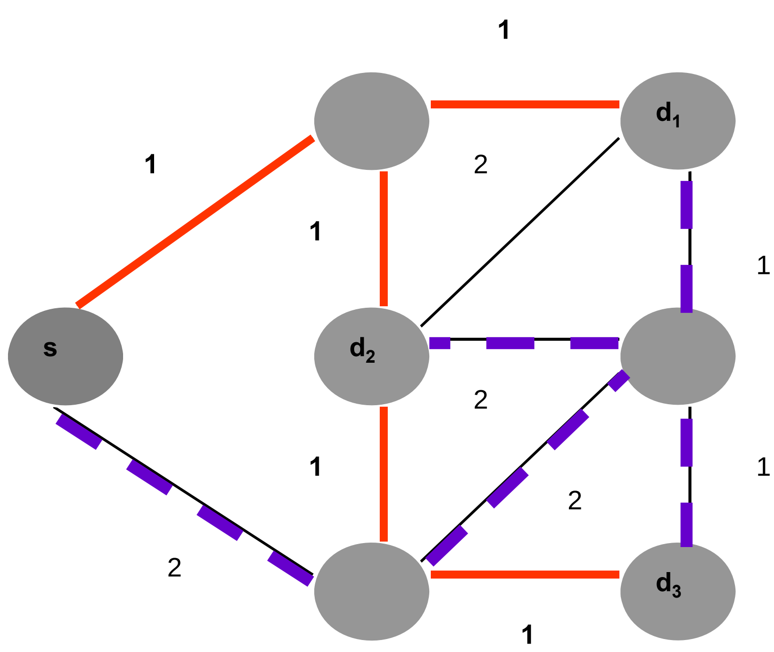
Link-Disjoint:

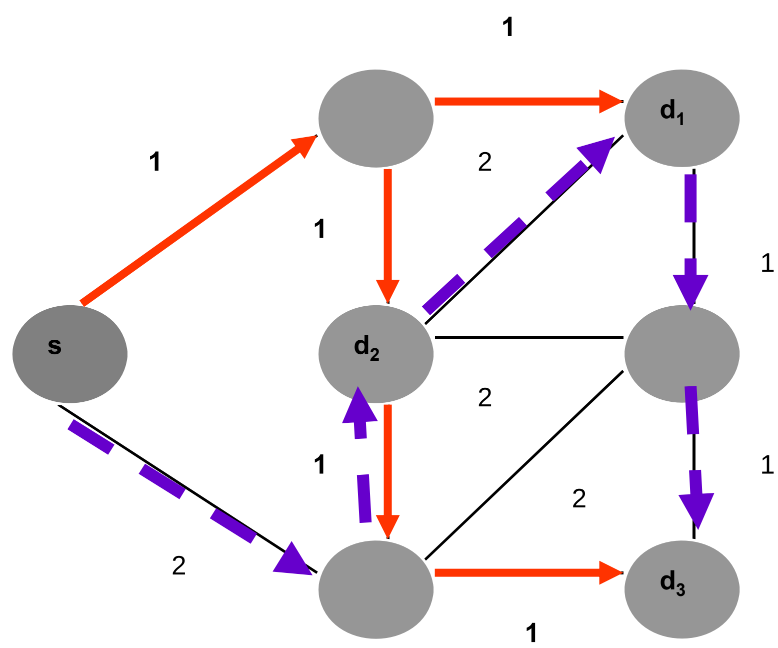
1. A primary tree.
2. A link-disjoint backup tree.

Arc-Disjoint:

1. A directed primary tree.
2. A directed arc-disjoint backup tree

Redundant capacity reaches the 100 %.

