Multicasting and groupcasting with physical layer constraints in metropolitan optical networks with mesh topologies.

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ΠΕΝΕΚ ΕΝΙΣΧ/0308 Mid-Project Report, 22 July 2010

Project Objectives

- General Objectives:

1. To support a young researcher (Ph.D. candidate) in order to perform cutting edge research in an area of high technological importance.
2. The student will obtain expertise that will be of great importance to the Cyprus economy, as he will be trained on a key priority area of Telecommunications Systems and Information Technology.
3. The results of this project will be utilized by Cypriot telecommunications companies or Cypriot service providers to better design their metropolitan optical networks for high data-rate applications.
4. The final software product developed in this project can be used by interested parties as a research/design tool for real-life network deployments.

Project Objectives

- Main Technical Objectives:

1. Model the physical layer constraints in a metropolitan area optical networks
2. Develop novel quality of transmission (QoT)-based MC/GC-RWA techniques taking into account different node designs and network engineering scenarios
3. Develop novel QoT-based MC/GC-RWA protection techniques to create networks that are survivable from a single failure scenarios
4. Develop novel QoT-based grooming techniques for multicast and groupcast connections in metro optical networks
5. Develop a software tool utilizing all the aforementioned novel techniques and algorithms that can be utilized by a telecom provider to better design, engineering, and deploy its fiber-optic networks.

Time Schedule (1/2)

Work-Package Number / Title	D U R A T I O N (months)																																		
			3			6			9			12			15			18			21			24			27			30			33			36
WP1. Project Management	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						
WP2. Dissemination and Exploitation of Results	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						
WP3. Development of algorithms for routing and wavelength assignment of multicast connections with physical layer constraints for metropolitan optical networks	x	x	x	x	x																															
WP4. Development of algorithms for routing and wavelength assignment of protected multicast connections with physical layer constraints for metropolitan optical networks						x	x	x	x	x																										
WP5. Development of algorithms for routing/grooming and wavelength assignment of multicast connections with physical layer constraints for metropolitan optical networks											x	x	x	x	x																					
WP6. Development of algorithms for routing and wavelength assignment of groupcast connections with physical layer constraints for metropolitan optical networks																x	x	x																		
WP7. Development of algorithms for routing and wavelength assignment of protected groupcast connections with physical layer constraints for metropolitan optical networks																			x	x	x															

Time Schedule (2/2)

WP8. Development of algorithms for routing/grooming and wavelength assignment of groupcast connections with physical layer constraints for metropolitan optical networks																						X	X	X	X	X	X																					
WP9. Development of a software simulation tool for metropolitan area networks that incorporates multicast and groupcast connections																										X	X	X	X	X																		
WP10.																																																
Progress Reports Submitted to RPF						X						X			X			X						X						X																		

Work Package 1:

Project Management

- **Deliverables for the first 15 months:**
  - First two six-month reports
  - D1:Development of algorithms for routing/grooming and wavelength assignment of protected multicast connections.
  - D2: Mid-project Report
- **Accomplishments for the first 15 months**
  - During the first 15 months WPs 3-5 and deliverables D1, D2, were successfully completed
    - Several novel algorithms, node designs, and network engineering techniques have been developed for QoT-based multicast provisioning.
  - 3 publications completed (1 journal paper and 2 conference papers) with another 3 journal publications to be submitted shortly
  - Work was presented in two international conferences, including the most prestigious conference on optical networks
  - A web site for the project has been set up.

Work Package 2:
Dissemination and Exploitation of Results

Publications:

- G. Ellinas, N. Antoniades, **T. Panayiotou**, A. Hadjiantonis, and A.M. Levine, "Multicasting Routing Algorithms Based on Q-Factor Physical Layer Constraints in Metro", *IEEE/OSA Photonics Technology Letters*, vol. 21, no. 6, pp. 365-367, 2009.
- **T. Panayiotou**, G. Ellinas, N. Antoniades, A. M. Levine, "Designing and Engineering Metropolitan Area Transparent Optical Networks for the Provisioning of Multicast Sessions", IEEE/OSA Optical Fiber Communications (OFC) Conference, San Diego, CA, March 2010.
- **T. Panayiotou**, G. Ellinas, N. Antoniades, and A. Hadjiantonis, "Node Architecture Design and Network Engineering Impact on Optical Multicasting Based on Physical Layer Constraints", in *Proc. International Conference on Transparent Optical Networks (ICTON)*, Munich, Germany, June/July 2010.

Work Package 2:
Dissemination and Exploitation of Results

- **Under Preparation:**

- **T. Panayiotou**, G. Ellinas, A. Hadjiantonis, and N. Antoniades, "On the Effect of Node Architecture/Engineering for Multicasting Based on Physical Layer Constraints", (under preparation), 2010. (Scheduled for submission to the *IEEE/OSA Journal of Lightwave Technology*)
- **T. Panayiotou**, G. Ellinas, A. Hadjiantonis, and N. Antoniades, "Multicast Protection in Metro Networks Based on Physical Layer Constraints", (under preparation), 2010. (Scheduled for submission to the *IEEE Photonics Technology Letters*).
- **T. Panayiotou**, G. Ellinas, A. Hadjiantonis, and N. Antoniades, "Multicast Grooming in Metro Networks Based on Physical Layer Constraints", (under preparation), 2010. (Scheduled for submission to the *IEEE/OSA Journal of Optical Communications and Networking*).

- A website is set up on which key results and project info are displayed (http://www.eng.ucy.ac.cy/gellinas/MULTIOPTI.html)

Work Package 3

Development of RWA algorithms for multicast connections with PLCs (5-month duration)

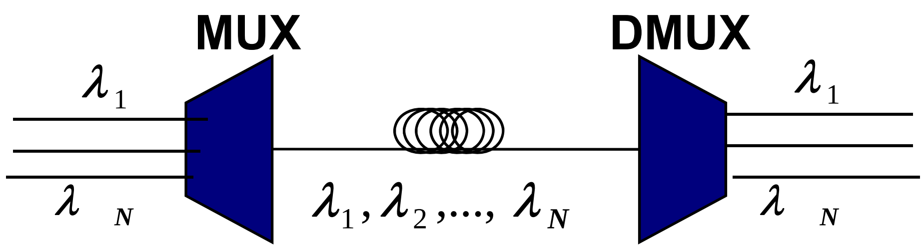
- Development of a Q-budgeting model for metropolitan optical networks.
- Development of a simulation code which performs the routing and the wavelength assignment under physical layer constraints.
- Development of new routing techniques for multicast connections which take into account physical layer constraints, such as:
  - BLT-Q heuristic
  - BLT-Q tolerance heuristic
  - Max Degree Node heuristic

  And their performance was compared with existing routing algorithms:
  - Steiner Tree heuristic
  - Shortest paths Tree heuristic
  - BLT heuristic
  - DAC heuristic
  - MHP tree heuristic

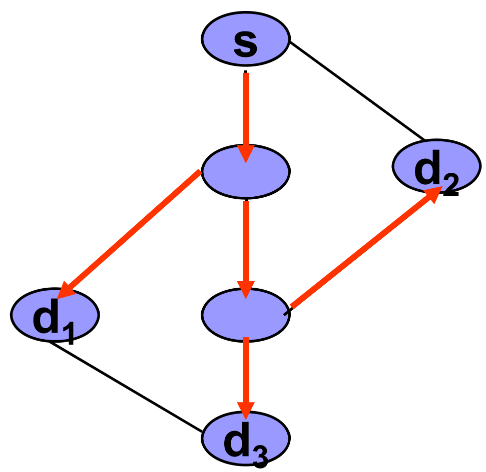
    That take only power budget constraints into account.
- Development and examination of different Node Architectures and Engineering Designs

Introduction

- **WDM networks**: multiple lasers transmit several wavelengths of light (lambdas) simultaneously over a single optical fiber. WDM has dramatically increased the carrying capacity of the fiber.

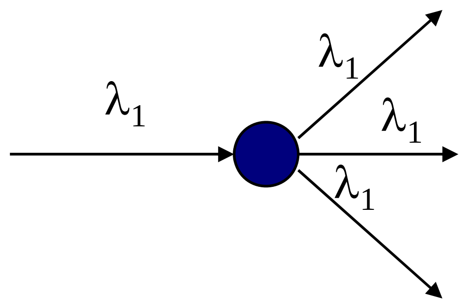


- **Multicast connection:** light from one source must reach many destinations.



Introduction

- In WDM Mesh Networks optical splitters must be used inside the nodes to split the incoming signal to multiple output ports.



- **Multicast Routing and Wavelength Assignment Problem (MC-RWA):**
  - **Routing:** Construction of a light tree that spans the source and the destinations set.
  - **Wavelength Assignment:** A wavelength must be assigned to the light-tree.
  - Multicast requests are blocked if there is no available wavelength for the entire tree.

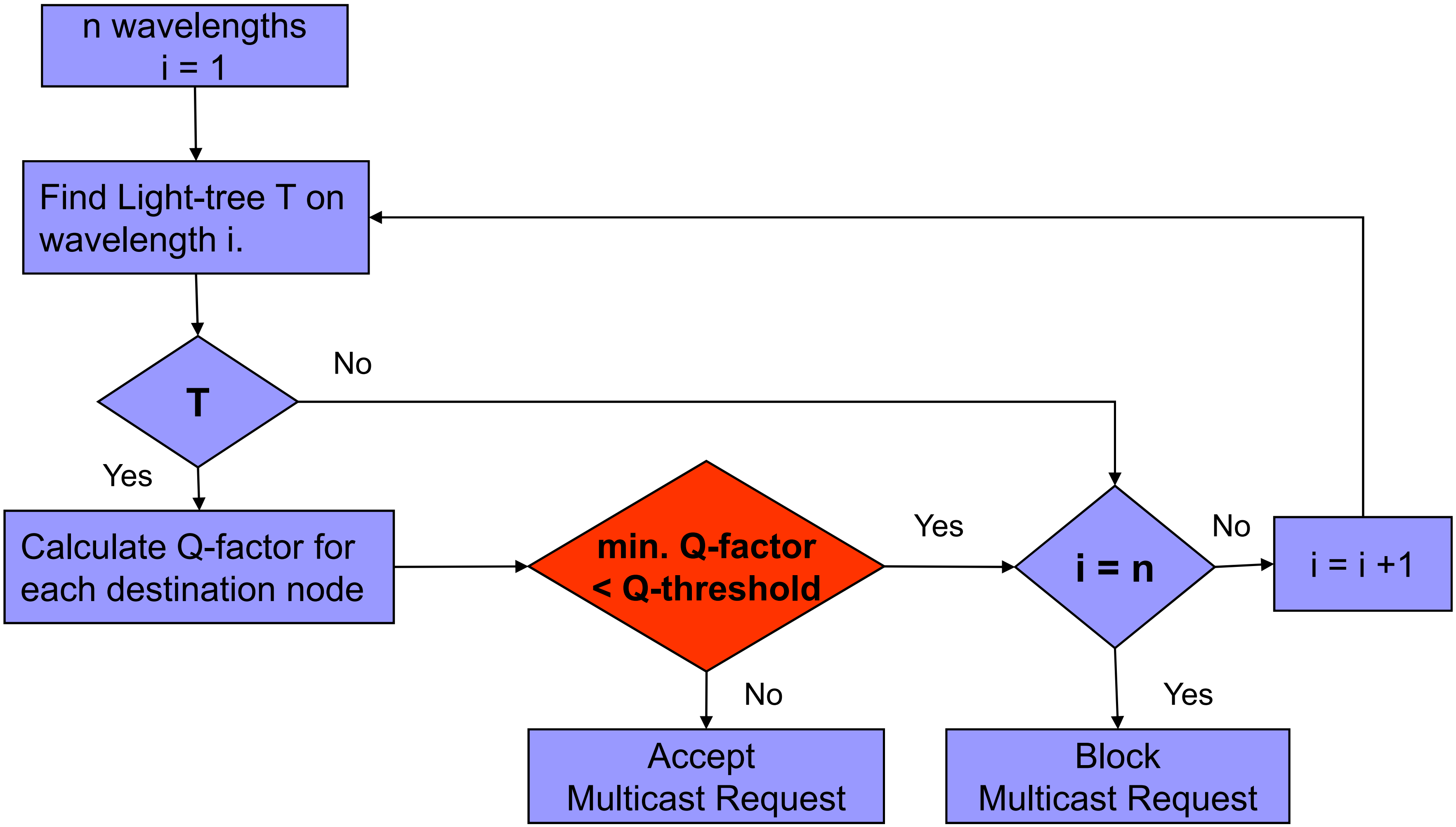
Introduction

- Physical Layer constraints have also taken into account in the MC-RWA.
  - Signal that reaches the destination nodes must have an acceptable quality otherwise it is blocked.

- Quality of Transmission (QOT) is affected by different impairments:
  - Shot noise, thermal noise, ASE noise
  - Incoherent crosstalk
  - Fiber nonlinearities
  - Polarization Mode Dispersion (PMD)
  - Component Aging

- **A Q-budgeting** approach is used that models all physical layer impairments**.**
  - Q- factor is calculated each time a light-tree and a wavelength assignment are found.
  - Multicast requests are blocked if we are below the acceptable Q-factor.

MC-RWA algorithm with physical layer constraints



Q- budgeting model

- We are interested in the Bit Error Rate (BER).
- As the BER is a difficult parameter to evaluate, we can derive the required system Q factor for a target BER using the following equation:

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

- The Q parameter for a system is calculated often in dBs so we use the following definition for QdB:

QdB = 10log (Qlinear)

- The value of the Q factor can be calculated using Equation:

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

- where σ_i is the sum of the variances of the thermal noise, shot noise, various components of beat noise, and RIN noise.

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

Q- budgeting model

- 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.
  - No polarization-dependent gain/loss (PDG/PDL) are present.

- This approach enables a network designer to calculate the impact of physical layer effects, such as non-linear effects, polarization effects, optical crosstalk, etc, in the design of an optical network.

Multicast Routing Algorithms

- Several multicast routing algorithms are used for the simulations.

1. **Steiner tree heuristic (ST):**
   - Finds the minimum cost tree.
   - NP-complete when the multicast group has more than two members.
   - Several heuristics have been developed for the Steiner tree problem.
2. **Shortest Paths Tree (SPT):**
   - Finds the multicast tree by merging all unicast shortest path connections from source to all destinations.
3. **Drop and Continue Tree (DAC)**:
   - Creates trees in which no splitting is required at the intermediate nodes.
   - It starts by connecting the source node with its shortest destination in the destinations set. Then, the last node in the tree chooses a destination from the remaining destinations (based on shortest paths criterion), and adds it to the tree. The same procedure is followed until all destinations are added.
   - This approach creates trees where nodes are connected together in a serial manner.

Multicast Routing Algorithms

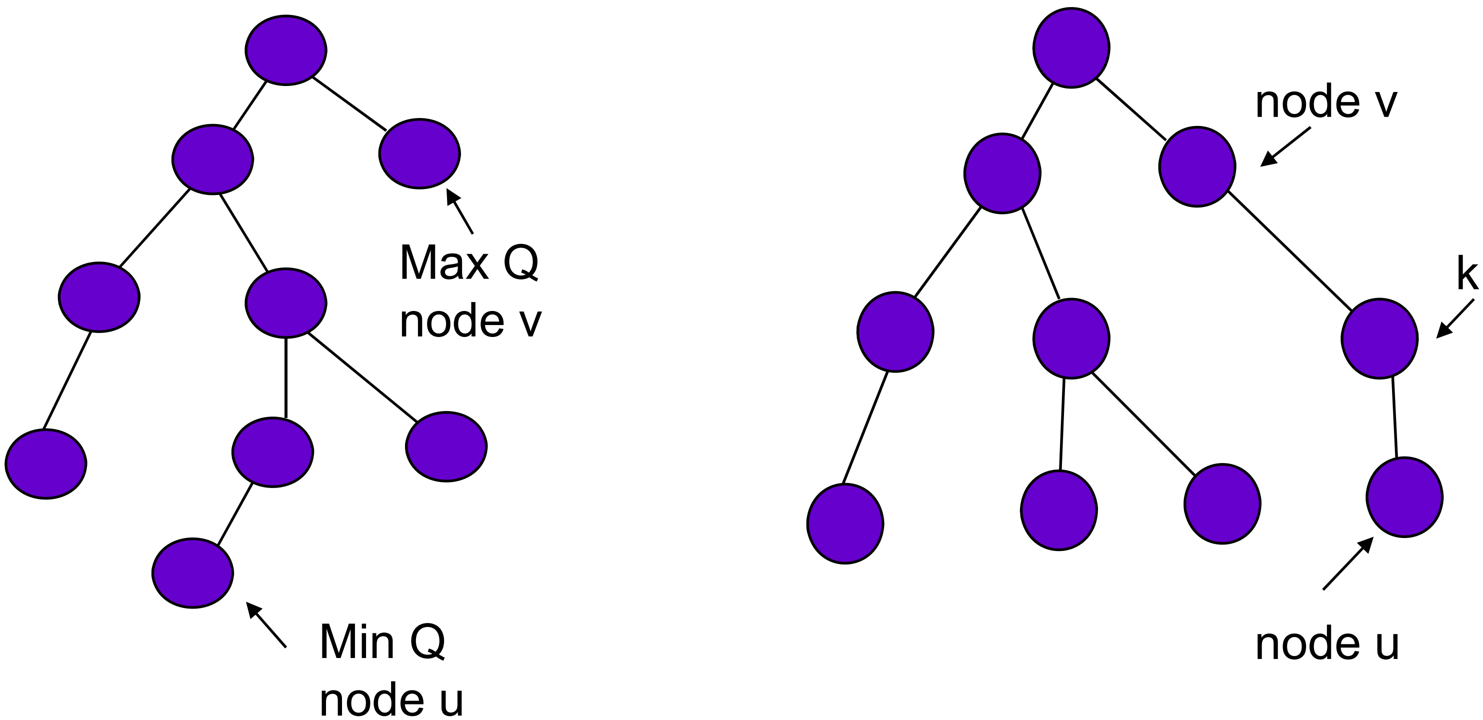
4. **Minimum Hop Tree (MHT):**
- Finds the minimum hop tree
- Steiner tree heuristic with equal weights assigned to the links of the network.

5. **Balanced Light-Tree (BLT):**
   - Balancing procedure that takes power budget constraints into consideration.
     - Aims at minimizing the average splitting losses of the tree.

6. **Max Degree Tree (MDT_F):**
   - It takes into account only the power budget.
   - Controls splitting losses at the nodes by not allowing the construction of trees with node degree greater than a predetermined value F.

Multicast Routing Algorithms

7. **Balanced Light Tree_Q (BLT_Q) :** Takes the Q-factor into consideration during the balancing procedure aiming at maximizing the average Q-value of the tree.



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.

8. **Balanced Light tree_Qtolerance (BLT_Qtolerance):**

- BLT Q algorithm is modified to BLT_Qtolerance to maximize the average Q-value of the tree and at the same time to keep the total number of the links in the tree as low as possible.
- Considering that the tolerance Q-factor is q, this algorithm maximizes the Q-factor only at those destination nodes that the Q-factor is below q.
- Terminates if the Q-value of all destination nodes in the tree is above q, 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

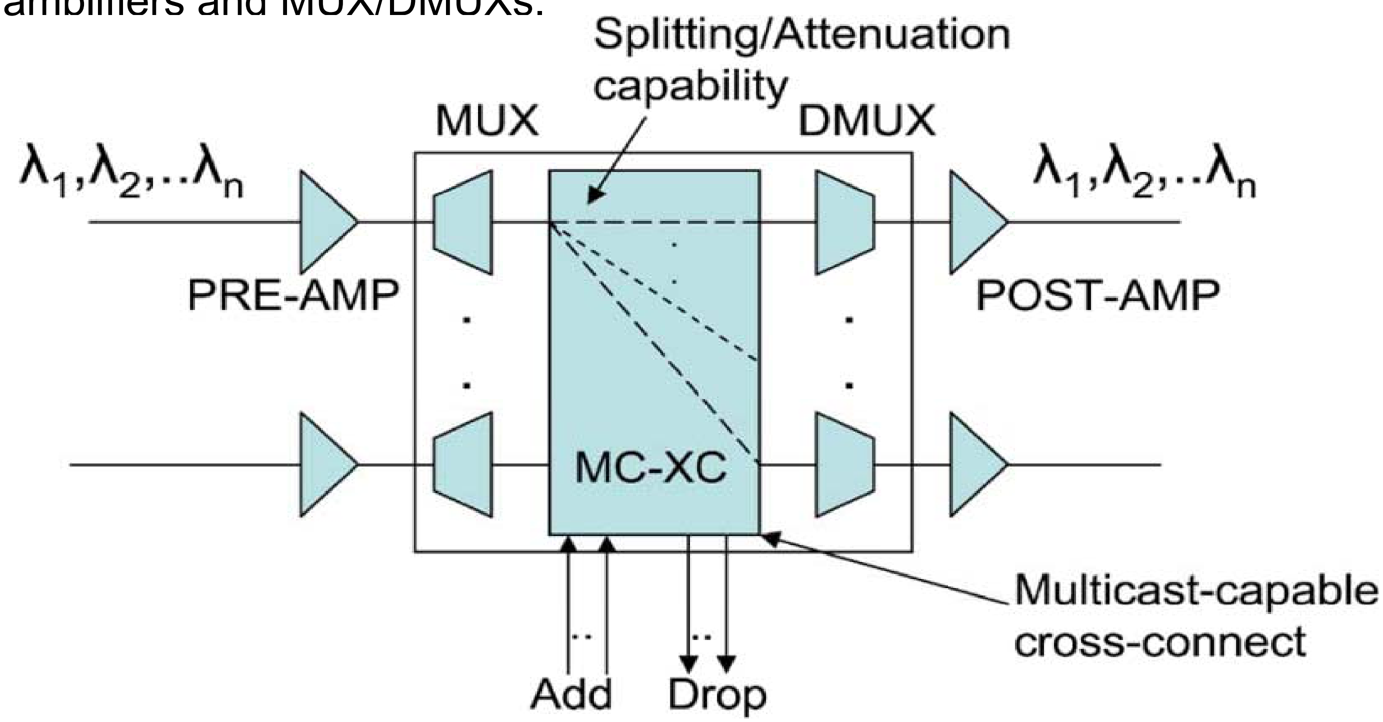
- Dynamic System:
  - Poisson arrivals
  - Exponentially distributed holding times with a unit mean.
  - 100 Erlangs load.
  - For each run 5.000 requests were generated for each multicast group size.
  - The results for each simulation point were obtained as the average of 5 runs .

