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

Coordinator: Dr. Georgios Ellinas
Participating Personnel: Dr. Georgios Ellinas, Tania Panayiotou, Dr. Antonis Hadjiantonis, Antonis Lambrou
Young Researcher: Tania Panayiotou

ΠΕΝΕΚ ΕΝΙΣΧ/0308 Final Project Report, 9 November 2011

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 network.

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 (30 months)

- **Deliverables**
  - D1:Development of algorithms for routing/grooming and wavelength assignment of protected multicast connections.
  - D2: Mid-project Report
  - D3: Development of algorithms for routing/grooming and wavelength assignment of protected groupcast connections.
  - D4: Development of a software simulation tool.
  - D5: Final-project Report
- **Accomplishments**
  - All WPs (1-9) and deliverables (D1,D2,D3,D4 and D5) were successfully completed
  - 4 publications completed (1 journal paper and 3 conference papers) with another 4 journal publications under submission/to be submitted.
  - Work was presented in three international conferences, including the most prestigious conference on optical networks
  - A web site for the project has been set up.
  - Two seminars were organized in Cyprus where the project results were presented

Work Package 2:
Dissemination and Exploitation of Results (30 months)

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.

- **T. Panayiotou**, G. Ellinas, N. Antoniades, and A. Hadjiantonis, “A Novel Segment-Based Protection Algorithm for Multicast Sessions in Optical Networks with Mesh Topologies”, IEEE/OSA Optical Fiber Communications (OFC) Conference, Los Angeles, CA, March 2011.

Work Package 2:
Dissemination and Exploitation of Results

- **Under Submission/Preparation:**

- **T. Panayiotou**, G. Ellinas, A. Hadjiantonis, and N. Antoniades, "On the Effect of Node Architecture/Engineering for Multicasting Based on Physical Layer Constraints", (Submitted to the *IEEE/OSA Journal of Lightwave Technology, 2011*)
- **T. Panayiotou**, G. Ellinas, A. Hadjiantonis, and N. Antoniades, "Multicast Protection in Metro Networks Based on Physical Layer Constraints", (Submitted to the *IEEE/OSA Journal of Optical Communications and Networking, 2011*).
- **T. Panayiotou**, G. Ellinas, A. Hadjiantonis, and N. Antoniades, "Multicast Grooming in Metro Networks Based on Physical Layer Constraints", (under preparation) (Scheduled for submission to the *IEEE/OSA Journal of Optical Communications and Networking, 2011*).
- **T. Panayiotou**, G. Ellinas, A. Hadjiantonis, and N. Antoniades, "Multicast Provisioning Based on Physical Layer Constraints and PDL/PDG considerations", (under preparation) (Scheduled for submission to the *IEEE/OSA Photonic Technology Letters, 2011*).

- 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 PLIs (5 months)

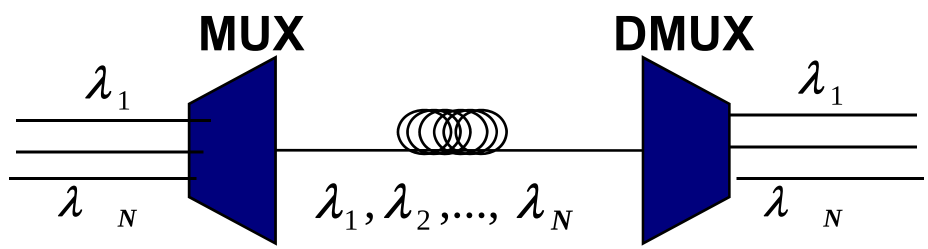
- Development of a Q-budgeting model for metropolitan optical networks.
- Development of a simulation code which performs the routing and the wavelength assignment under physical layer constraints.
- Development of 3 new routing techniques for multicast connections which take into account physical layer constraints, such as:
  - BLT-Q heuristic
  - BLT-Q tolerance heuristic
  - Max Degree Node heuristic

  And their performance was compared with 5 existing routing algorithms:
  - Steiner Tree heuristic
  - Shortest paths Tree heuristic
  - BLT heuristic
  - DAC heuristic
  - MHP tree heuristic

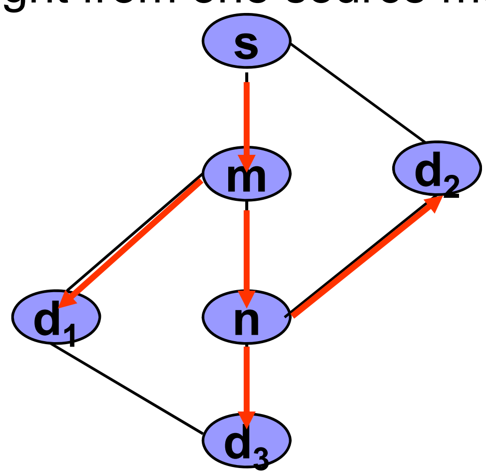
    That take only power budget constraints into account.
- Development and examination of different Node Architectures and Engineering Designs

Introduction to Multicasting

•**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.