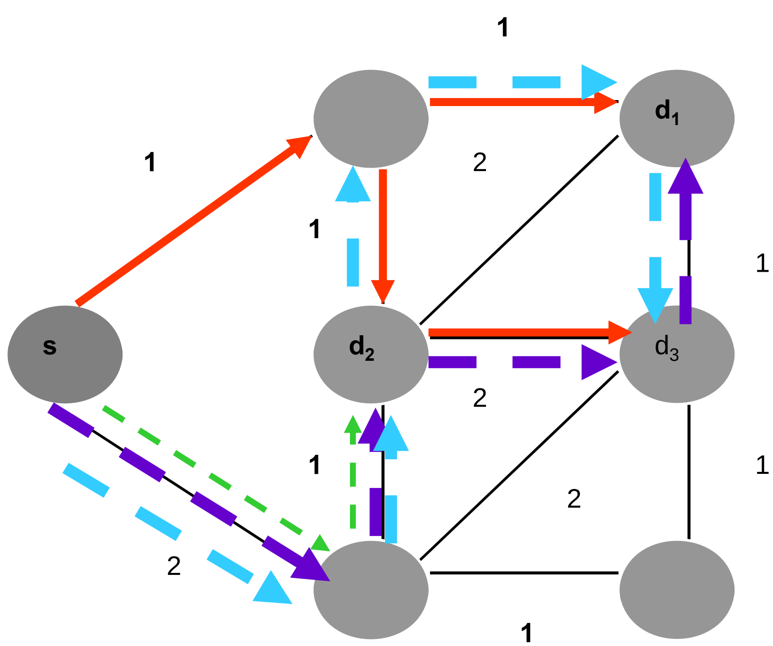




Multicast Protection-
Path-based

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 – d_1}
2. {s – d_2}
3. {s – d_3}