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

1st Node Architecture and Engineering design

- Several Node architectures and Engineering Designs were investigated to determine the impact of the physical layer :

A. **Node Architecture:** The node design uses a MC-XC, EDFAs as post and pre amplifiers and MUX/DMUXs.



1st Node Architecture and Engineering design

- **Engineering scenarios:**

1. Pre-amplifier's gain compensates for the fiber losses, whereas post-amplifier's gain is set to 14 dB. Signal launched power into the fiber is 0 dBm and each EDFA is assigned a 7 dB Noise Figure.
2. Signal launched power into fiber is now increased to 3 dBm. The gain of the postamplifiers is reduced to 12 dB with an output power of 20 dBm. The noise figure of each EDFA is adjusted depending on its gain.
3. The node parameters of case 2 are used and in addition in-line amplifiers are introduced on each network span that exceeds 40 km thus improving the -performance of each link.

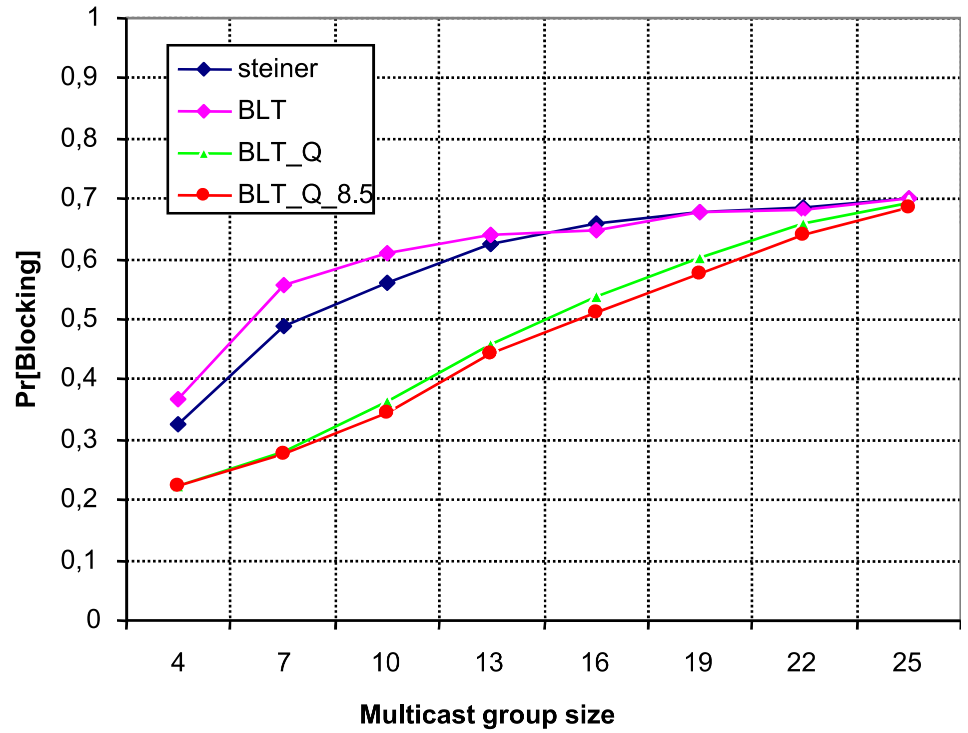
Gain in dB	NF
G<13	7
13<G<15	6.7
15<G<17	6.5
17<G<20	6
G>20	5.5

Simulation Results

❑ Engineering Scenario 1:

•The Steiner tree heuristic and the BLT algorithm that only takes power budget constraints into consideration have much higher blocking probability than the BLT_Q and BLT_Qtolerance algorithms.

•This is the case as with the new algorithms the trees tend to become “shallower” which means that the Q threshold is not exceeded.

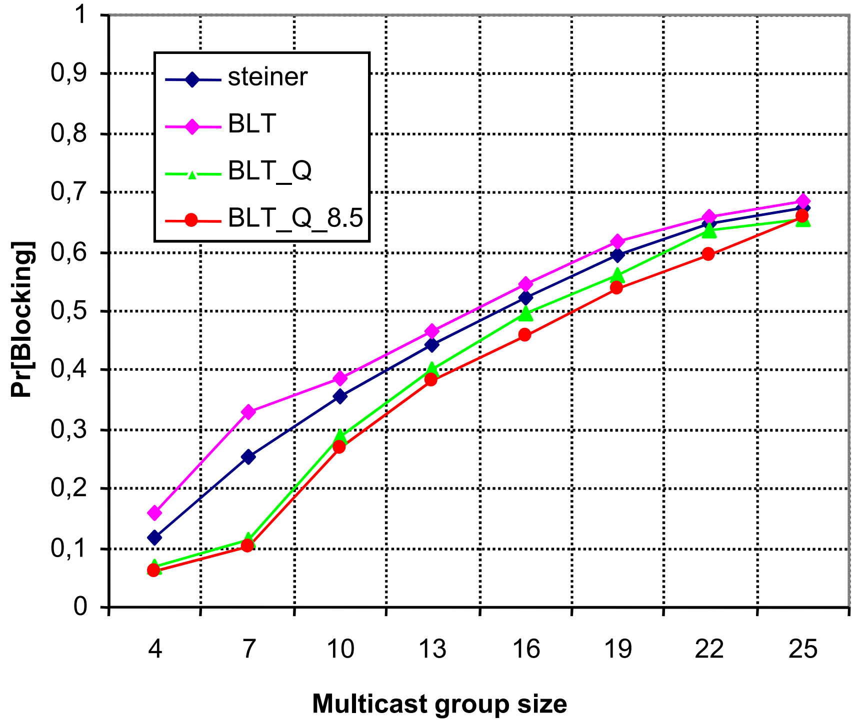


Simulation Results

❑Engineering Scenario 2:

•The network is reengineered so that the launched power into the fiber is 3dB higher and each network node has more gain shifted from the post-amplifier to the pre-amplifier resulting in improved node noise figure.

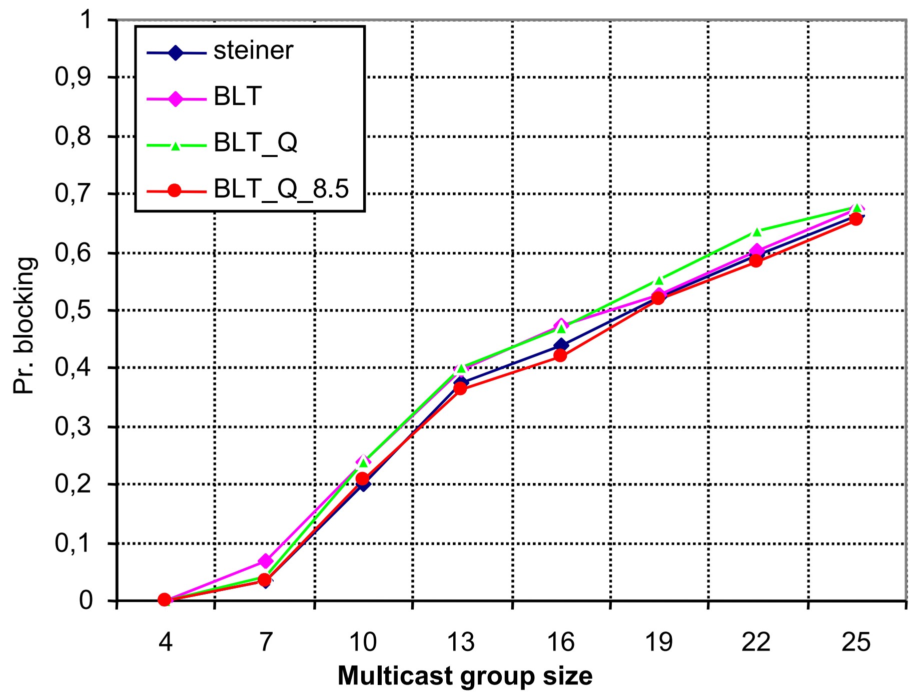
• Improvement in the overall blocking probability compared to the engineering scenario 1.



Simulation Results

❑**Engineering Scenario 3:**

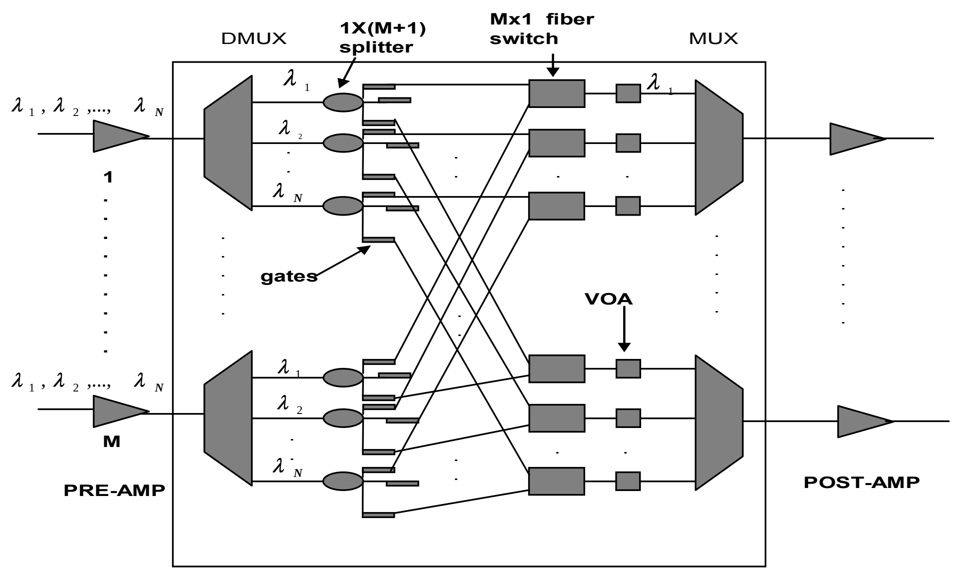
•The fiber links now include in-line amplifiers.
•All multicast algorithms provide approximately the same results as the calculation of the Q factor is now improved and the limiting factor is now the number of wavelengths in the network.



2nd Node Architecture and Engineering design

B. Active /Passive optical Splitters

- Generic node architecture for passive splitters:



- Component Insertion Loss:

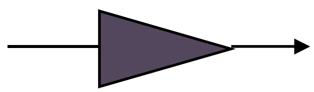
Component	Mux/Dmux	VOA	Splitter	SOA	Switch
Losses in dB	3	0.5	10*log(fan out)	0.6	1

2nd Node Architecture and Engineering design

❑Worst case scenario :

Calculated based on the maximum insertion loss a signal will encounter passing through the maximum degree node in both active and passive cases.

❑Components:



➢EDFAs:

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

- Noise Figures are based on realistic device specifications.
- Post-Amplifiers: Compensate for the node losses and their gain is set for the worst case scenario with an output power of +3dBm.
- Pre-Amplifiers: Preceding the fiber span to compensate for the fiber losses that are set at 0.3dB/Km. Output power is +6dBm
- +3dBm power launched into the system .

2nd Node Architecture and Engineering design

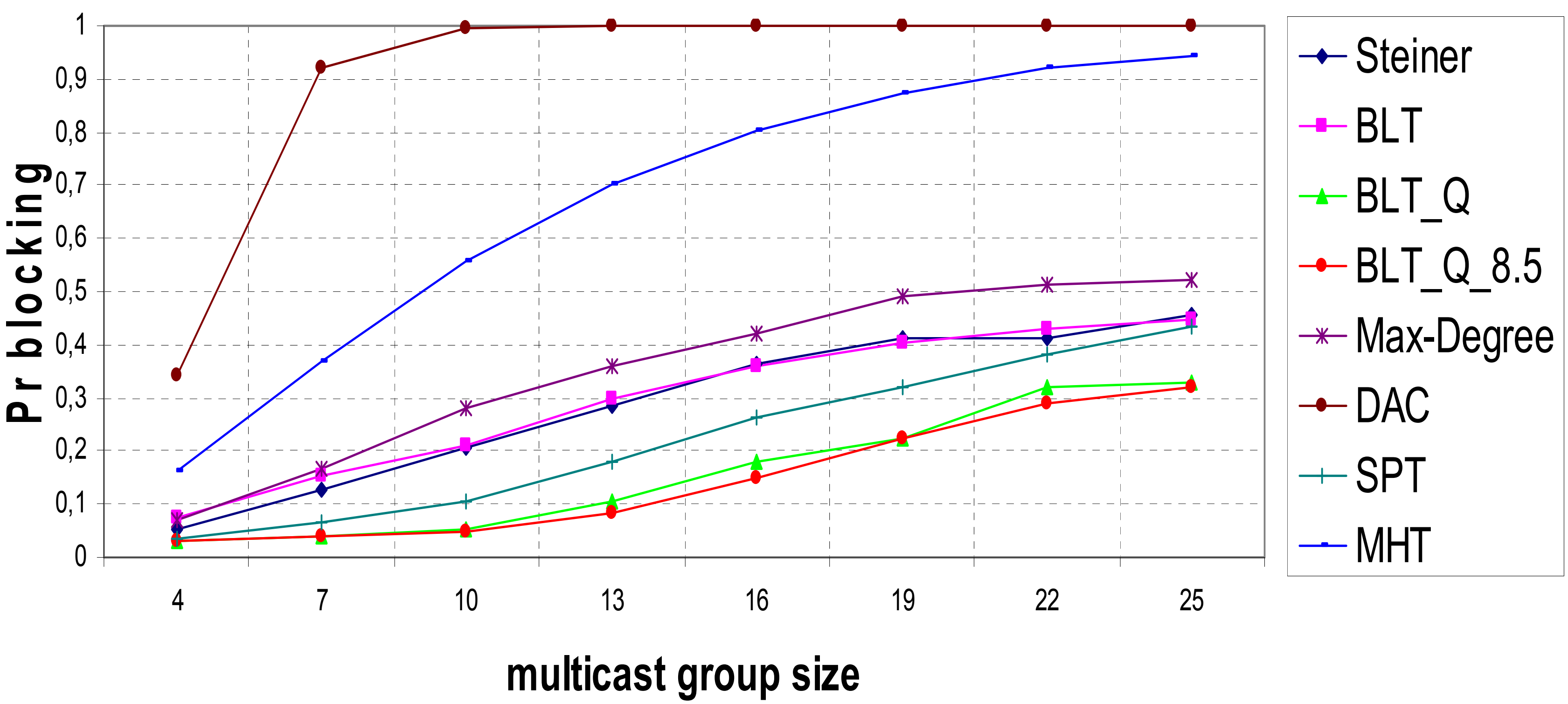
- Variable Optical Attenuators (VOAs):
  - Required to equalize the individual total input powers to the post amplifiers and signals are attenuated for the worst case scenario.

- Optical Splitters:
  - Active: Split the power only as many times as needed for the signal to be forwarded to the destined outputs.
  - Passive: Split the power as many times as the degree of the node plus one to account for the drop operations. Gates are required to block the power at outputs where the signal is not destined for.

- PIN photodiodes:
  - Used at the destination nodes. Their pre-amplifier gain is assumed to depend on the degree of the node, with a maximum output power of -4dBm and a noise figure of 4.5dB.

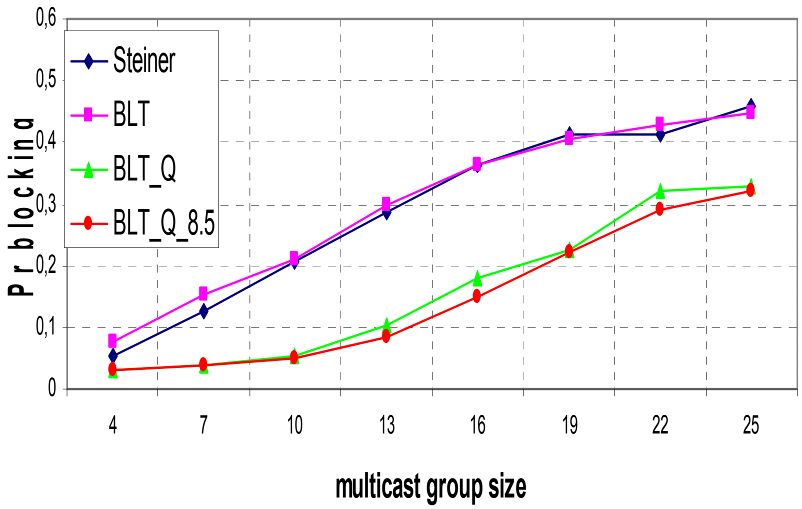
Simulation Results

Blocking probability versus the multicast group size for node architecture with active splitters.

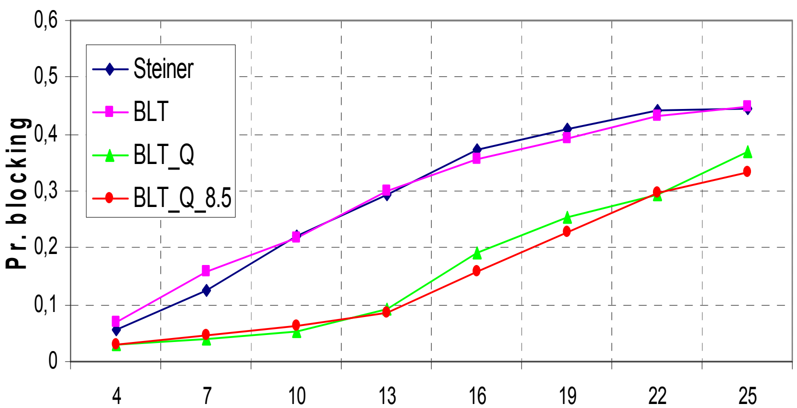


Simulation Results

a) active



b) passive



- $BLT_{Qtolerance}$ and BLT_Q heuristics perform the best for both passive and active splitting cases since they take physical layer impairments into account.
- No particular advantage when using active instead of passive splitters.
  - VOAs are used to attenuate the total power to a predetermined value that is calculated based on the worst case scenario.
  - Results were slightly better for active splitters since at the destination nodes the signal is dropped to the Rx before facing VOA attenuation and since no gates are required, thus resulting in an improvement on the Q-factor.