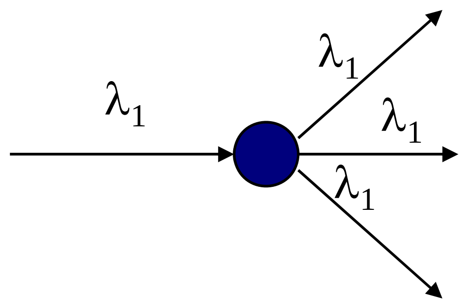


•**Multicast connection:** light from one source must reach many destinations.



Introduction to Multicasting

- 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.

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:

$$QdB = 10\log(Q_{linear})$$

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

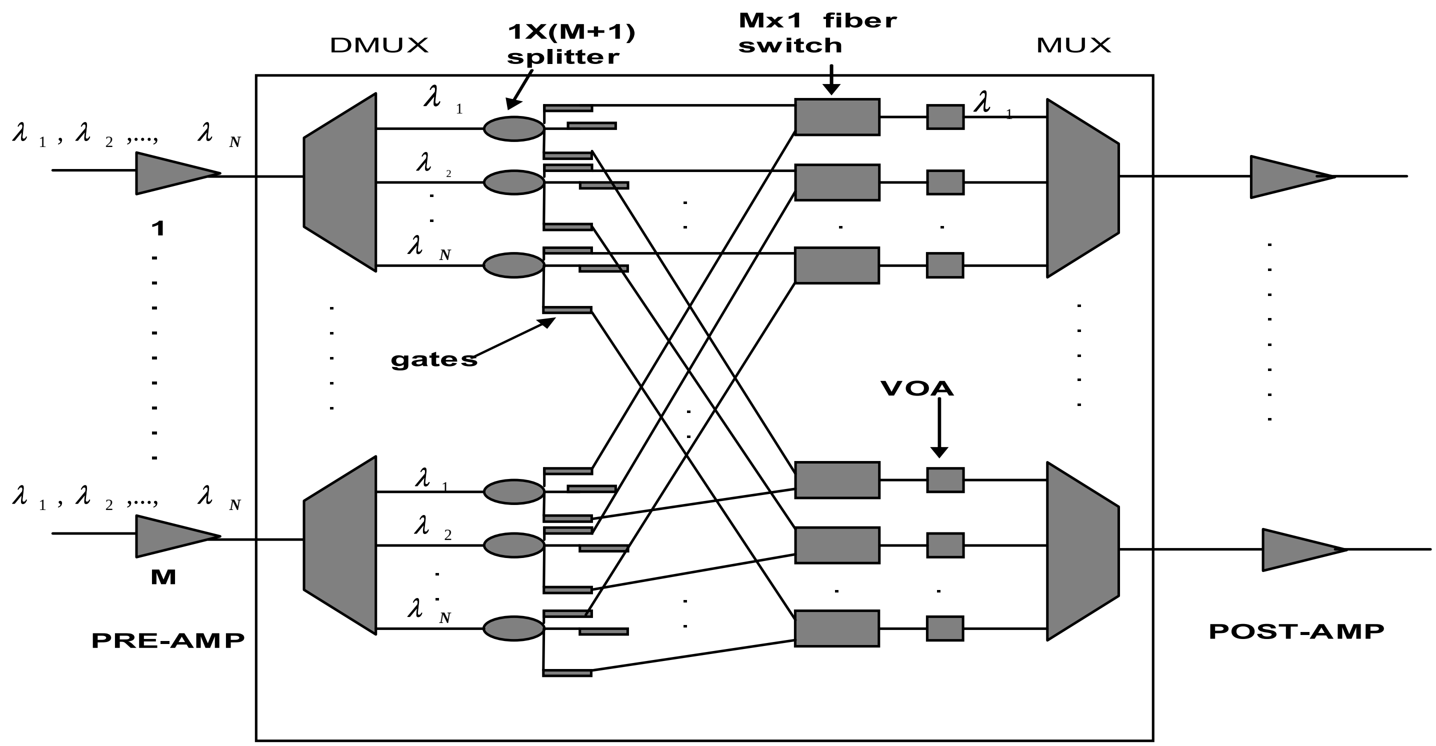
$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$