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

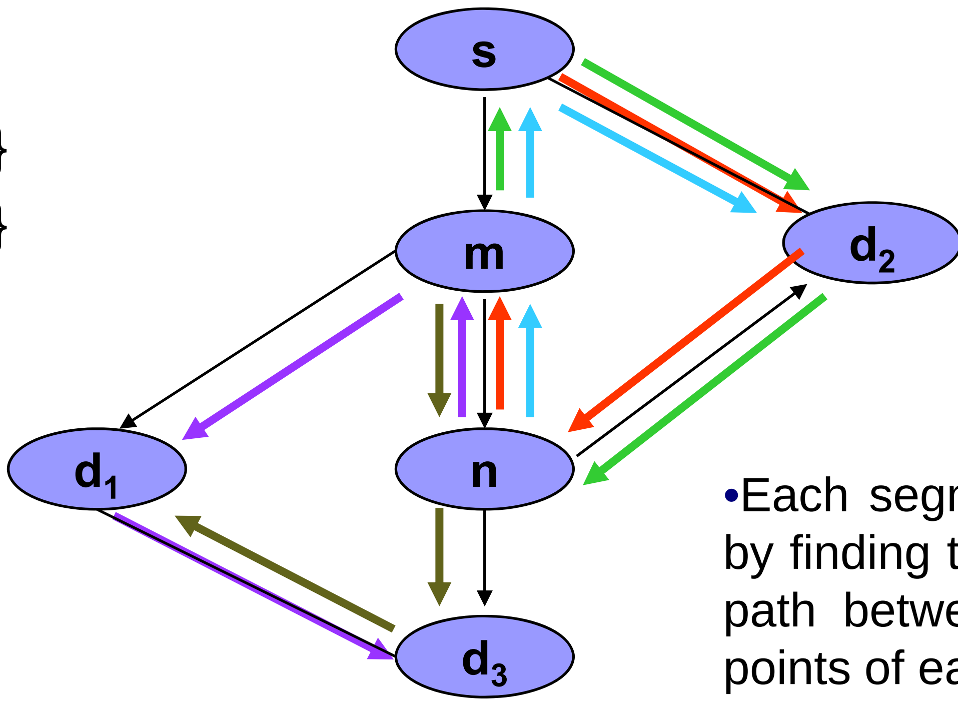
Multicast Protection-
Segment-based

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}



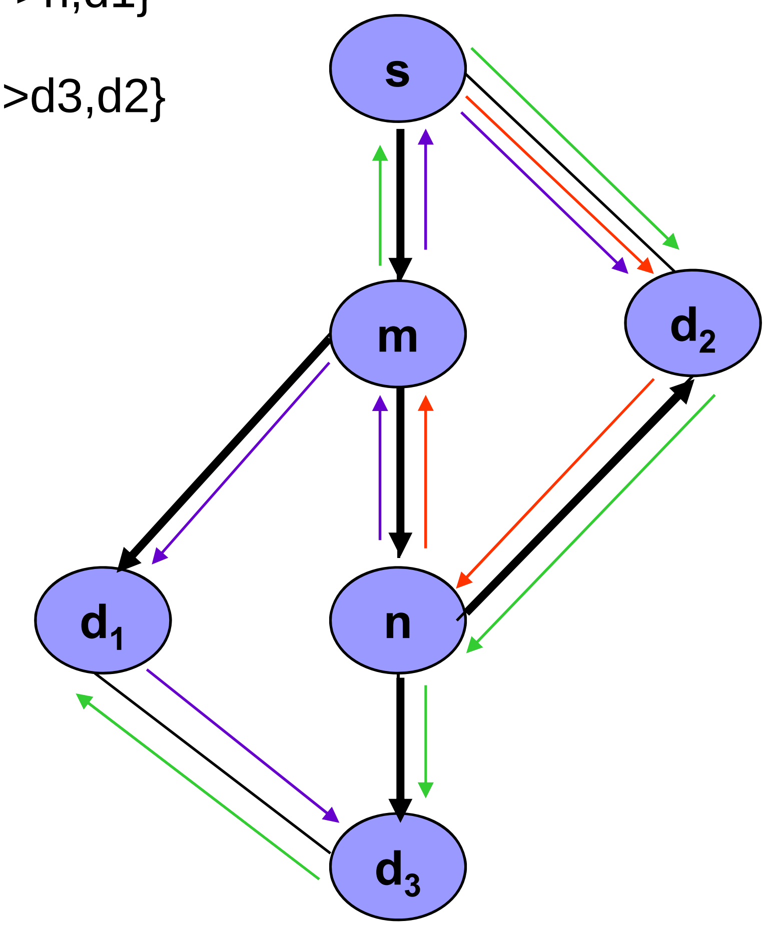
- Each segment is protected by finding the minimum cost path between the segment points of each segment.
- The backup paths must be arc-disjoint from their primary segments.