3rd Node Architecture and Engineering design

C. Transmitter/Receiver Designs:

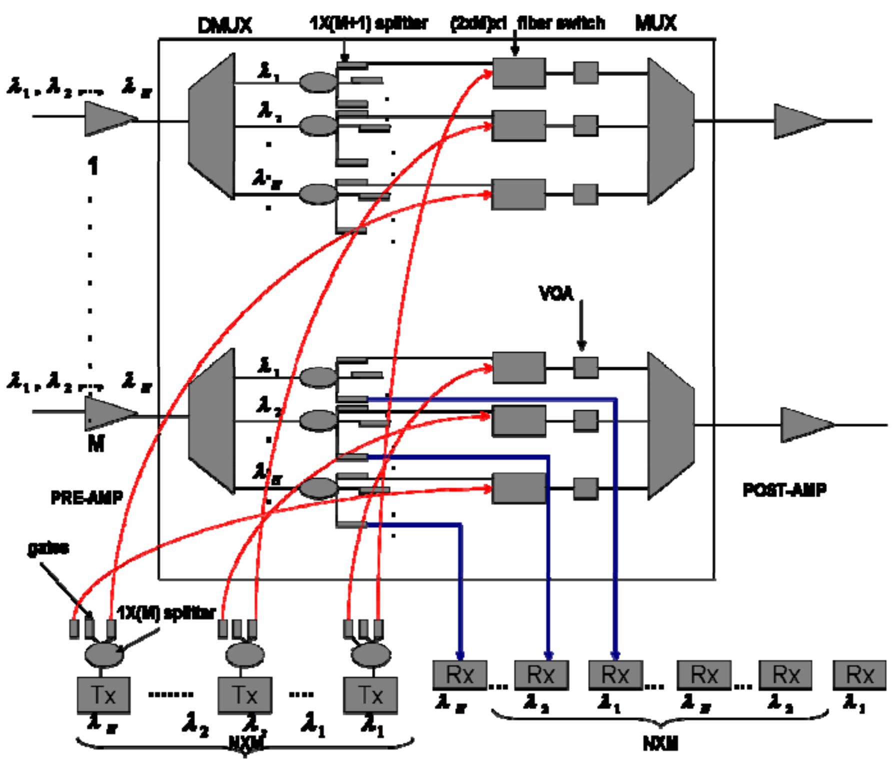
1. Fixed Txs/Rxs
2. Tunable Txs/Rxs
3. Tunable Txs/ Fixed Rxs
4. Fixed Txs /Tunable Rxs

Assumptions:

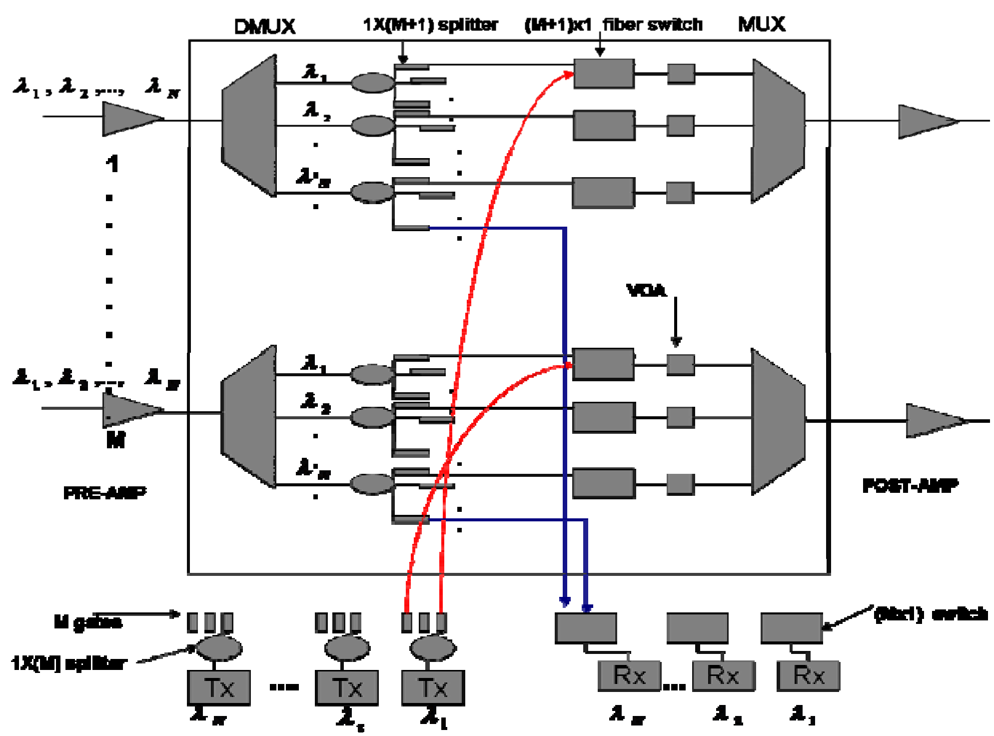
- Passive splitting.
- Component losses are as described for the case of passive splitters.
- Noise Figures of the amplifiers used are as previously described.
- Worst case scenario is the maximum insertion loss a signal encounters passing through the maximum degree node of the network.

3rd Node Architecture and Engineering design

1. Fixed Txs/Rxs:



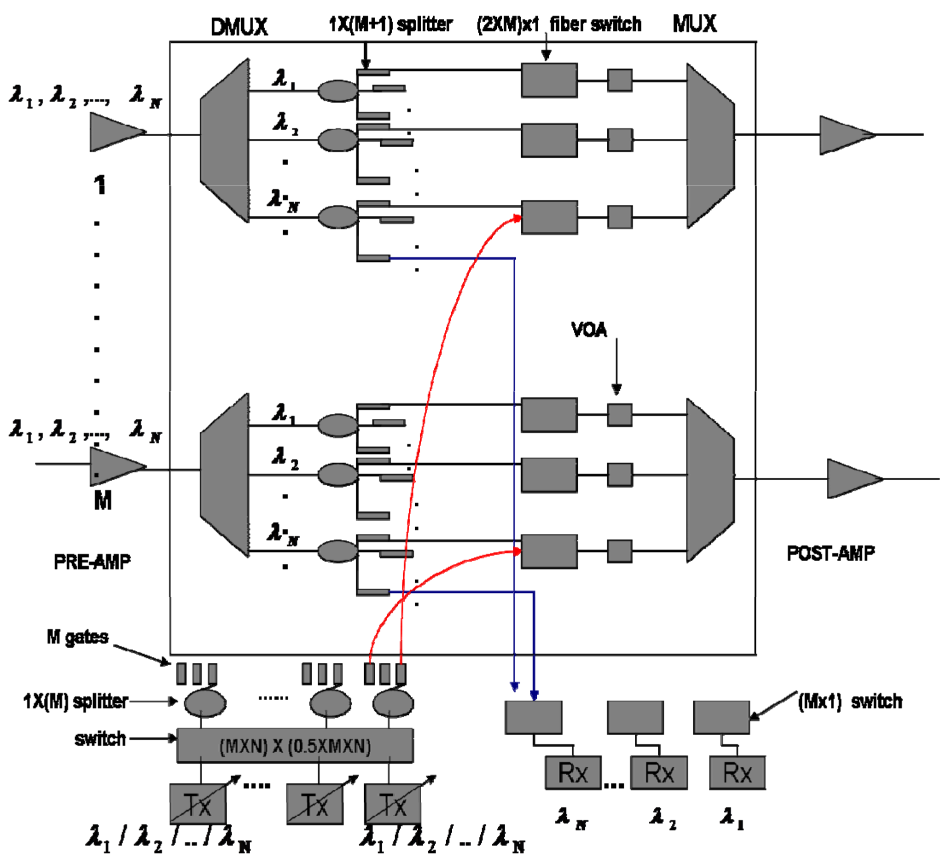
a) Number of Tx/Rx is equal to the number of wavelengths times the degree of the node



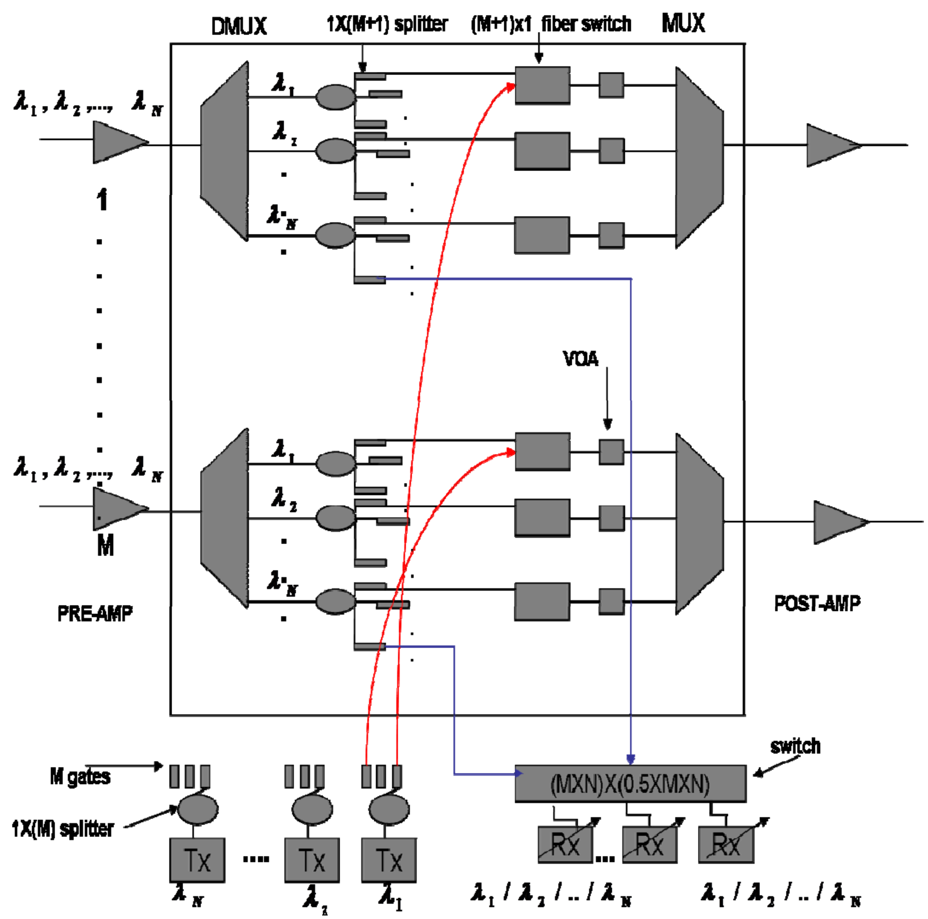
b) Number of Tx/Rx is equal to the number of wavelengths.

3rd Node Architecture and Engineering design

2. Tunable Txs/ Fixed Rxs:

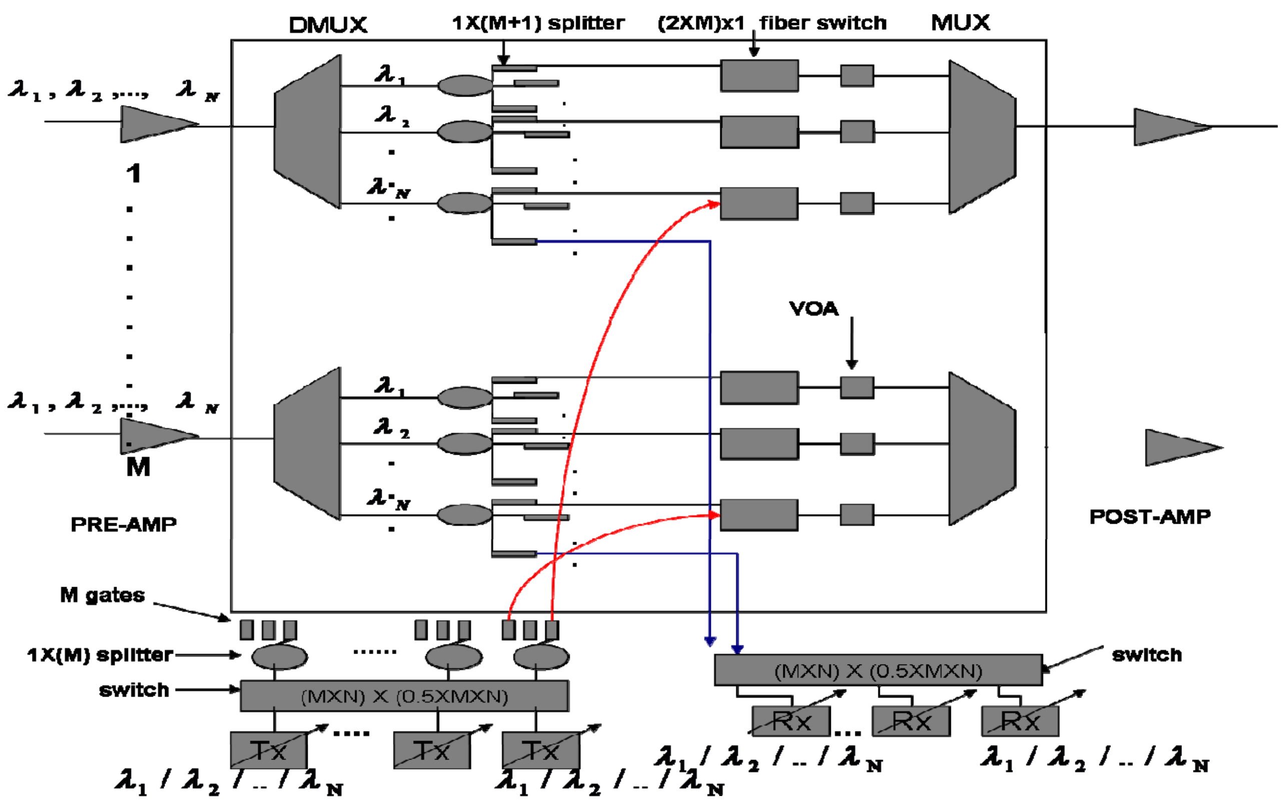


3. Fixed Txs/ Tunable Rxs:



3rd Node Architecture and Engineering design

4. **Tunable Txs/ Rxs:** Number of Tx/Rx is equal to the number of wavelengths.



3rd Node Architecture and Engineering design

- Tunable cases:
  - 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.

- Node engineering is modified to account for the various new architectures

- Output power of pre and post amplifiers is now set to +7dBm.

- Signal launched power into the fiber is now set to +5dBm.

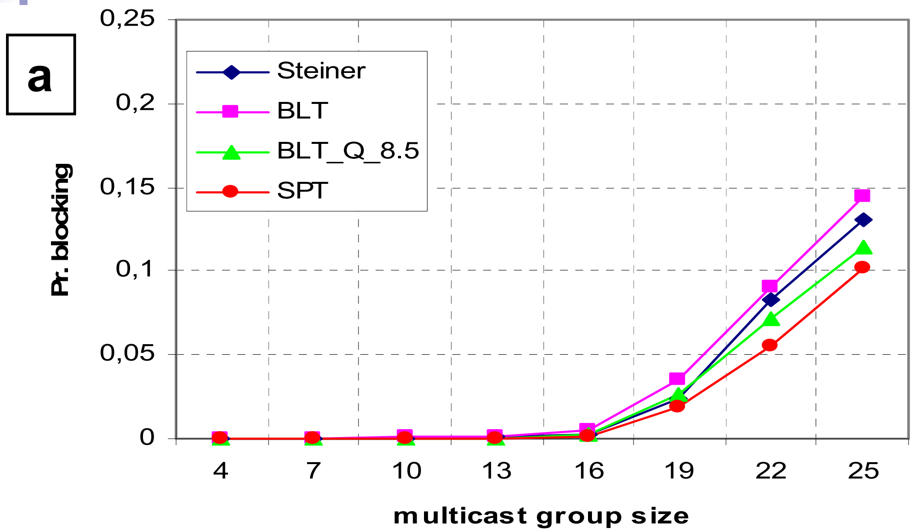
Size	Switches Losses in dB
X<25	1
25<X<36	1.5
36<X<56	2.2
56<X<68	3
68<X<80	3.7
80<X<100	4.5
X>100	5

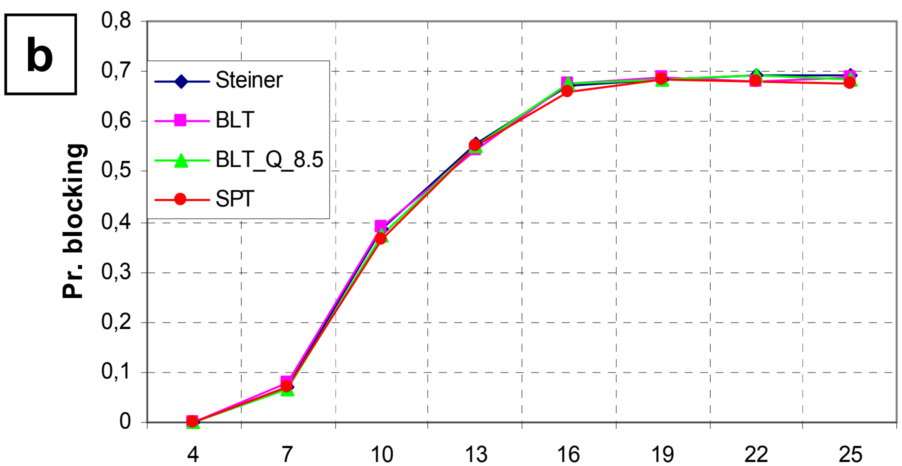
3rd Node Architecture and Engineering design

- MC-RWA:

- 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





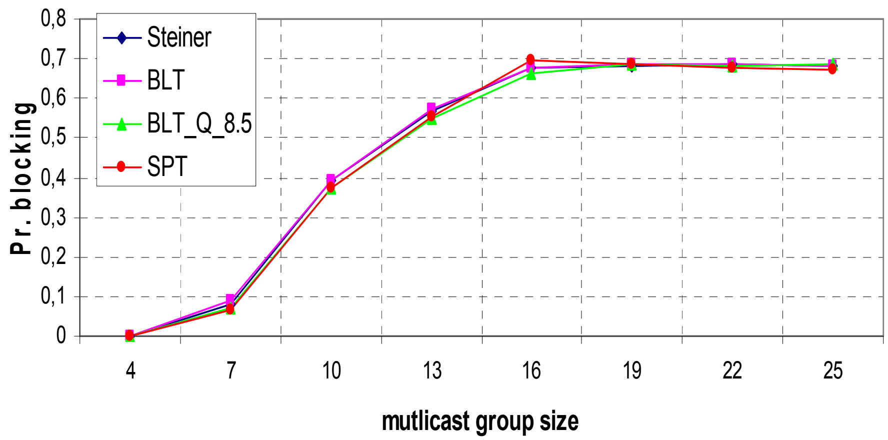
1. **Fixed Txs/Rxs:**

a. Number of Txs/Rxs equal to the number of wavelengths times the degree of the node.
b. Number of Txs/Rxs equal to the number of wavelengths.

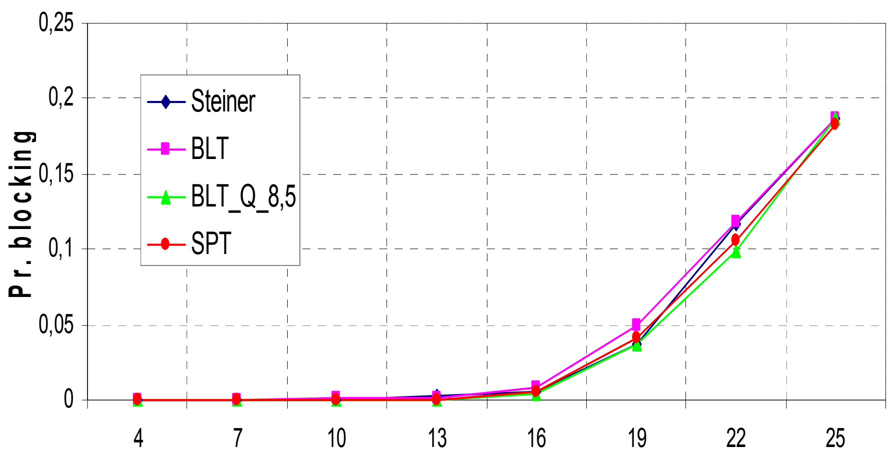
- In case a blocking probability is greatly reduced since there is more flexibility in the network to assign wavelengths to the connections.

Simulation Results

Tunable Txs/ Fixed Rxs



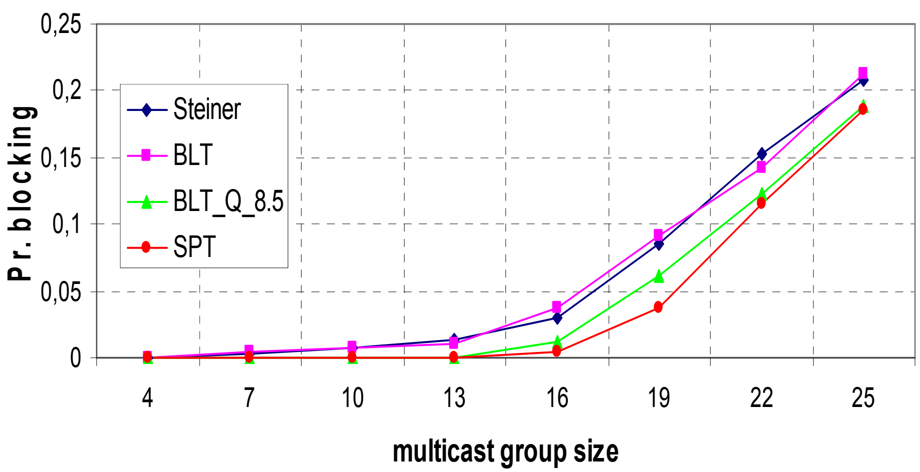
Fixed Txs/ Tunable Rxs



- Blocking probability in fixed Txs/tunable Rxs is greatly reduced compared to the tunable Txs/ fixed Rxs.
- Flexibility in the Rxs is of high importance for the provisioning of multicast sessions.

Simulation Results

Tunable Txs/ Rxs



▪Blocking probability in this case is reduced but still fixed Txs/Rxs of case a perform better among the other engineering designs.

❑BLT_Q_threshold and SPT heuristics perform the best compared to the other routing algorithms for all Txs/Rxs cases apart from fixed Tx/Rx of case b and tunable Tx/ fixed Rx where all heuristics perform almost the same (blocking probability is limited by the Tx/Rx constraint.)

Work Package 4

RWA for protected MC connections with PLCs (5-month duration)

- Development of a simulation code that performs the routing/protection and wavelength assignment under physical layer constraints.