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

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

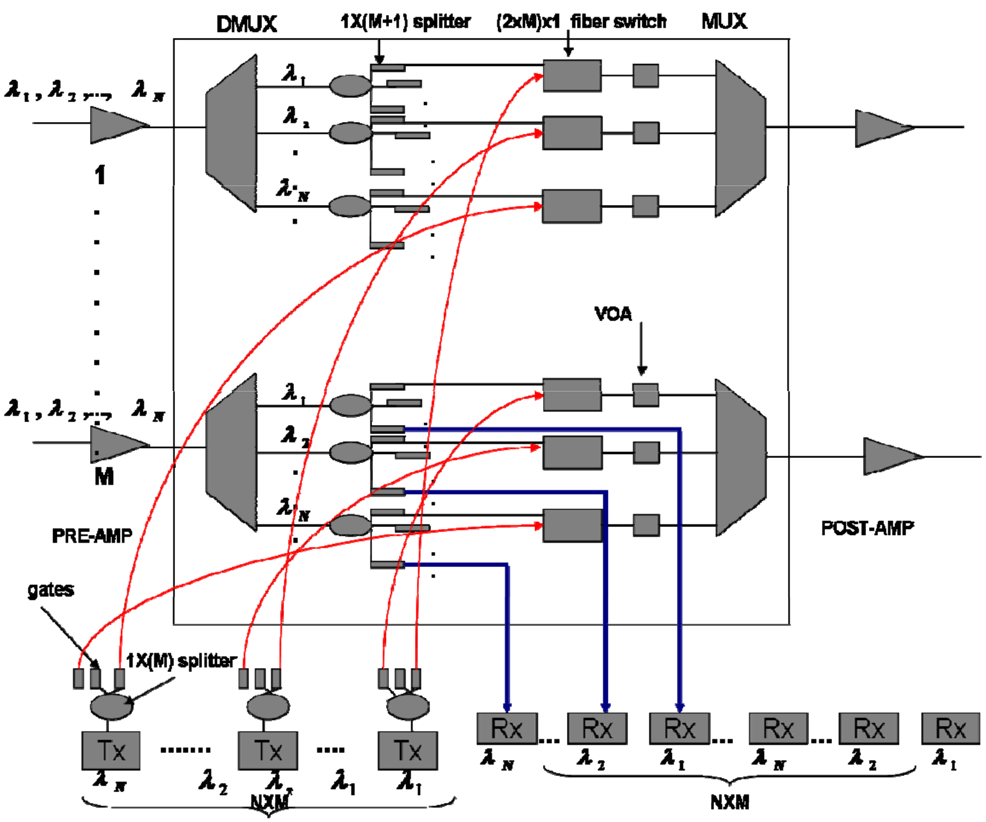
Node Architecture and Engineering design