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}



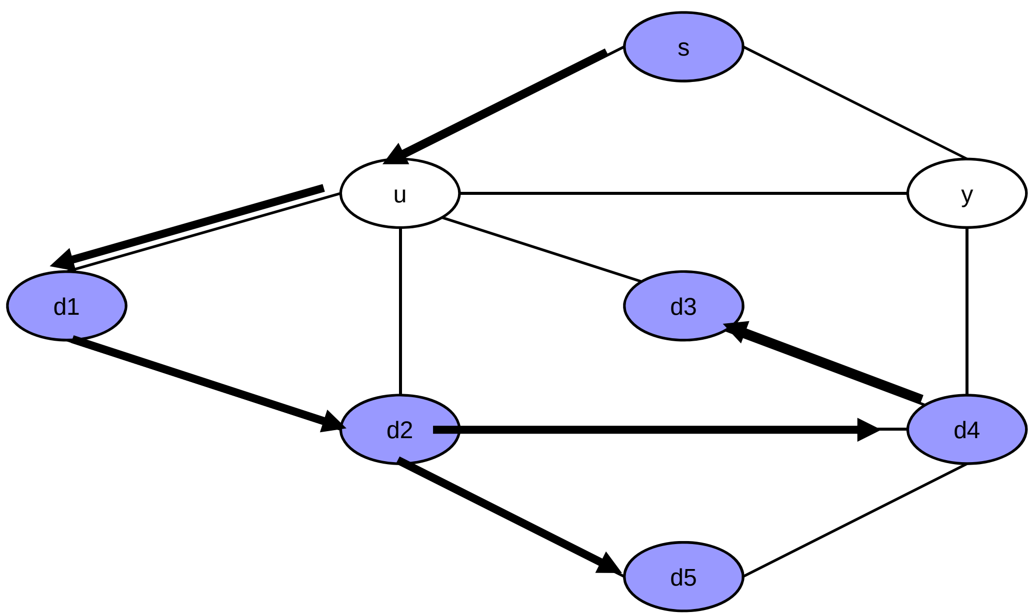
Multicast Protection-
Segment-based

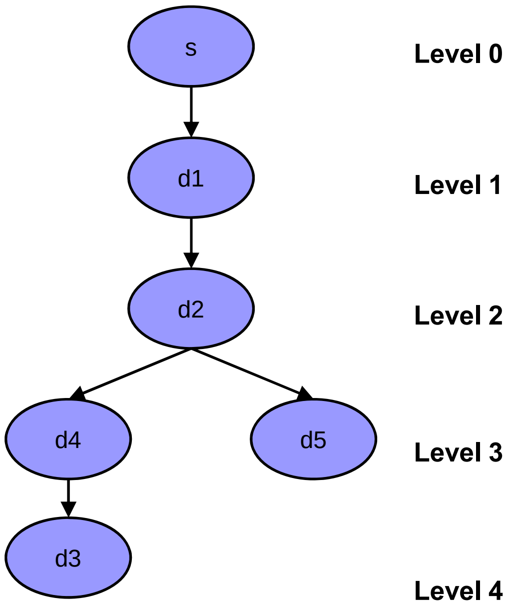
- Level Protection Algorithm (LPA)
  - Differs from other segment based schemes in the way the segments are identified

- 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.

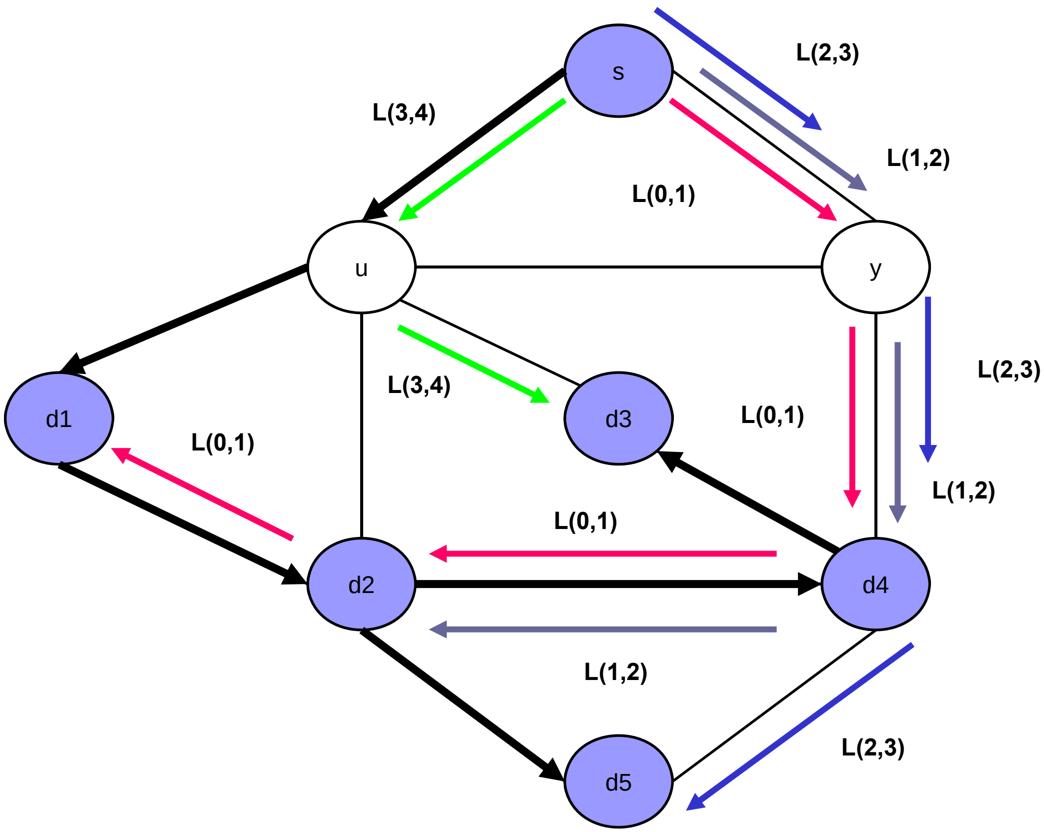
Multicast Protection-
Segment-based (LPA)





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 .