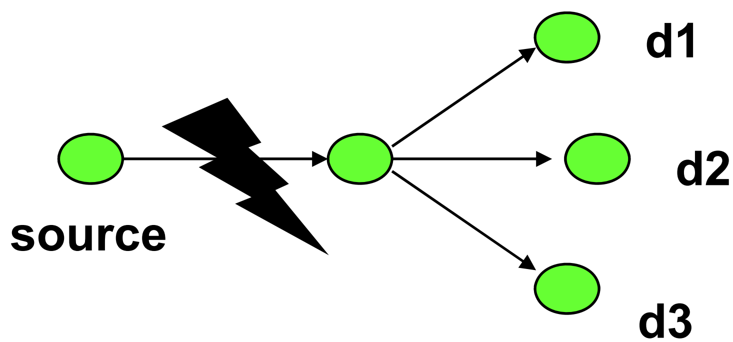
- Development of novel protection techniques for multicast connections taking into account the physical layer constraints:
  - LEVEL protection heuristic
  - PCH protection heuristic
  - Q Based PCH protection heuristic

  And compared with existing protection techniques
  - MCH heuristic
  - MC-CR heuristic
  - Segment Protection Heuristic
  - SSNF heuristic

- Self Sharing and Cross Sharing approaches were considered.

Introduction

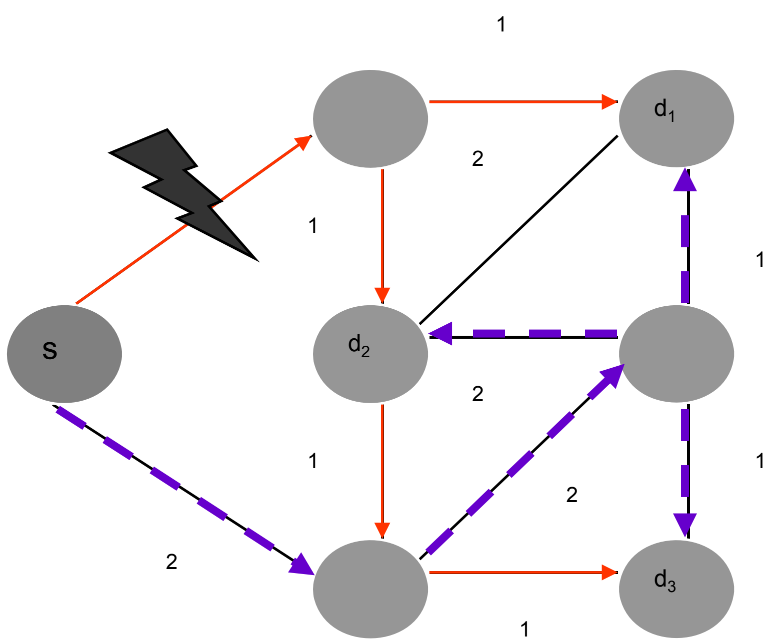
- Protection techniques are used for the restoration of traffic in case of a link failure.
- Fiber cuts occur often and are the predominant form of failure.



- A fiber cut (link failure) may jeopardize the entire multicast session
- We need fast recovery of the traffic when a link failure occurs.

Introduction

- Link Disjoint Techniques
  - A working light tree.
  - A link disjoint protection tree.



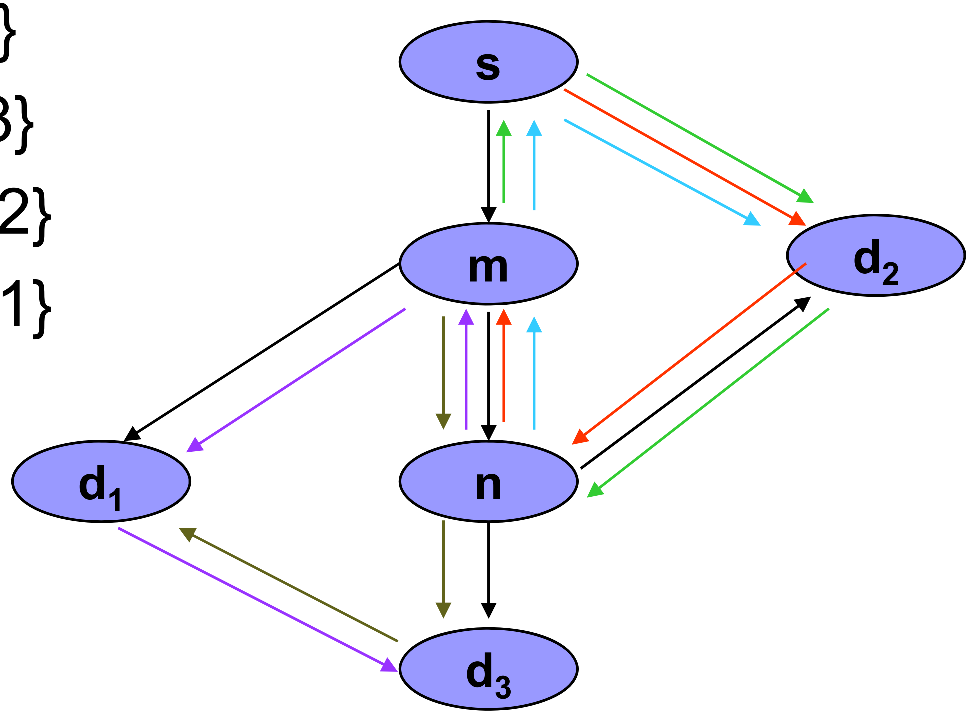
Introduction

- Shared backup Techniques:
  - Backup paths are predefined but not created until a failure occurs.
  - Backup paths can be used to protect different multicast connections.
  - Self and Cross Sharing Techniques.

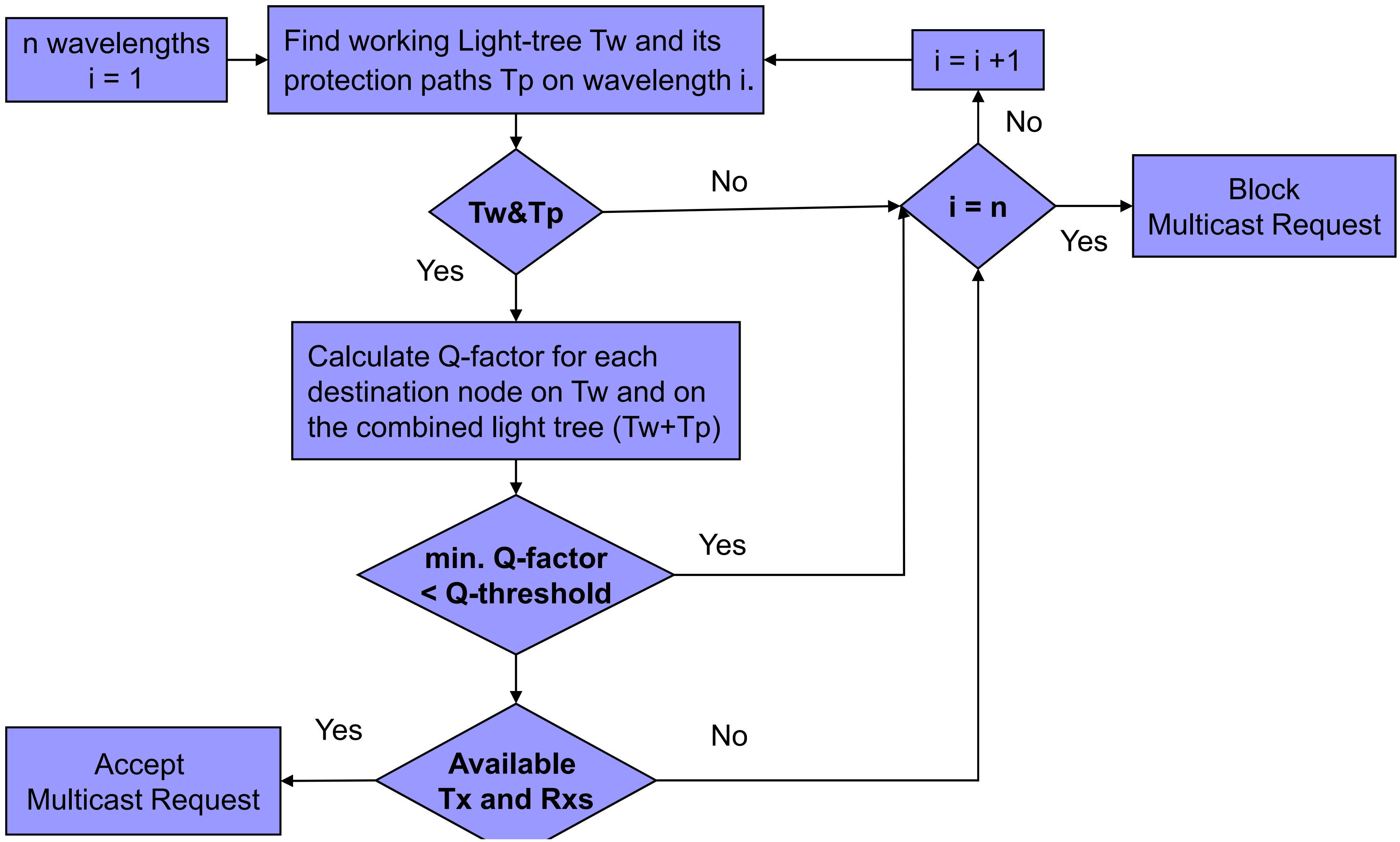
- Segment based protection Techniques:
  - Working light-tree is divided into segments, and each segment is separately protected using Self Sharing Techniques.

Introduction

- {s ->m}
- {m ->n}
- {n ->d3}
- {n -> d2}
- {m ->d1}

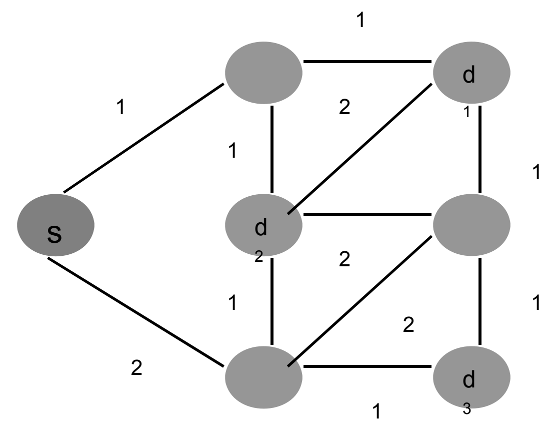


Multicast Routing/Protection and Wavelength Assignment Algorithm (MC-RWA)

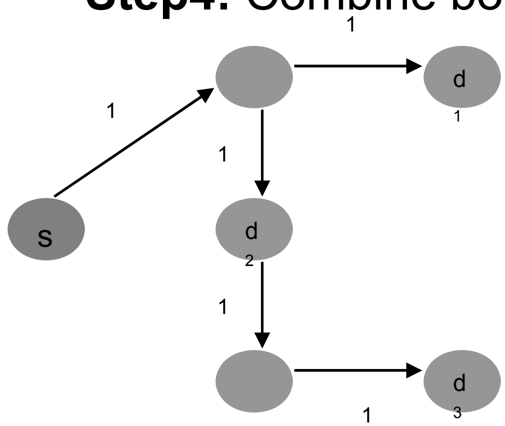


Multicast routing and protection algorithms

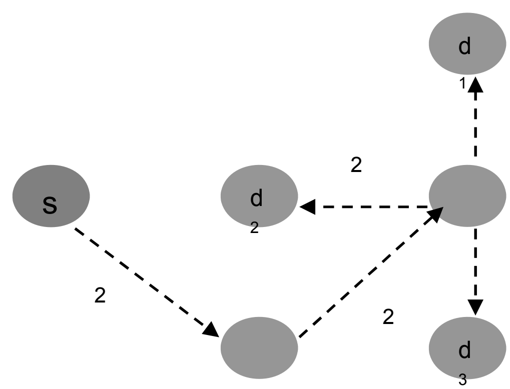
1. Minimum Cost Heuristic:



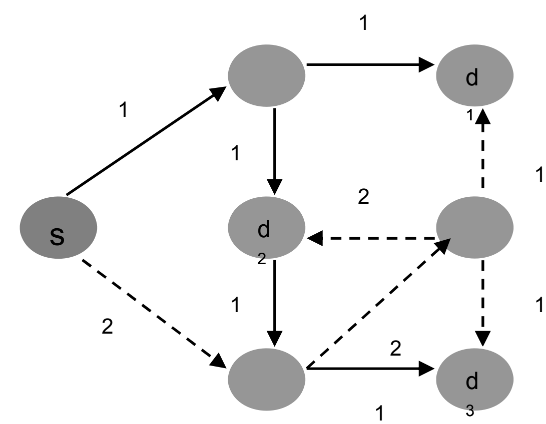
Step1: Compute a light tree from source to each destination using Steiner tree heuristic.
Step2: Remove edges used to construct the light tree from G and save the resulting graph G'.
Step3: Compute a protection light tree on G' using Steiner tree heuristic.
Step4: Combine both light trees into one light tree.



- Working light tree



- Protection light tree

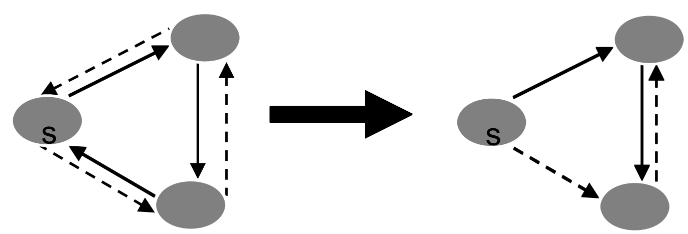


- Combined light tree

Multicast routing and protection algorithms

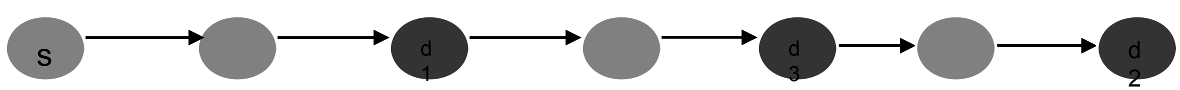
2. MC-Collapsed Ring Algorithm:

- In a ring topology signal leaves from the source node in two opposite directions and reaches every node providing 1+1 protection.



Steps:

I. Finding working light path in graph G.
   - Compute a linear tree (path) from source to all destinations in a serial fashion. (DAC heuristic).
     - Example: {s, d1,d2,d3}

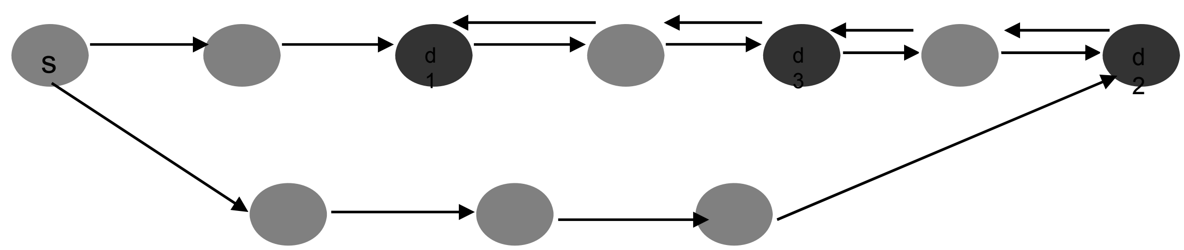


Multicast routing and protection algorithms

II. Remove edges used to construct the light tree from G and save the resulting graph G'.

III. Finding protection light path in graph G':

- Find min. cost path from source to the last destination node in the ring.
- Traverse the working path backwards till first destination node is reached.



Multicast routing and protection algorithms

3. Level Protection Algorithm

- Definitions:

   I. **Segment points**: a vertex is said to be a segment point if it is the source or a desination node of the multicast request.

   II. **Segments:** a path between two segmnet points is said to be a segment.

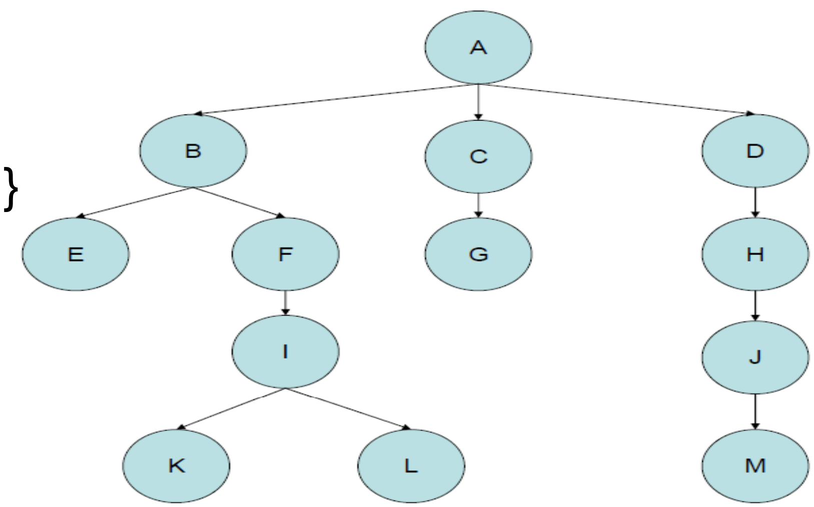
   III. **Level_i of segment points:** the level of a segment point is the number of the segments between that segment point and the source.

   IV. **$\text{Level}_{(i-1,i)}$ segment:** is the set of all the segments of the tree that are between the segment points of $\text{level}_{(i-1)}$ and the segment points of level_i.

Multicast routing and protection algorithms

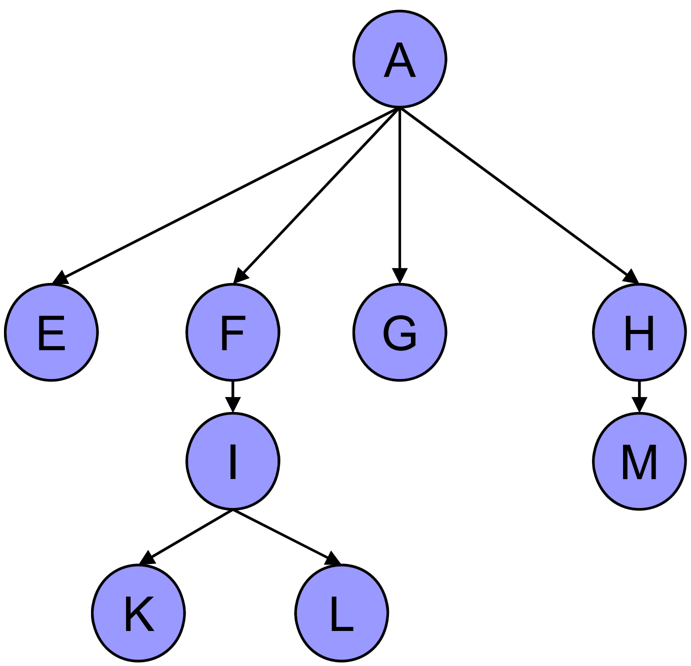
- The idea behind the level protecion aglorithm is the hierarchical structure that a graph has if it can be constructed in the form of a pyramid graph.
- The construction of such a graph in our case can be achieved if we find protection paths for the working light-tree in such a way that a pyramid graph can be create.
- Working path is constructed using Steiner tree heuristic.

Multicast request:
{A, E, F, G,H, I, K, L, M}

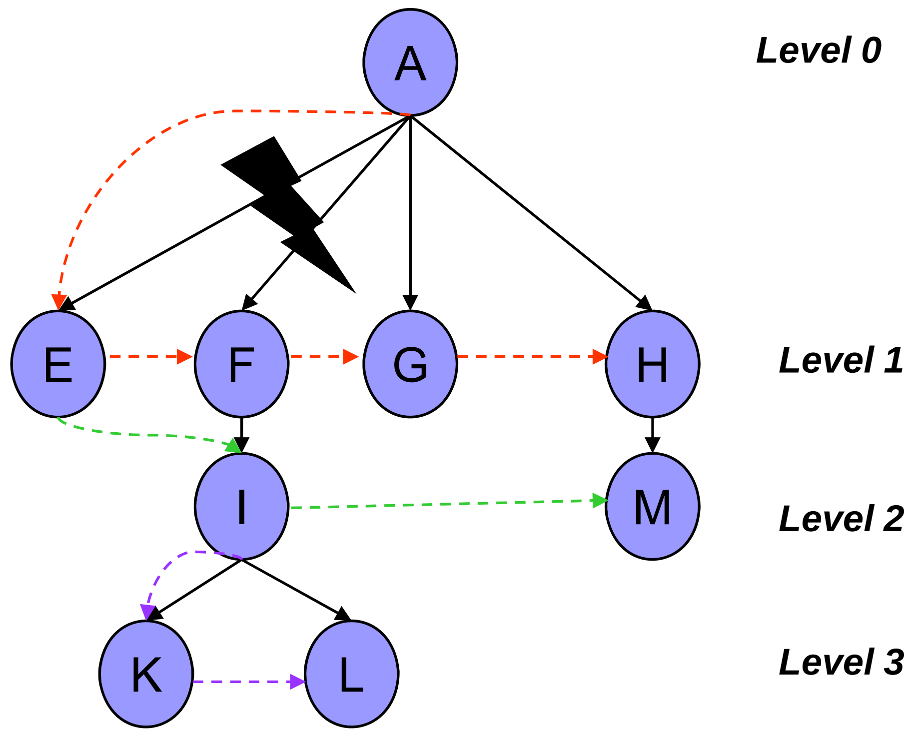


Multicast routing and protection algorithms

•Auxiliary Graph of working path with segment points A, E, F, G,H, I, K, L, M.



•Protection paths between the levels of the auxiliary graph.



Multicast routing and protection algorithms

- **Self-Sharing technique:**
  - Backup paths can share the links on the working tree of the same multicast request if there are disjoint with the links of the level segment under examination.
  - Backup paths of the same multicast request can be reused in the calculation of the protection path if there are disjoint with the links of the level segment under examination.
- **Cross-Sharing technique:**
  - The different backup paths on any multicast connection can share the common backup wavelengths if their corresponding primary segments are link-disjoint.
- Sharing techniques reduce the total number of links required for the working and protection paths.

Multicast routing and protection algorithms

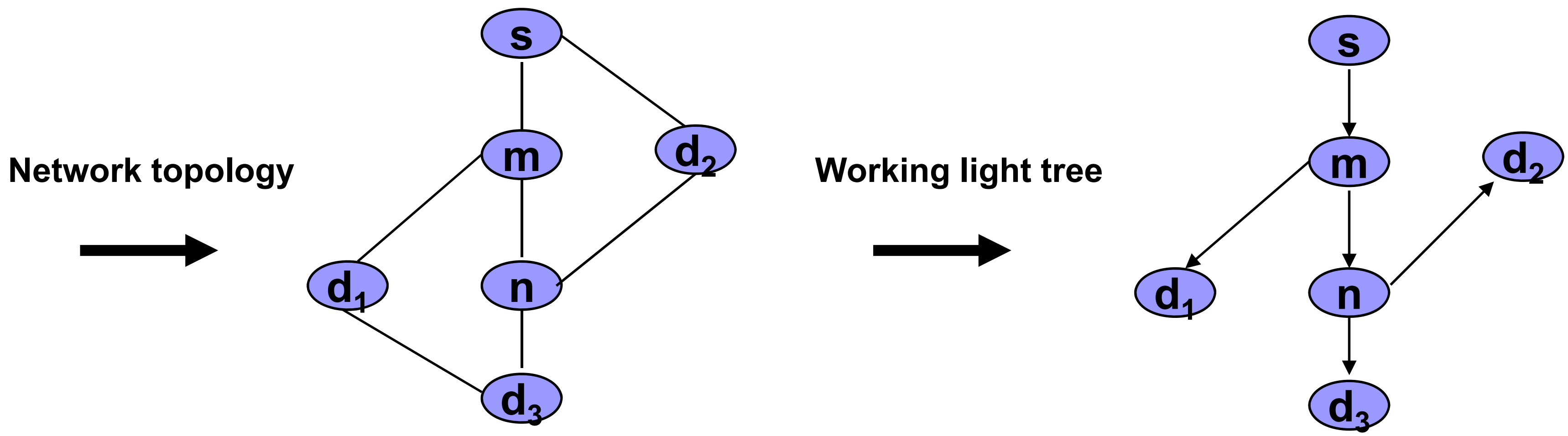
4. Segment Protection Algorithm (SP)

- Definitions:
  I. **Branch point of a tree:** a vertex with nodal degree greater than 3 and the root.
  II. **Segment point of a tree:** Branch points and destination nodes of the tree.
  III. **Segment of a tree:** A path between two segment points.

- Sharing techniques are used for the calculation of the protection paths.

Multicast routing and protection algorithms

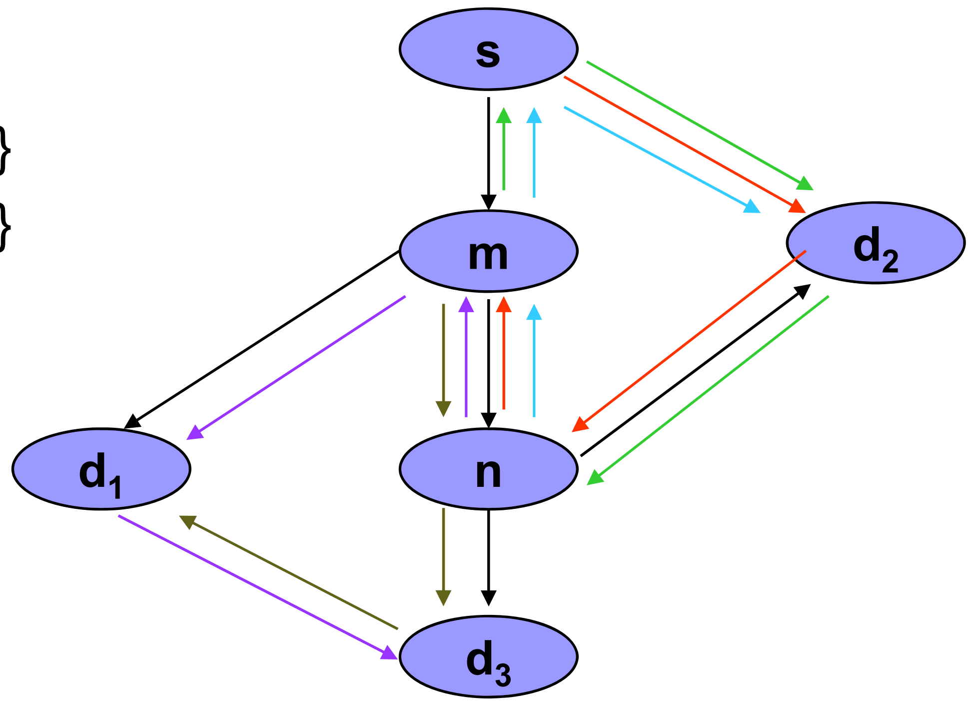
- Working light-tree is calculated using Steiner tree heuristic



- Once the protection light tree is created, the branch points, segment points and the segments are identified.
  - Branch points: s, m, n
  - Segment points: s, m, n, d1, d2, d3
  - Segments: {s ->m}, {m ->n}, {n ->d3}, {n -> d2}, {m ->d1}
- Auxiliary graph is created.

Multicast routing and protection algorithms

- {s ->m}
- {m ->n}
- {n ->d3}
- {n -> d2}
- {m ->d1}



Multicast routing and protection algorithms

5. Segment-Based Protection with Sister Node First Algorithm (SSNF)

- Modification of Segment protection algorithm.
- Definitions:
  - **Sister Nodes:** Nodes with a common parent in the auxiliary graph.
  - **Branch points**, **segment points** and **segments** are as previously defined.

Multicast routing and protection algorithms

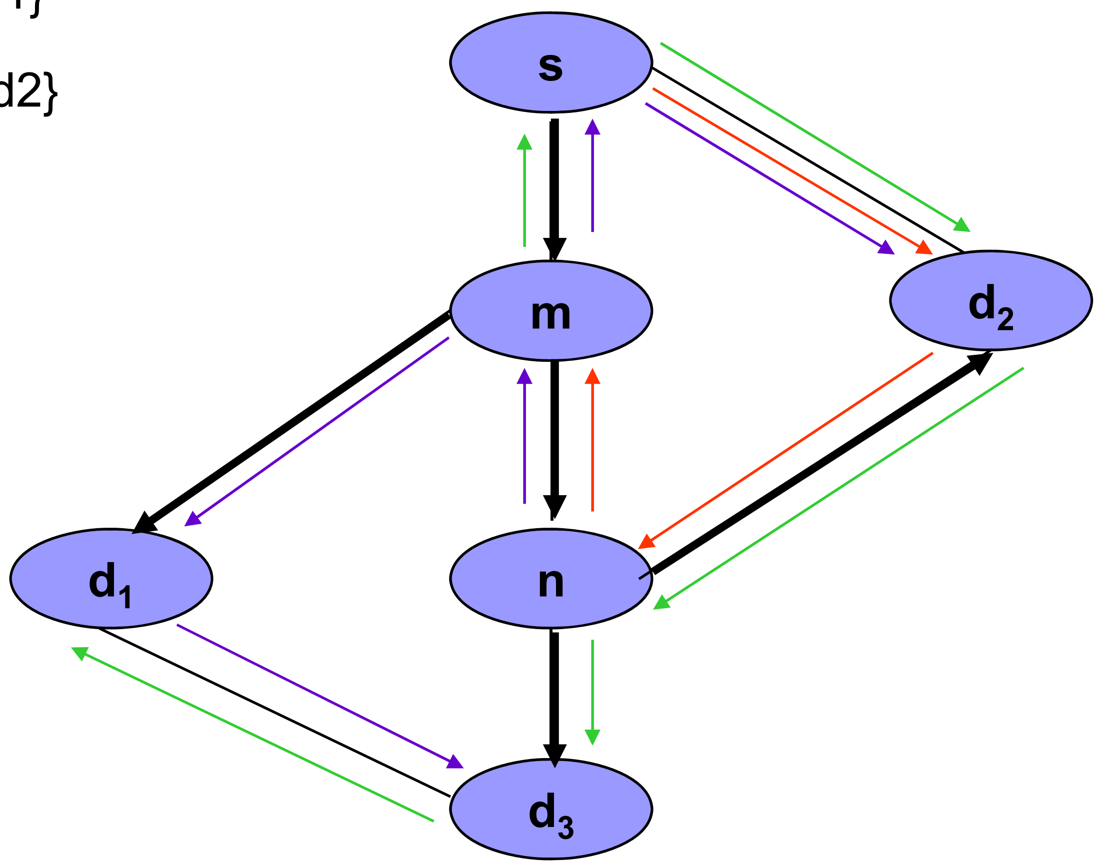
- Working light tree is constructed using Steiner tree heuristic.
- Branch points, segment points and segments are identified in working light tree.
- Auxiliary graph is created based on the segment points and the segments of the working light tree.
- Sister nodes are identified in the auxiliary graph.
- Protection paths are calculated
  - Using SP heuristic to the segments which have only one child.
  - Sister nodes are first attempted to be protected by a directed protection path that connects sister nodes with their parent and if this approach fails then SP heuristic is used.

Multicast routing and protection algorithms

Network topology

Protection path

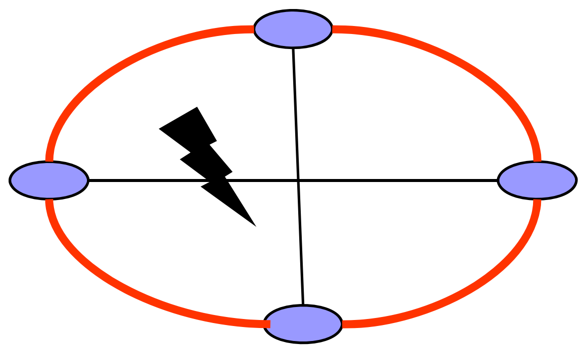
- {s ->m}
- {m ->n,d1}
- {n ->d3,d2}



Multicast routing and protection algorithms

6. P-cycles Based Protection heuristics.

- The network is decomposed into a set of p-cycles and each link in the network is covered by at least one p-cycle.



- Achieves fast restoration times since
  - p-cycles are preconfigured
  - Signaling only between the nodes of the failing link is required for the identification of the failing link and its protection.
- Achieves high capacity efficiency since a p-cycle can protect both on-cycle links and straddling links.

Multicast routing and protection algorithms

- The size of the p-cycles is an important parameter:
  - Small in size p-cycles lead to short backup paths that are not capacity efficient.
  - Large in size p-cycles lead to extremely long backup paths which are subject to prominent physical layer impairments.

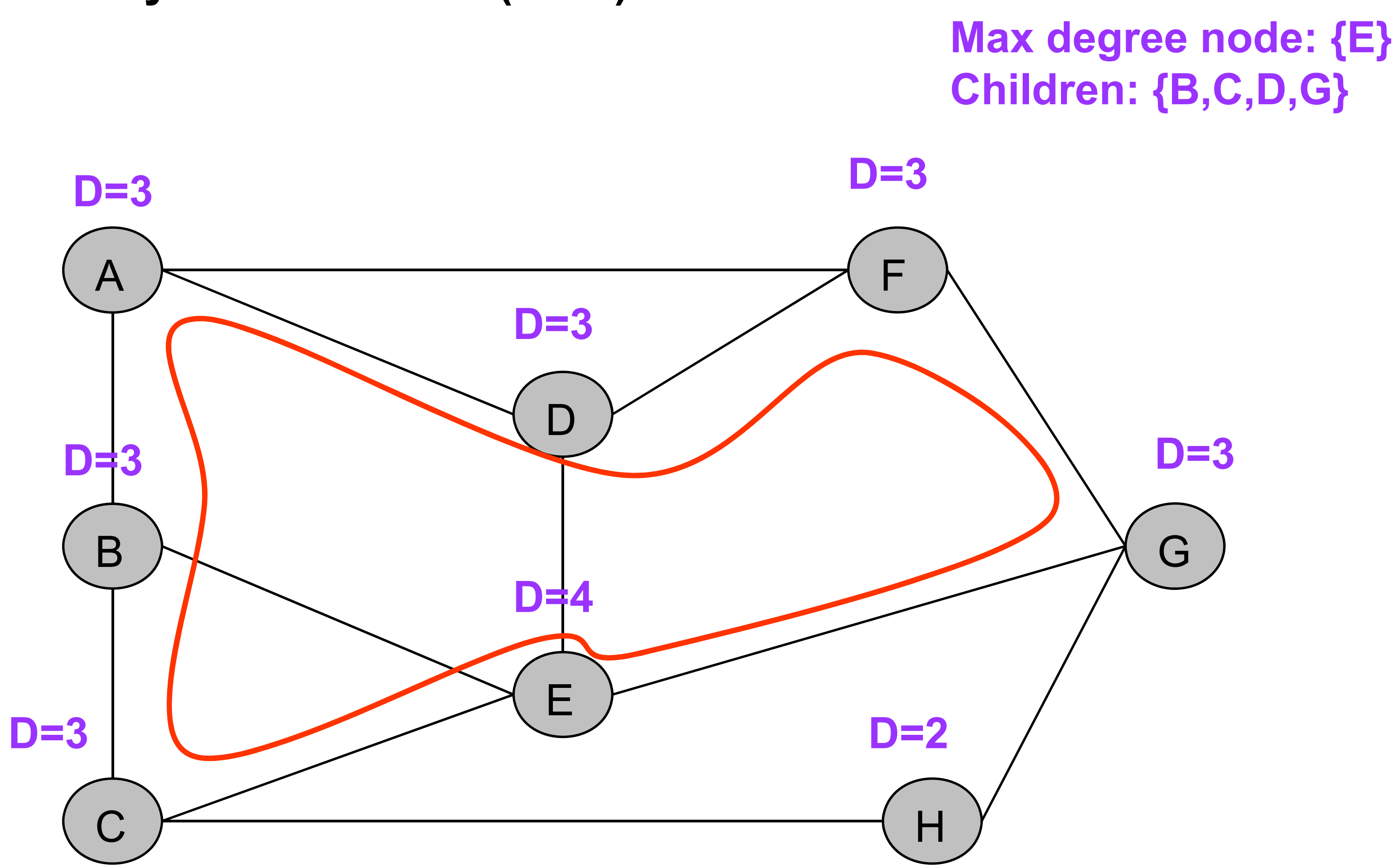
- Two p-cycles heuristics are developed:

  I. **P-Cycles Heuristic (PCH):** Decomposes the network into p-cycles starting from the links that are connected with the maximum degree node.

  II. **Q-factor Based P-Cycles Heuristic (QBPCH) :** Modification of PCH that controls the length of the p-cycles setting a Q-threshold on the resulting Q-factor of each p-cycle.

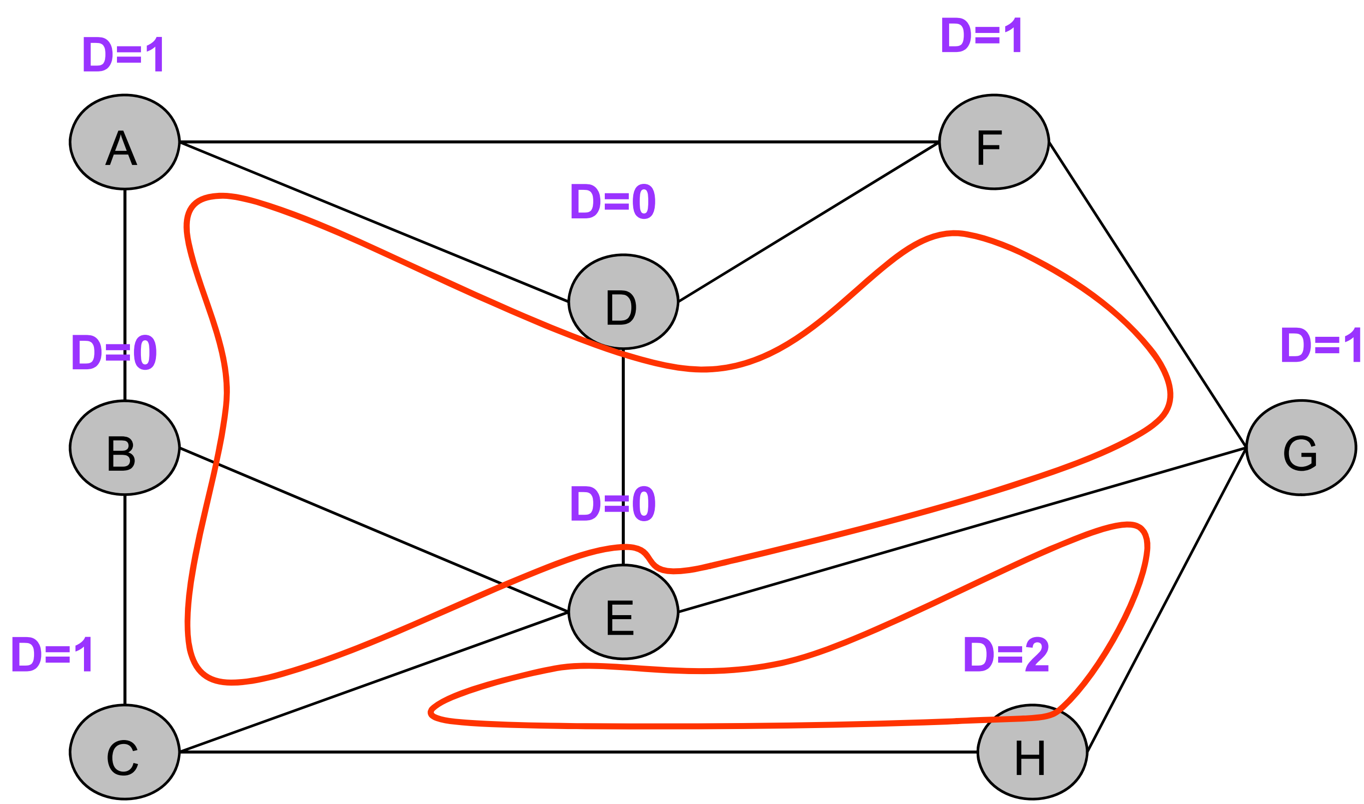
Multicast routing and protection algorithms

I. **P-Cycles Heuristic (PCH)**



Multicast routing and protection algorithms

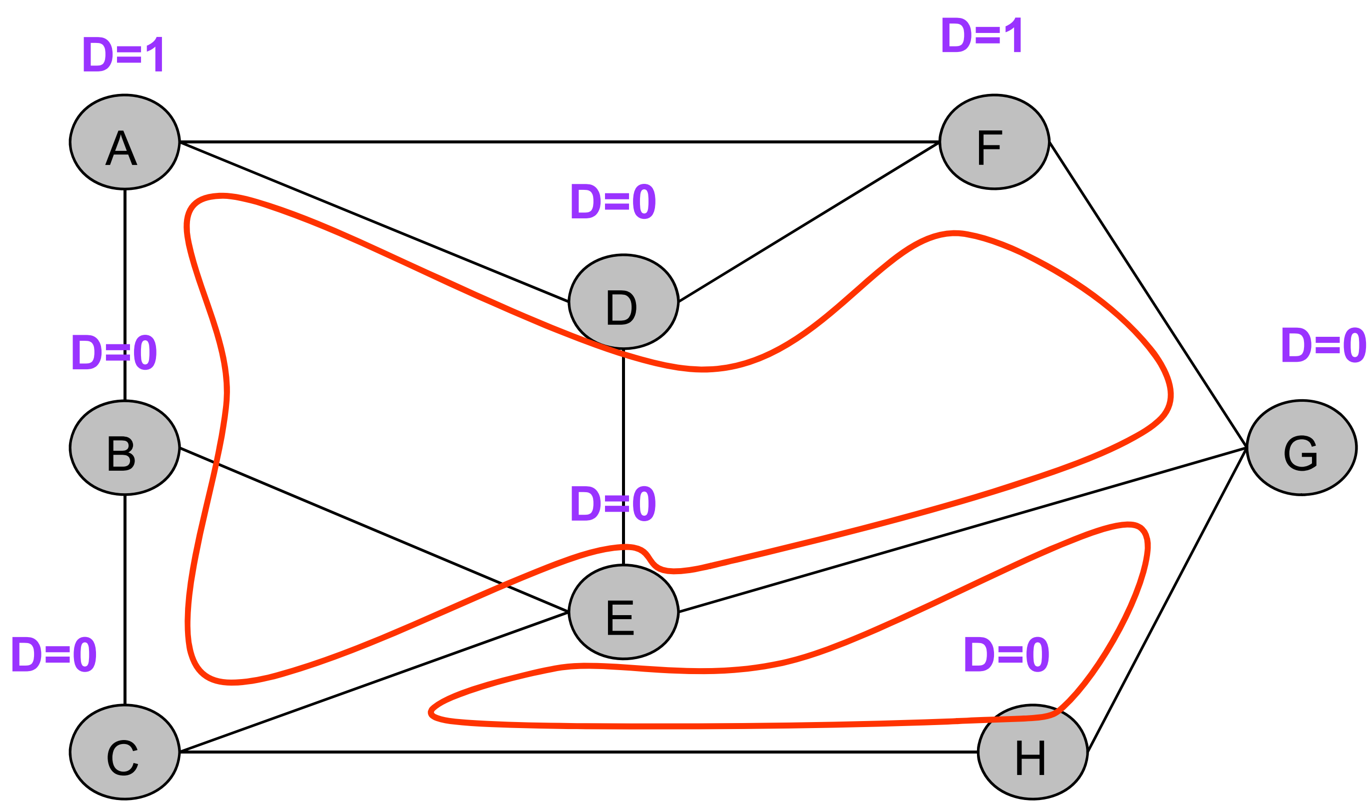
Max degree node: {H}
Children: {C,G}



Multicast routing and protection algorithms

Terminates since A and F belong to the same p-cycle.