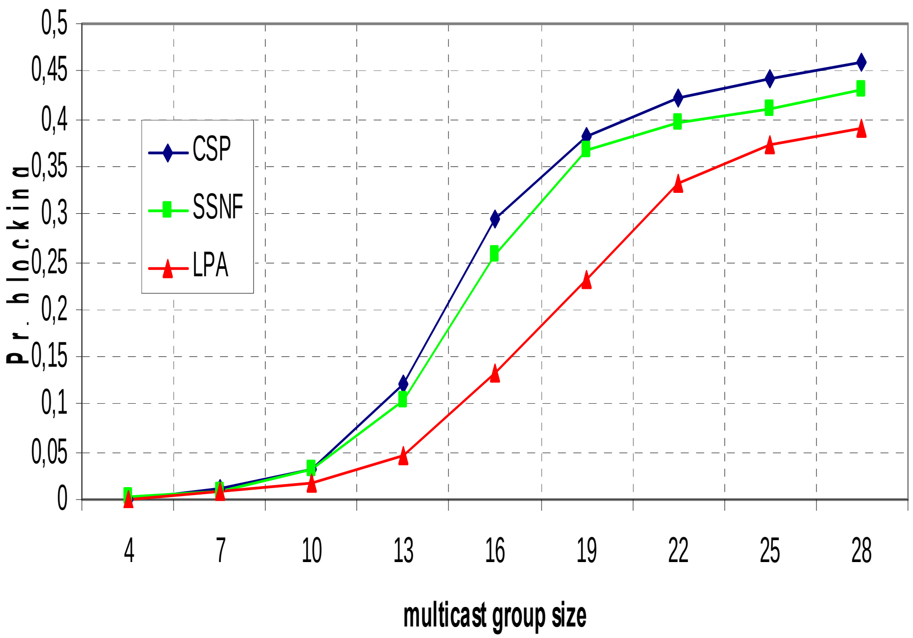
- **MC-RWA algorithm:**

  Accepted:

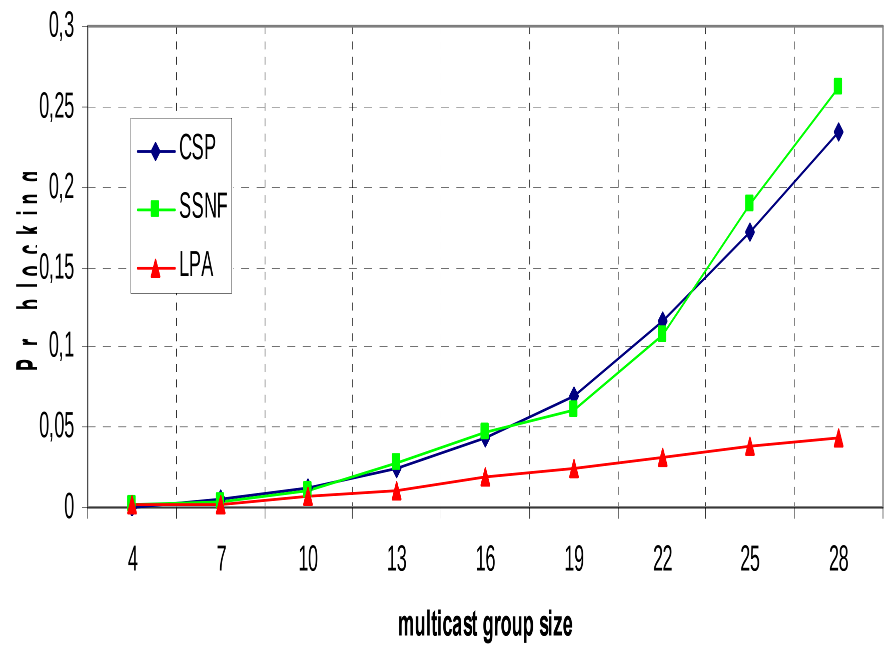
  - A route and wavelength assignment can be found for both the primary and the backup trees,
    - The Q-factor for each path on both trees is above the predetermined Q threshold.
    - There are available Txs and Rxs for that connection.

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).