Max degree node: {A}
Children: {F}



Multicast routing and protection algorithms

II. Q-factor Based P-Cycles Heuristic (QBPCH)

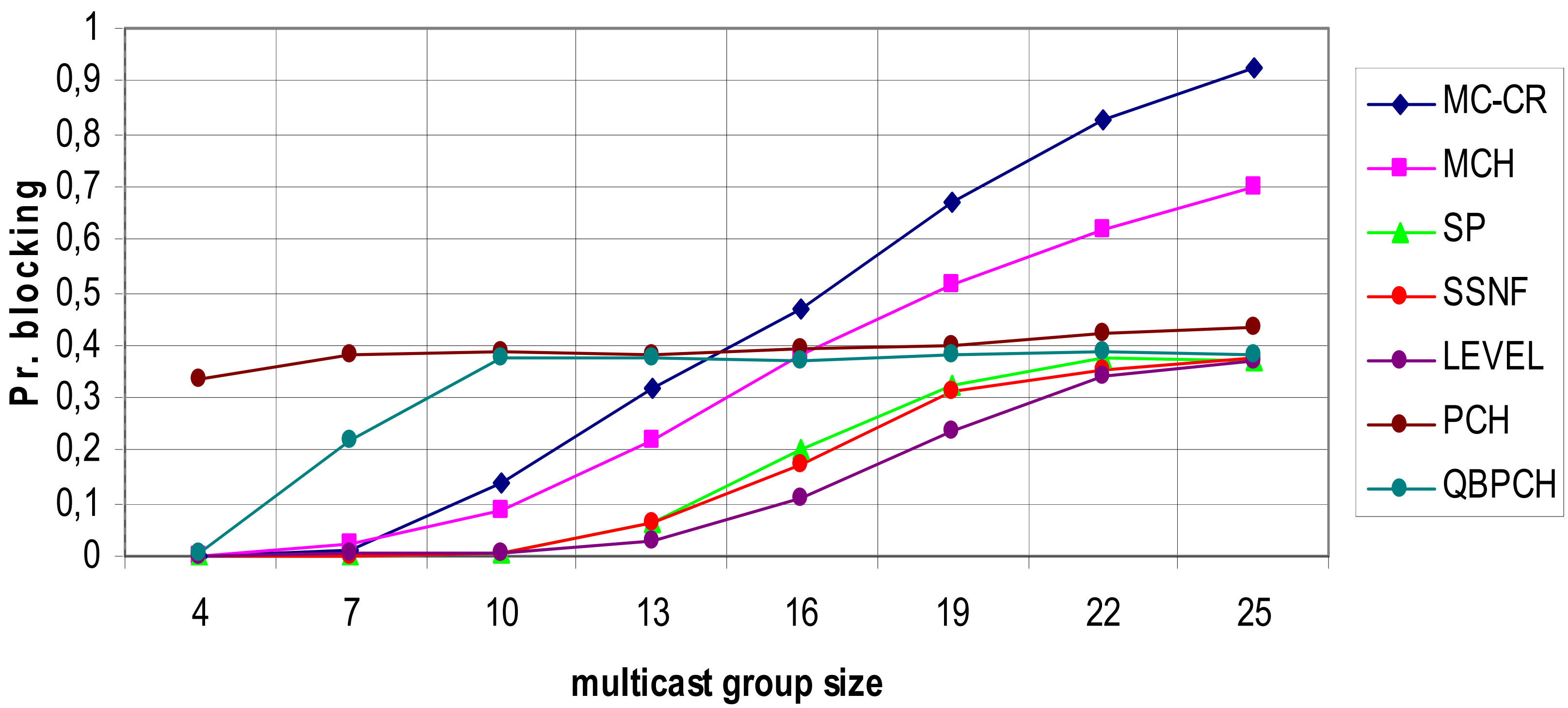
- Controls the length of the p-cycles by taking into account the physical layer constraints.
- Modification of PCH:
  - Sets a Q-threshold.
  - Calculates the Q-factor on each constructed p-cycle starting from the maximum degree node and if Q is below the predetermined threshold then it deletes consequently nodes from the p-cycle, starting from the last node, until the calculated Q-factor is above the Q-threshold.
  - Deleted nodes are taken into account for the creation of next p-cycles.

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 .
- 64 wavelengths spaced at 100 GHz were utilized
- Q threshold was set at 8.5 dBQ which corresponds to a BER of 10^{-12} .
- Node architecture and engineering design of fixed Txs/Rxs (case 1) was assumed.

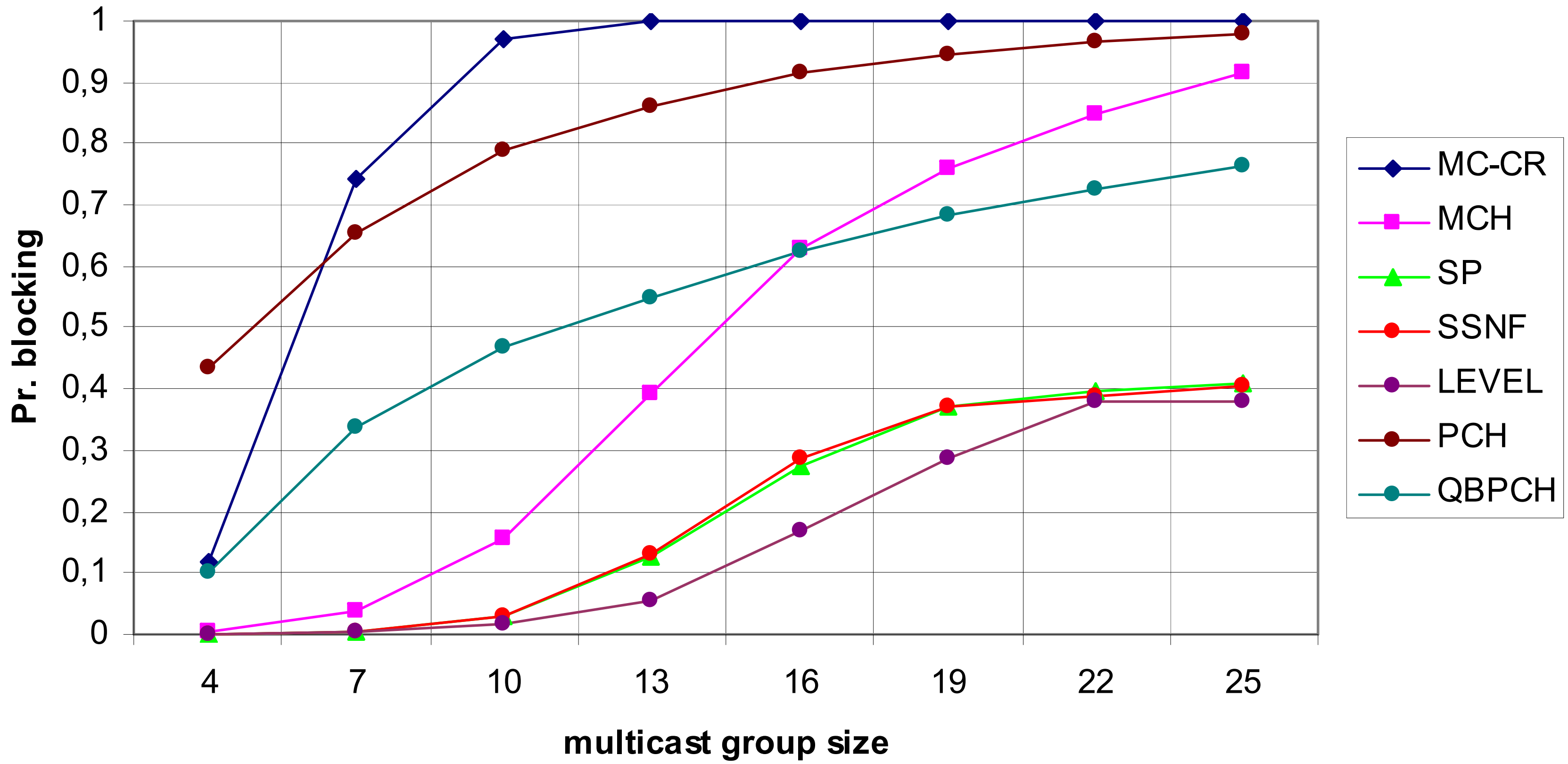
Simulation Results

• **Blocking probability versus the multicast group size without physical layer constraints.**



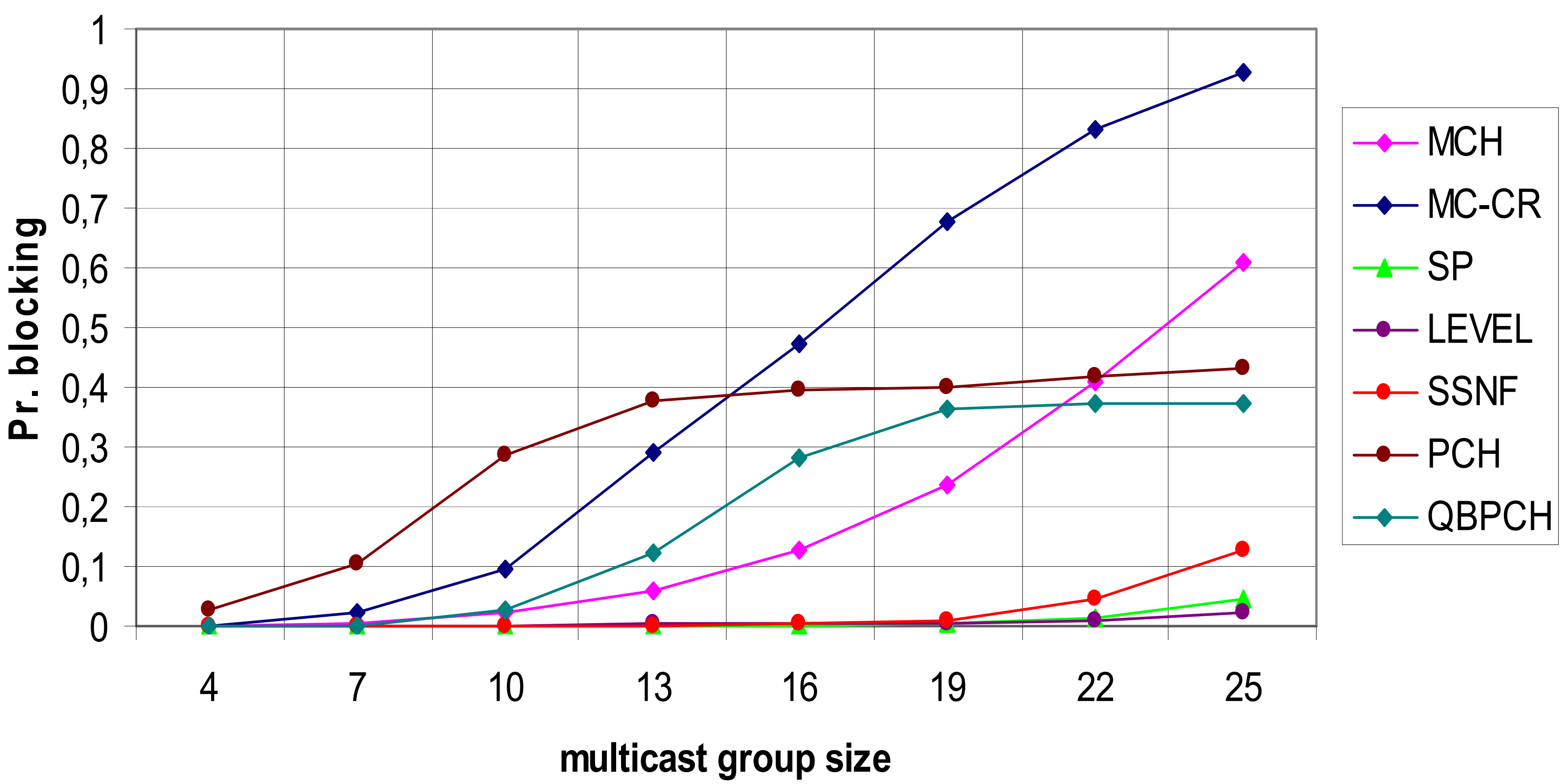
Simulation Results

• **Blocking probability versus the multicast group size with physical layer constraints.**



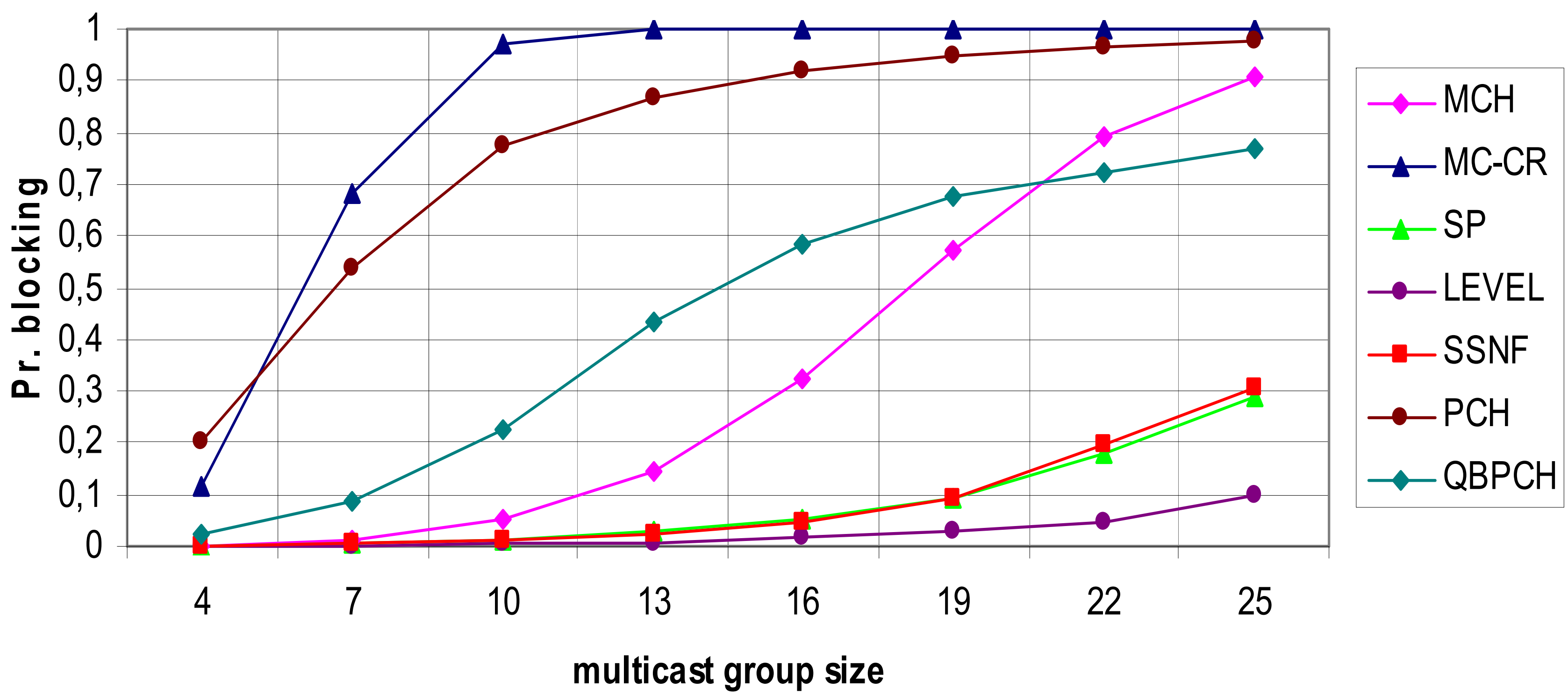
Simulation Results

• **Blocking probability versus the multicast group size without physical layer constraints when Cross Sharing techniques are considered.**



Simulation Results

• **Blocking probability versus the multicast group size with physical layer constraints when Cross Sharing techniques are considered.**



Work Package 5

RWA with grooming under PLCs (5-month duration)

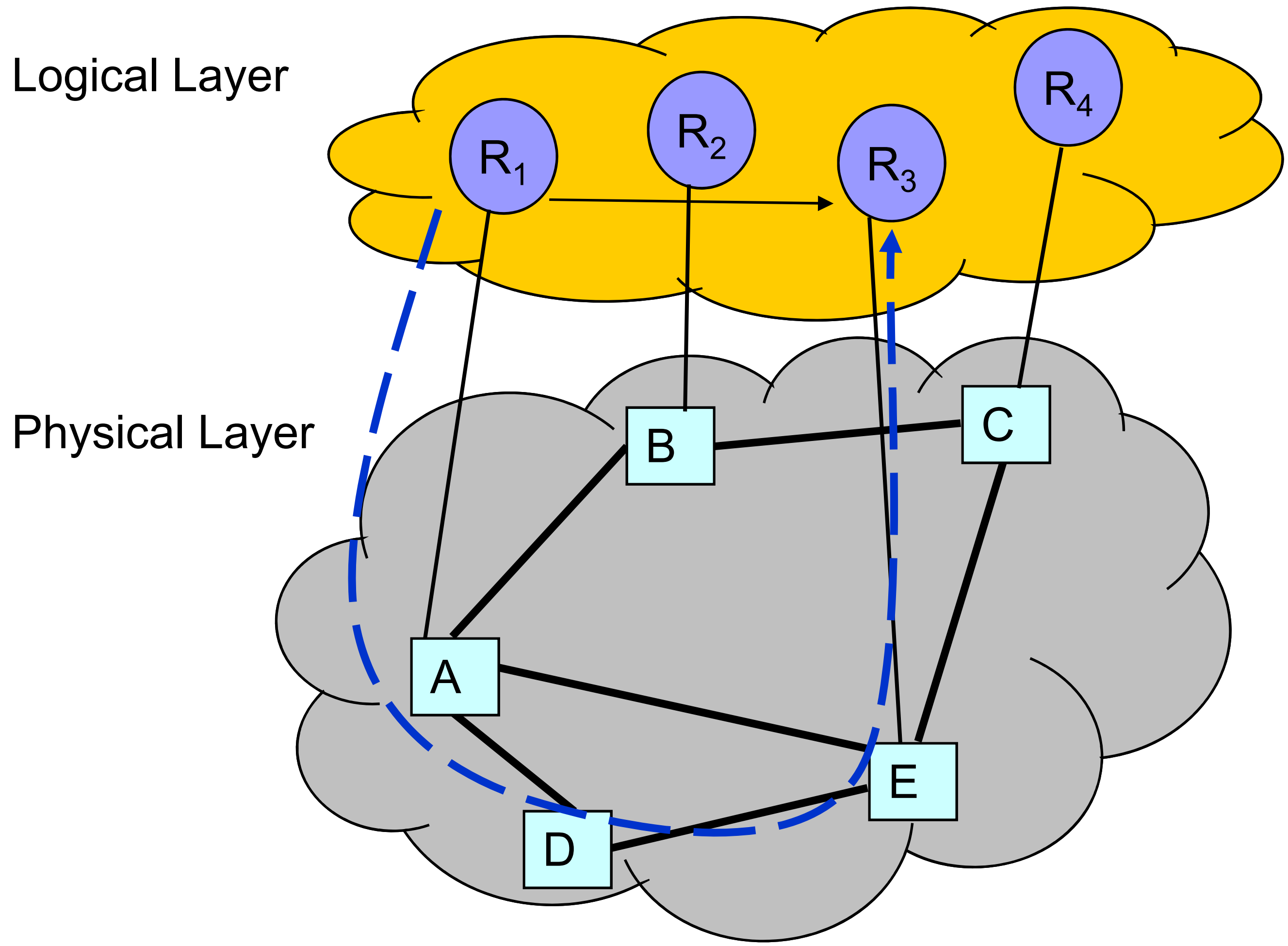
- Development of a simulation code that performs the routing/grooming and wavelength assignment under physical layer constraints.
- A node Architecture capable of grooming was designed.
- Development of novel traffic grooming techniques for multicast connections while taking into account the transmission effects:
  - Grooming with Maximum Overlapped Lightpath (GMOL) heuristic.
  - GMOL heuristic with constraints on the number of hops.

  Where different grooming policies were taken into consideration:
  - Sequential Single-Hop provisioning
  - Sequential Multi-Hop provisioning
  - Non-Restricted Sequential Multi- Hop Provisioning
  - Hybrid Provisioning
- For the provisioning of multicast calls with sub-wavelength traffic rates, two approaches were used:
  - Logical First Hybrid Routing (LFHR)
  - Physical First Sequential Routing (PFSR)

Introduction

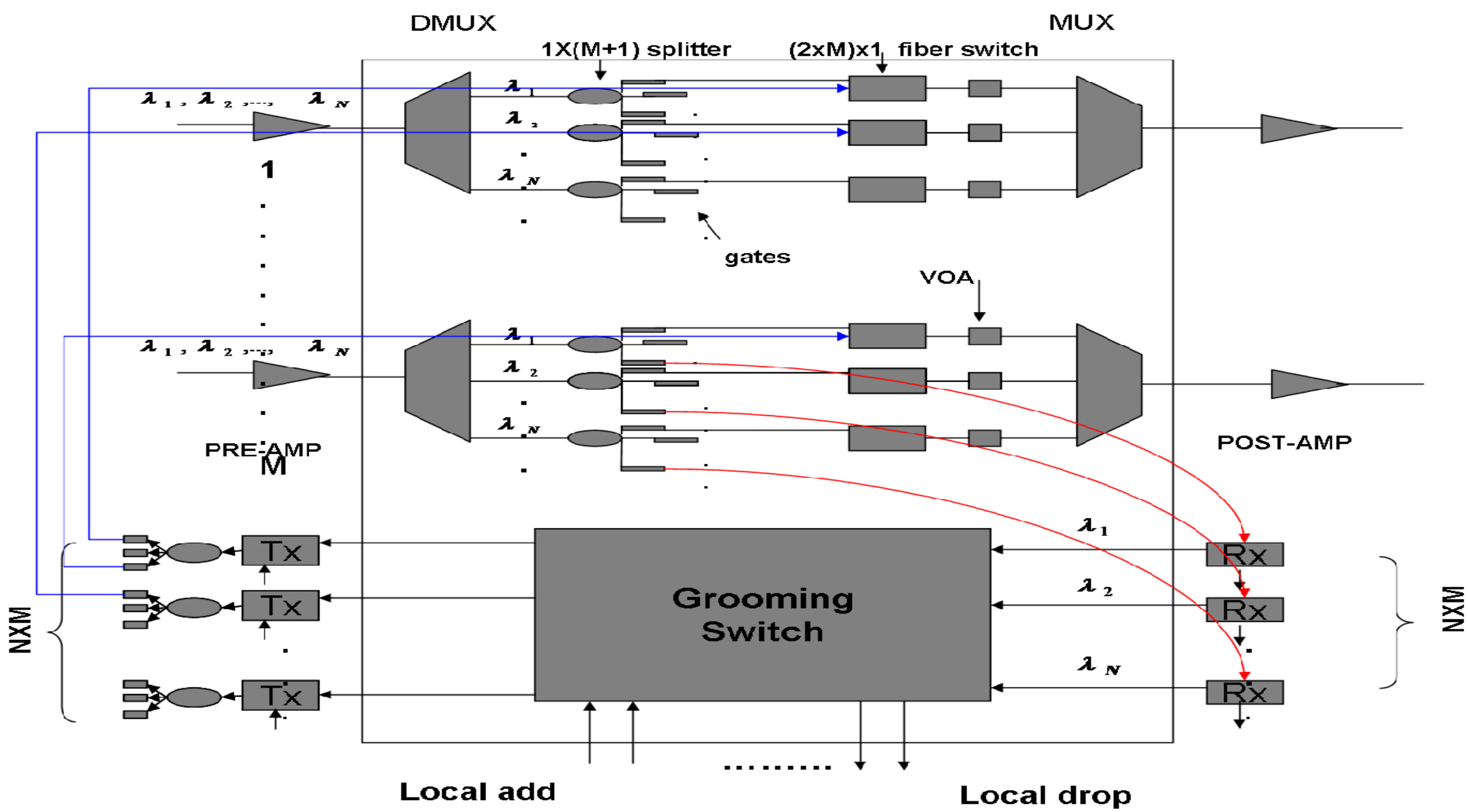
- Connections use only a portion of the bandwidth that a wavelength can offer.
- Grooming refers to the techniques that are used to multiplex low-speed traffic streams onto different high-speed wavelength channels.
- Grooming Techniques increase the bandwidth of the network.
- Example: If we have a wavelength with capacity 100Mbps, then two connections with capacity 50Mbps can be groomed onto the same wavelength.
- Routing of the new multicast requests can be divided into to categories:
  - Physical Routing
  - Logical Routing

Introduction



Node Architecture and Engineering

- Grooming of low-speed traffic streams onto different high-speed wavelength channels.



Multicast Grooming Policies

1. **Sequential Single-Hop Provisioning:** An already established light-tree, with the same source and reaching the same set of destinations, with sufficient bandwidth is used to provision the arriving session.
2. **Sequential Multi-Hop Provisioning:** An already established light-tree serving the same set of destinations but with traffic from a different source, with sufficient bandwidth is used to provision the arriving session. One more light-tree that connects source node with the source node of the logical light-tree is needed.
3. **Non-Restricted Sequential Multi-Hop Provisioning:** An already established light-tree serving only a subset of the destinations with traffic from a different source or with traffic from the same source, with sufficient bandwidth is used to provision the arriving session. Several hops may be needed to serve the entire arriving session.

Multicast routing/grooming heuristics

- For the provisioning of multicast calls with sub-wavelength traffic rates, two approaches are used:

  I. **Logical First Hybrid Routing (LFHR):** An already provisioned logical route is searched for first and if no logical light-paths exist to serve the request then a physical light-tree is searched for.
  II. **Physical First Sequential Routing (PFSR):** A physical light-tree is searched for first, and if no such a path exists to serve the request then a logical route is searched for.

- For the physical routing Minimum Hop Tree (MHT) heuristic is used.

- For the logical routing Grooming with Maximum Overlapped Light-path heuristic (GMOL) is used.

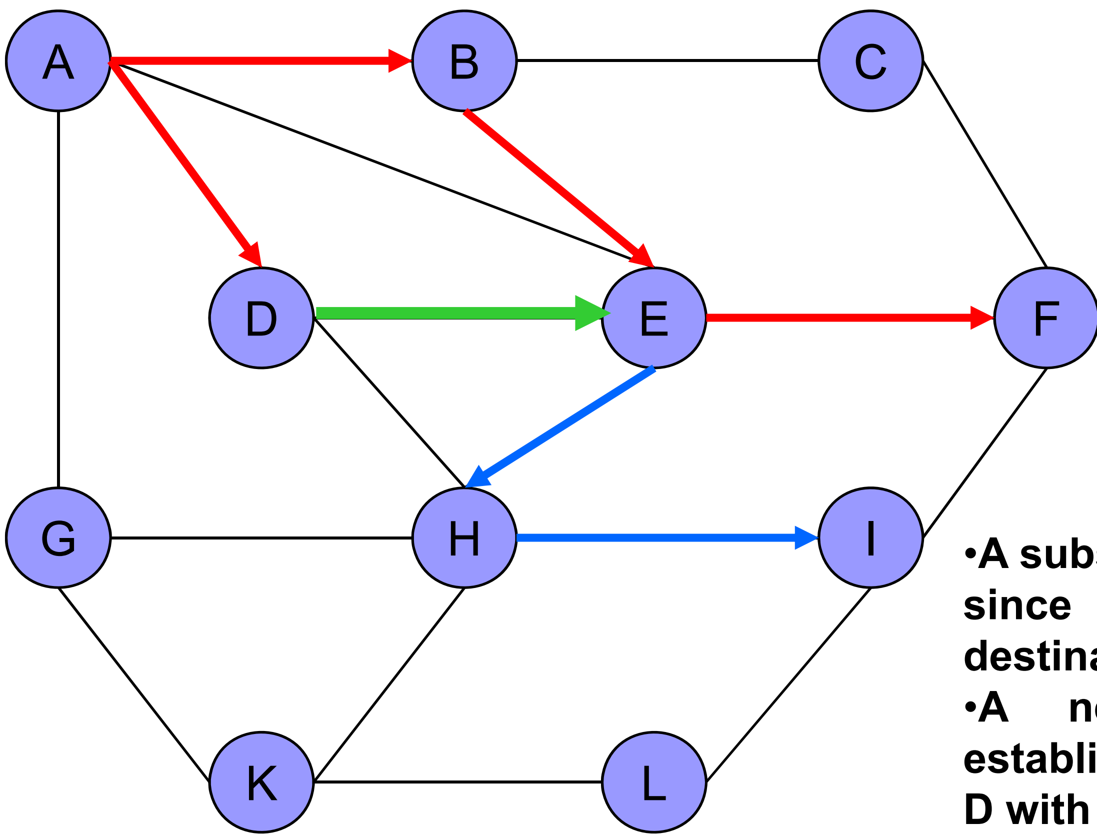
Multicast routing/grooming heuristics

❑ Grooming with Maximum Overlapping Lightpath (GMOL) heuristic

- GMOL heuristic permits
  - Sequential Single-Hop provisioning
  - Sequential Multi-Hop provisioning
  - Non-Restricted Sequential Multi- Hop Provisioning
  - Hybrid Provisioning in case that GMOL fails to find logical lightpaths to provision the entire multicast request by searching for physical routes to accommodate the remaining multicast group.
- Attempts to groom each multicast request onto the maximum overlapped light path first.
- Once a multicast request arrives, all logical lightpaths with available bandwidth are examined and a sorted list is created with the maximum overlapping logical lightpath first on the list.

Multicast routing/grooming heuristics

Example: One wavelength is present. Every links has 4 units of capacity and each request uses 1 units of capacity.



Logical Light paths

$$L_1 : \{A \to B, D, F\}$$

$$L_2 : \{E \to H, I\}$$

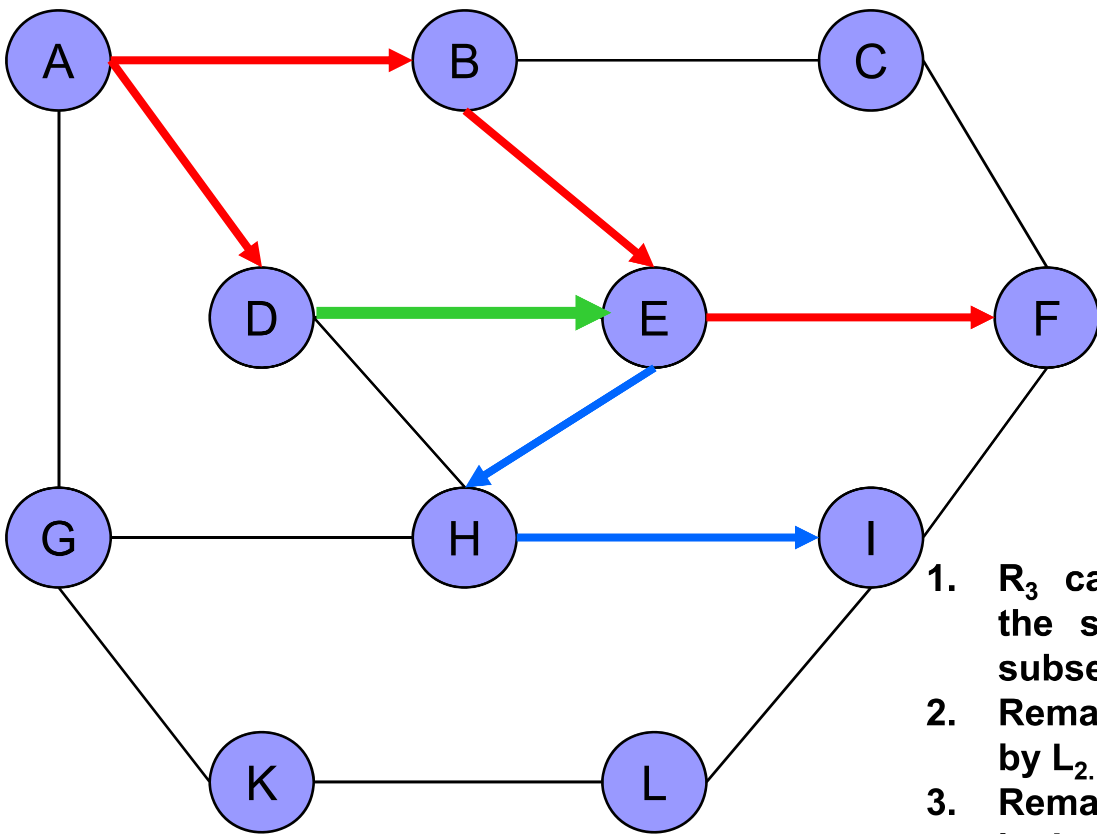
$$L_3 : \{D \to E\}$$

Multicast Request

$$R_1 : \{D \to H, I\}$$

- **A subset of R1 can be served by L2 since they have the same destinations set.**
- **A new path needs to be established to connect source node D with L2 source node E.**

Multicast routing/grooming heuristics



Logical Light paths

$$L_1 : \{A \rightarrow B, D, F\}$$

$$L_2 : \{E \rightarrow H, I\}$$

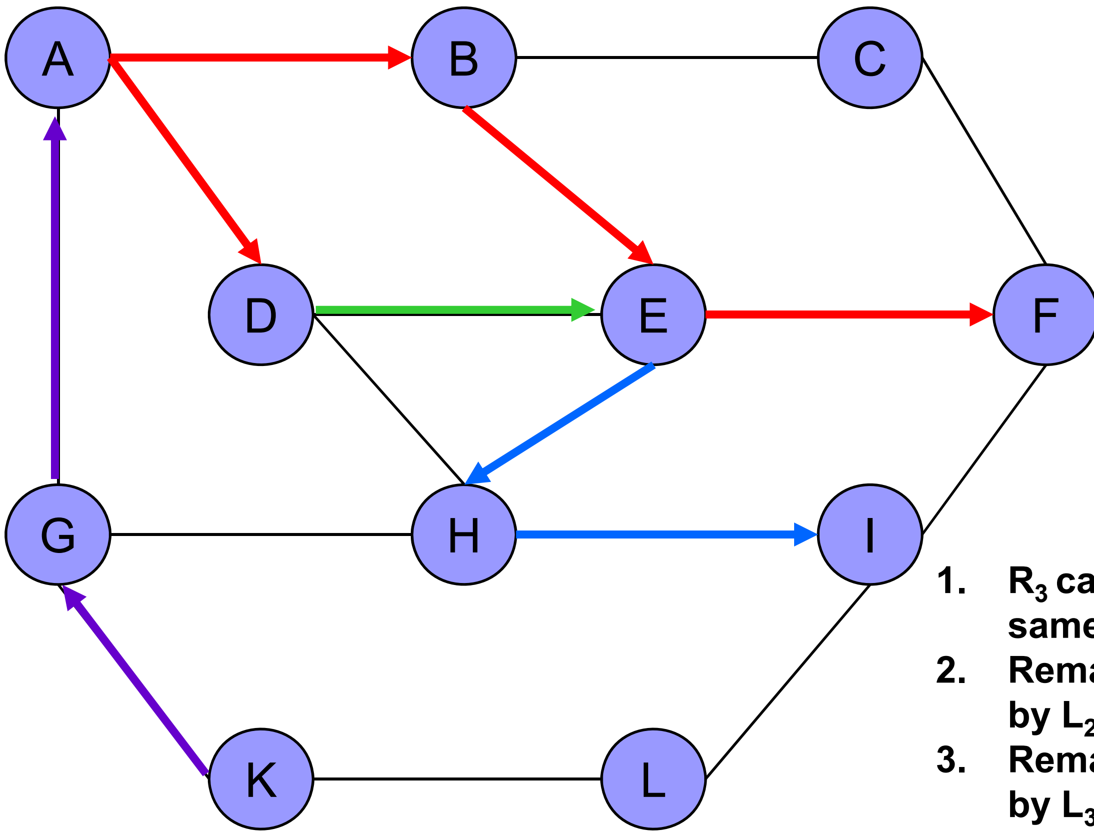
$$L_3 : \{D \rightarrow E\}$$

Multicast Request

$$R_3 : \{A \rightarrow D, H, F\}$$

1. R_3 can be served by L_1 since they have the same source node and the same subset of destination nodes D and F.
2. Remaining subset {A -> H} can be served by L_2.
3. Remaining subset {A -> E} can be served by L_3.
4. Remaining subset {A -> D} is already served by L_1.

Multicast routing/grooming heuristics



Logical Light paths

$$L_1 : \{A \rightarrow B, D, F\}$$

$$L_2 : \{E \rightarrow H, I\}$$

$$L_3 : \{D \rightarrow E\}$$

Multicast Request

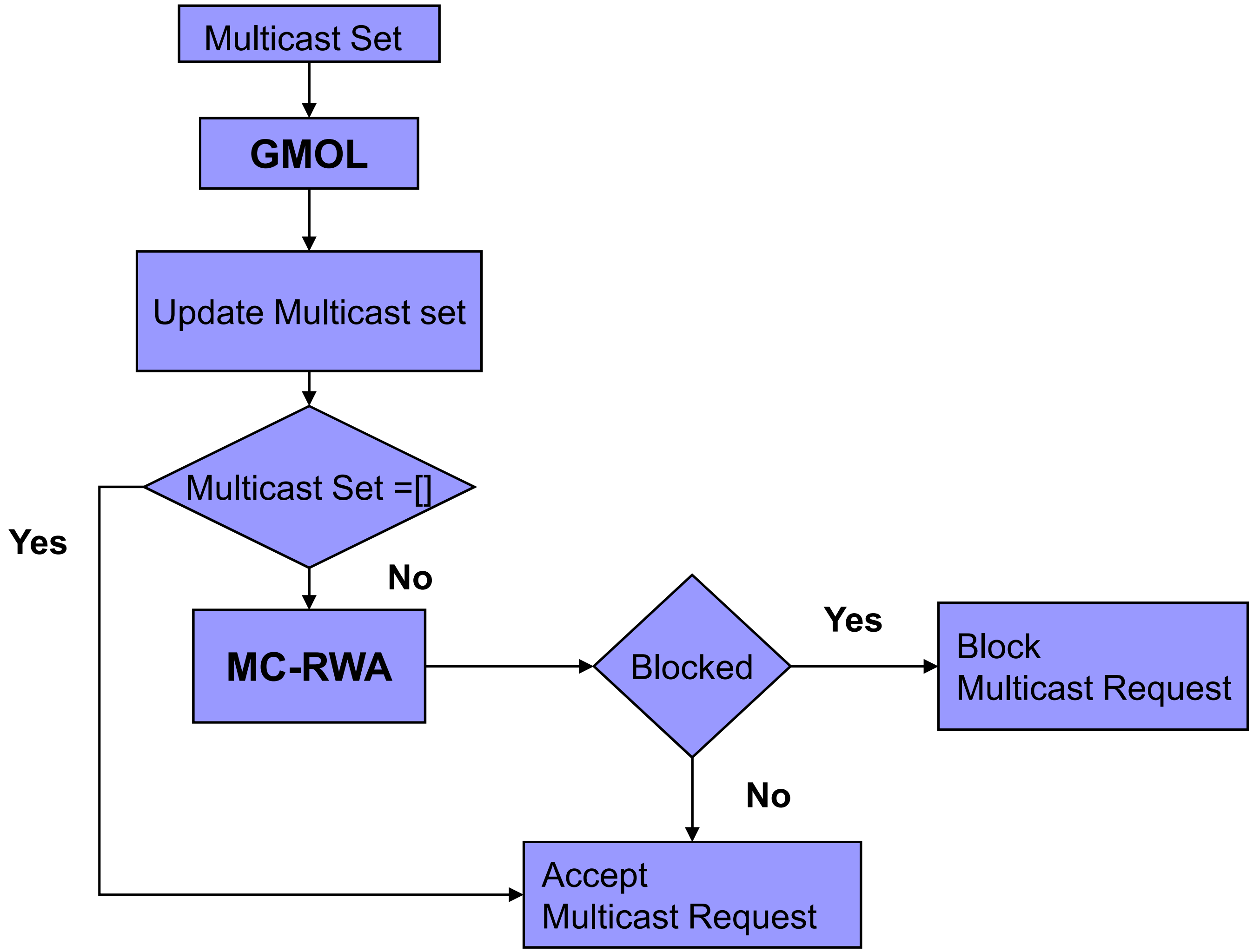
$$R_3 : \{K \rightarrow H, D, B\}$$

1. R_3 can be served by L_1 since they have the same subset of destinations.
2. Remaining set {K -> A, H} can be served by L_2.
3. Remaining set {K -> A, E} can be served by L_3.
4. Remaining set {K -> A,D} overlaps with L_1 which is already accounted and therefore set is updated to {K->A }.
5. A new light path L_4 is created.

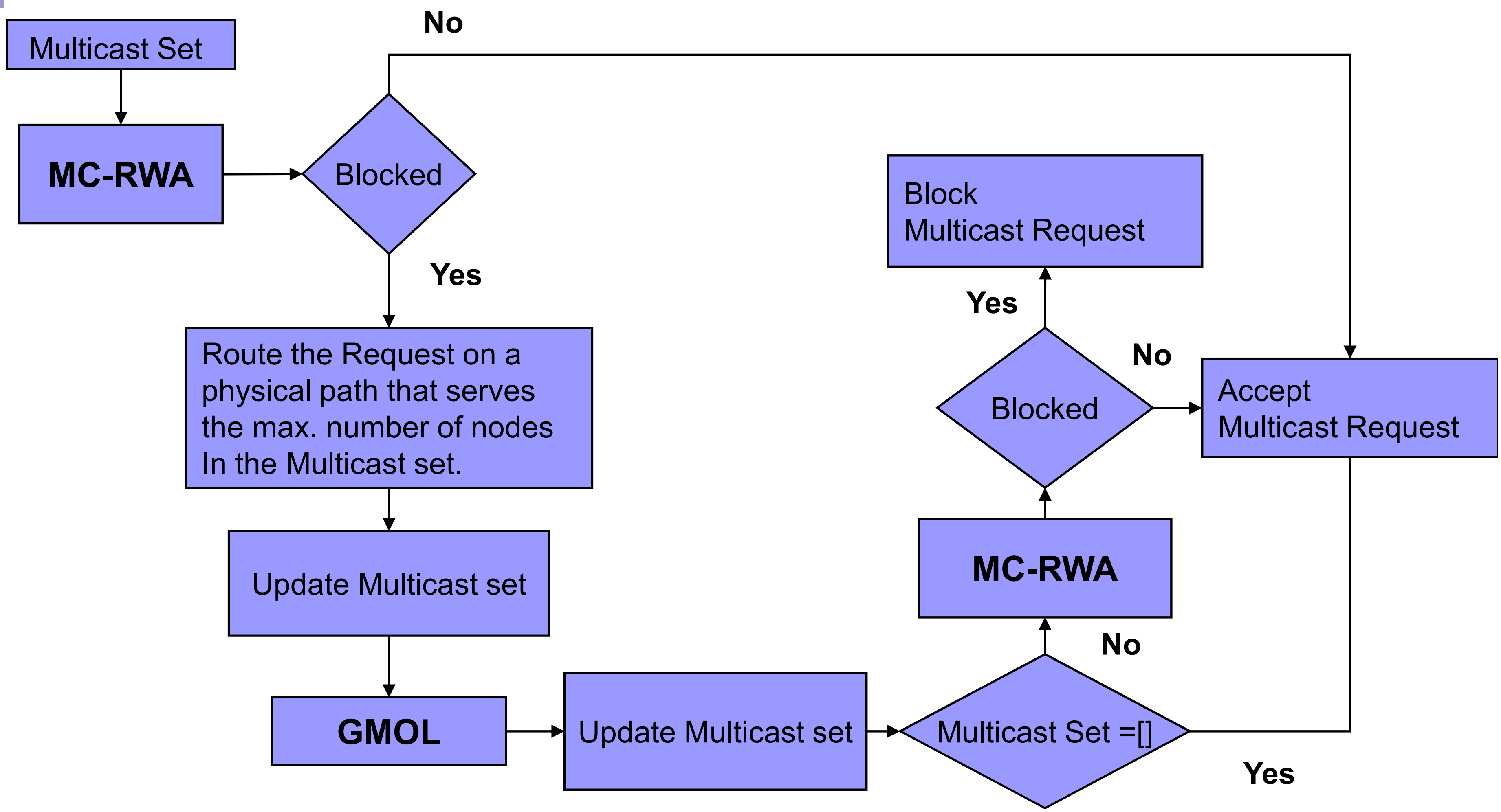
Multicast routing/grooming heuristics

- GMOL heuristic with constraints on the number of hops.
  - Multihop means the number of logical hops needed to serve a call.
  - In GMOL multiple hops may be found to serve a call without any constraint on the number of hops.
  - Unlimited number of hops in a dynamic system where request arrive and depart dynamically may be inefficient in terms of capacity.
  - GMOL is modified to control the number of hops:
    - Sets a threshold percentage *(P)* on the overlapping percentage (*p*).
    - Finds the overlapping percentage (*p*) between the multicast group request and the logical light path.
    - *If p>P* then the logical hop is accepted.

Logical First Hybrid Routing (LFHR):



Physical First Sequential Routing (PFSR):

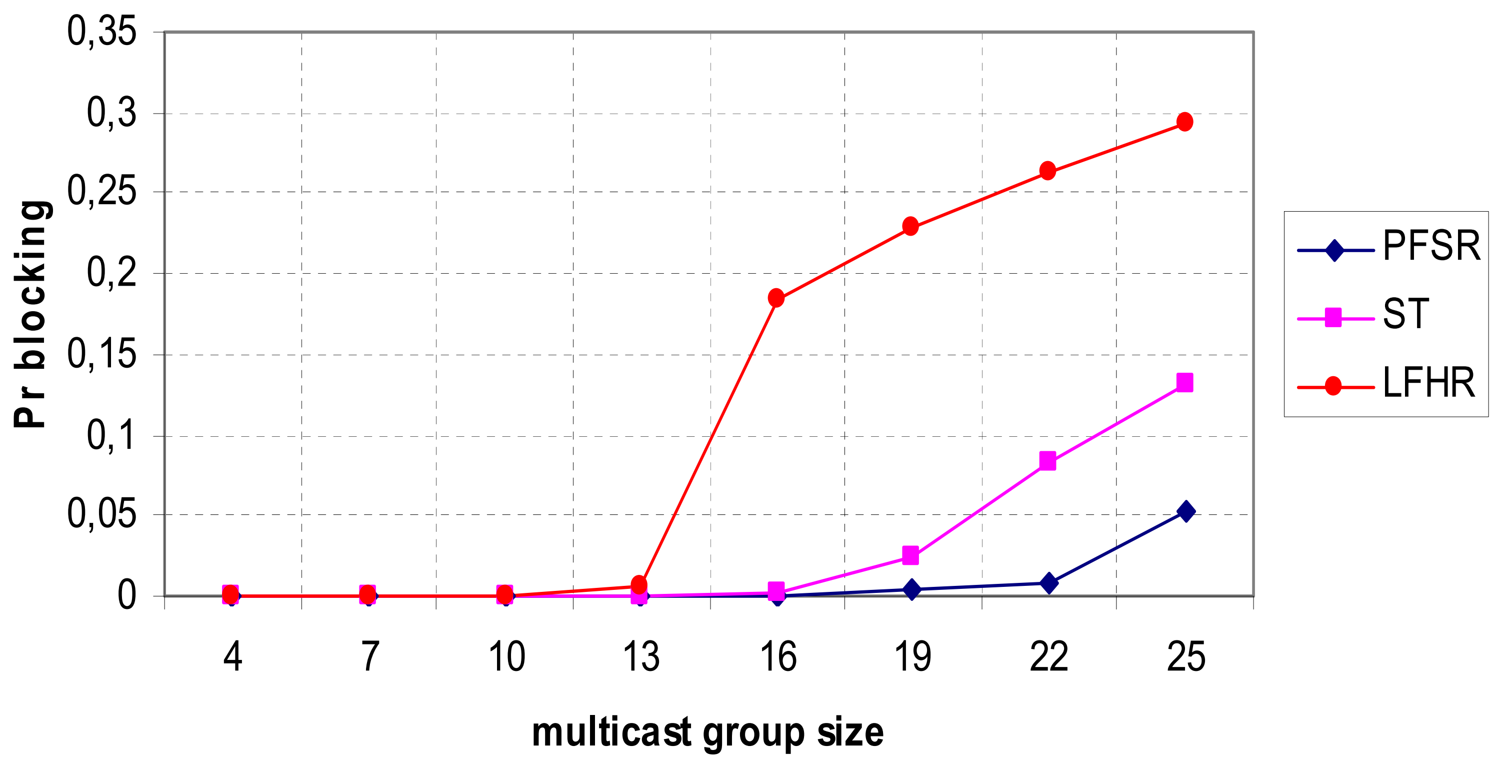


Simulation Parameters

- 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.
  - The rate of each request is an integer randomly generated between the set o integer [1-10].
  - 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 .
- 32 wavelengths spaced at 100 GHz were utilized.
- Each wavelength is assumed to have 10 units of capacity
- Q threshold was set at 8.5 dBQ which corresponds to a BER of 10^{-12} .
- Fixed Txs/Rxs of case 1 node engineering was assumed.

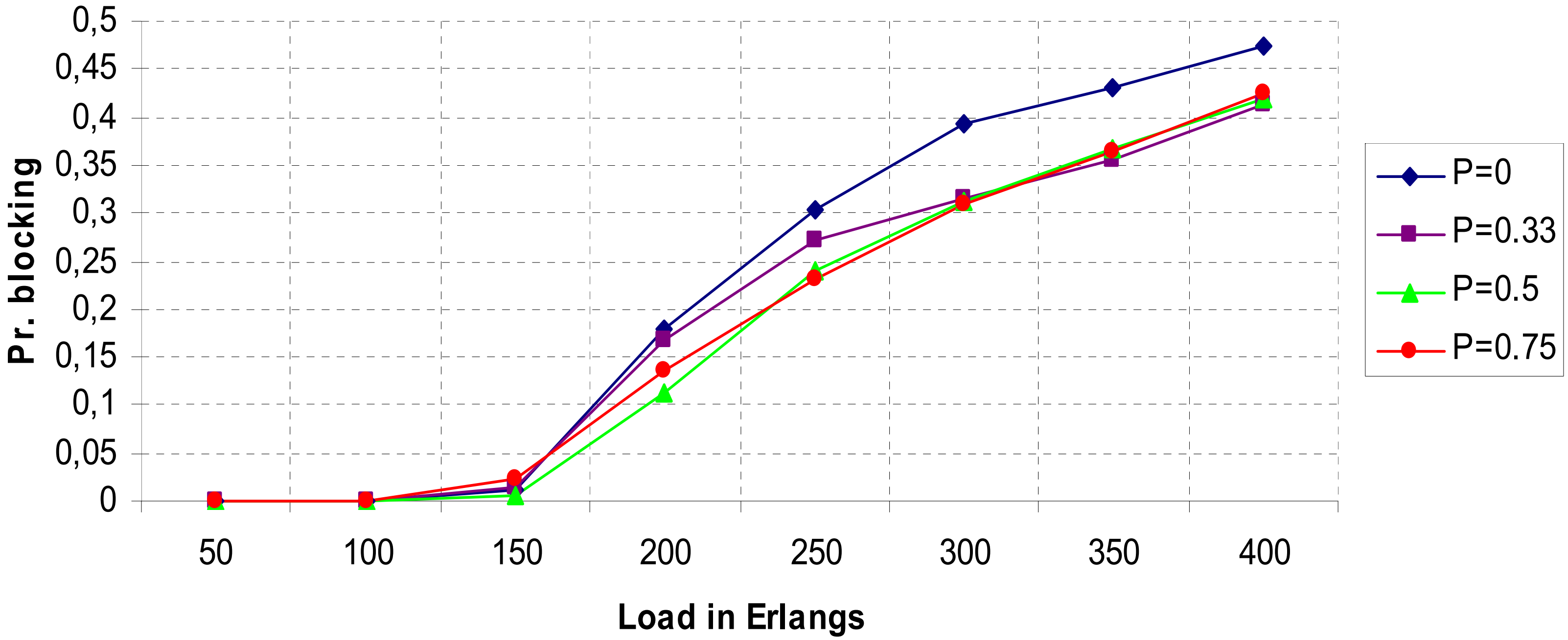
Simulation Results

Blocking probability versus the multicast group size for PFSR and LFHR approaches using GMOL heuristic.



Simulation Results

Blocking probability versus the load in Erlangs for a mixed traffic scenario. PFSR approach is assumed and GMOL heuristic is used for different P- thresholds on the p- overlapping percentage.



Work Package 6

RWA for GC connections with PLCs

- Development of a simulation code that performs the routing and wavelength assignment of groupcast requests under physical layer constraints.
- Development of three groupcast routing algorithms:
  - Light-Trees heuristic
  - Light-Paths heuristic
  - Linear Light-Trees heuristic

Groupcast heuristics

- In an optical network one multicast light tree must be established for every node in the groupcast request.
  - Example: Groupcast request {n_1 n_2 n_3} can be decomposed into 3 multicast sets {n_1 n_2 n_3}, {n_2 n_1 n_3} and {n_3 n_2 n_1}.

- Three heuristics were developed and compared:
  1. **Light-Trees heuristic:** Finds a set of light-trees using Steiner Tree heuristic for the construction of each light-tree.
  2. **Light-Paths heuristic:** Finds a set of light-trees using Shortest Paths Tree heuristic.
  3. **Linear Light-Trees heuristic**: Finds a set of light-trees using Drop And Continue heuristic

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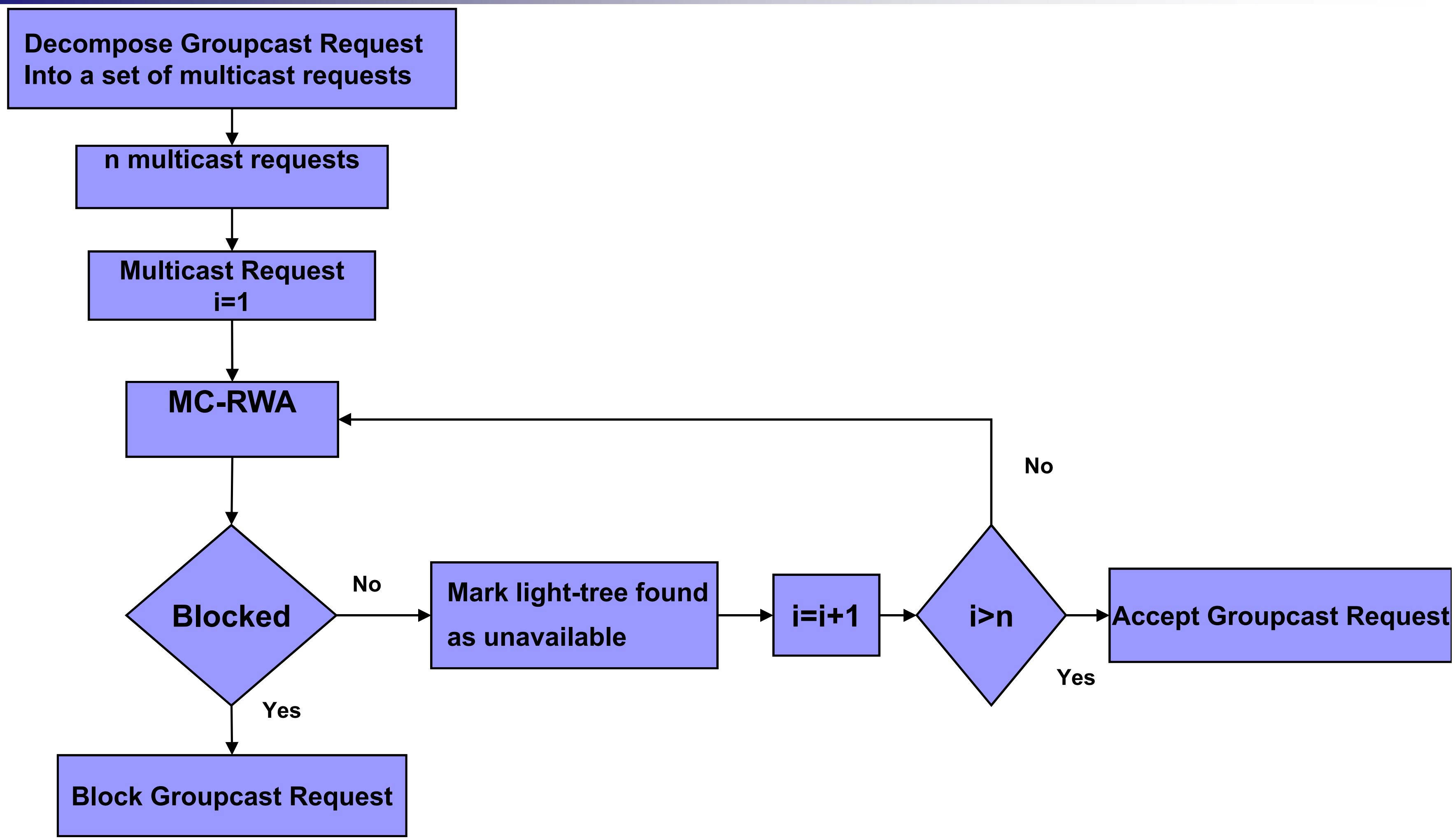
Groupcast Routing Algorithm and Wavelength Assignment problem (GR-RWA)



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

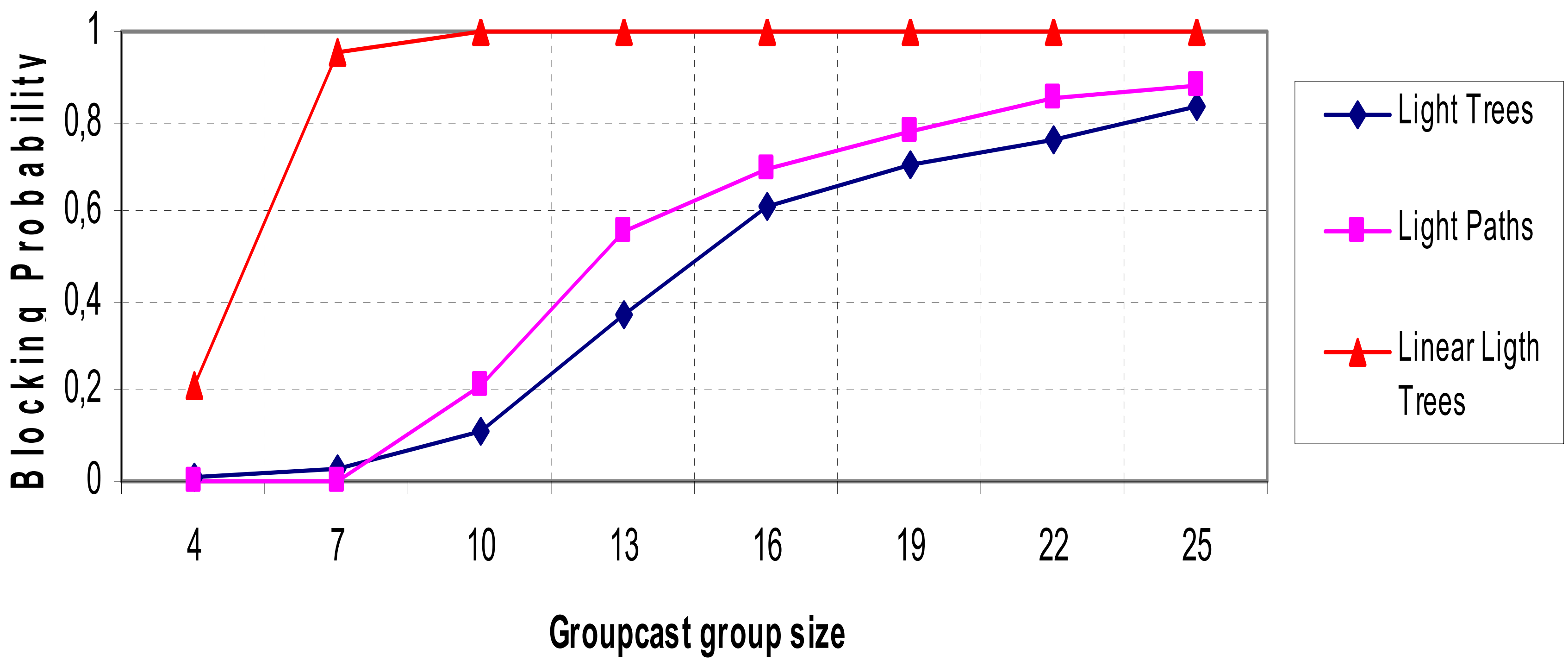
- Dynamic System:
  - Poisson arrivals
  - Exponentially distributed holding times with a unit mean.
  - 50 Erlangs load.
  - For each run 5.000 requests were generated for each multicast group size.
  - The results for each simulation point were obtained as the average of 5 runs .

- 100 wavelengths spaced at 100 GHz were utilized

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

Simulation Results

Blocking probability versus the Groupcast group size when physical layer constraints are taken into account.



Summary

- Several novel and noteworthy results were obtained during the implementation of WPs 3-5 including:
  - Novel QoT-Based MC-RWA algorithms
  - Novel node design and network engineering approaches
  - Novel QoT-based protection techniques for multicast connections
  - Novel QoT-based grooming techniques for multicast connections
- No major problems were observed during the implementation of the first half of the project
- No deviation from the original timetable is expected for the remaining work-packages and deliverables.
  - Work-package 6 has been completed
  - Research is currently progressing on work-package 7