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

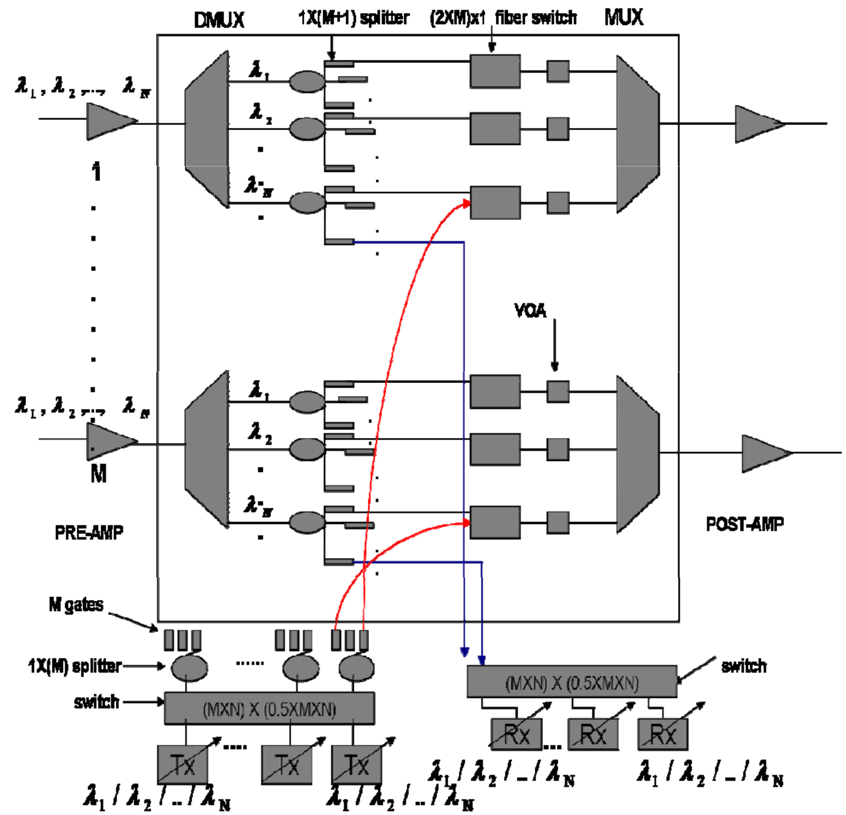


Node Architecture and Engineering designs

1. **Fixed Txs/Rxs:**

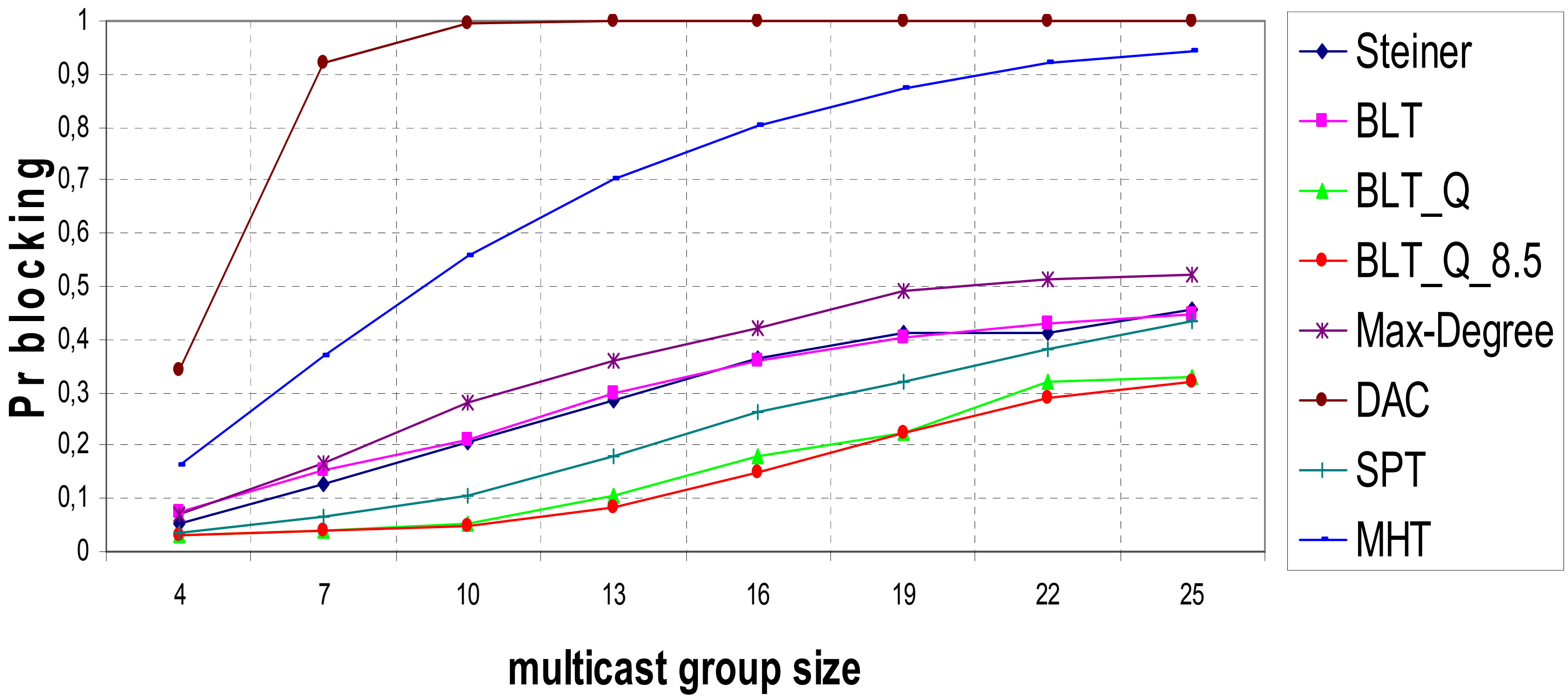


1. **Tunable Txs/Rxs:**



Simulation Results

- Active splitters.



Work Package 4

RWA for protected MC connections with PLIs

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

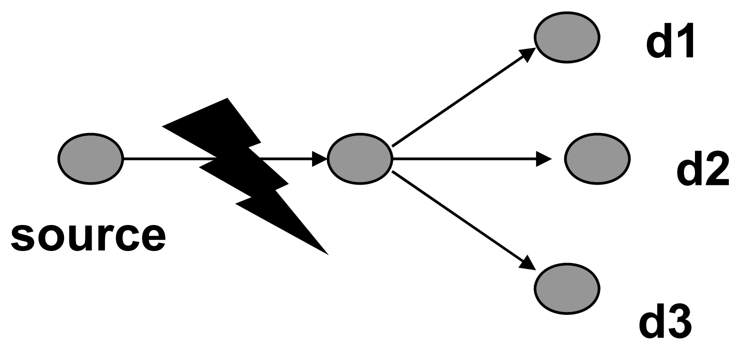
- Development of novel protection techniques for multicast connections taking into account the physical layer constraints:
  - LEVEL protection heuristic
  - PCH protection heuristic
  - Q Based PCH protection heuristic

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

Introduction to Protection

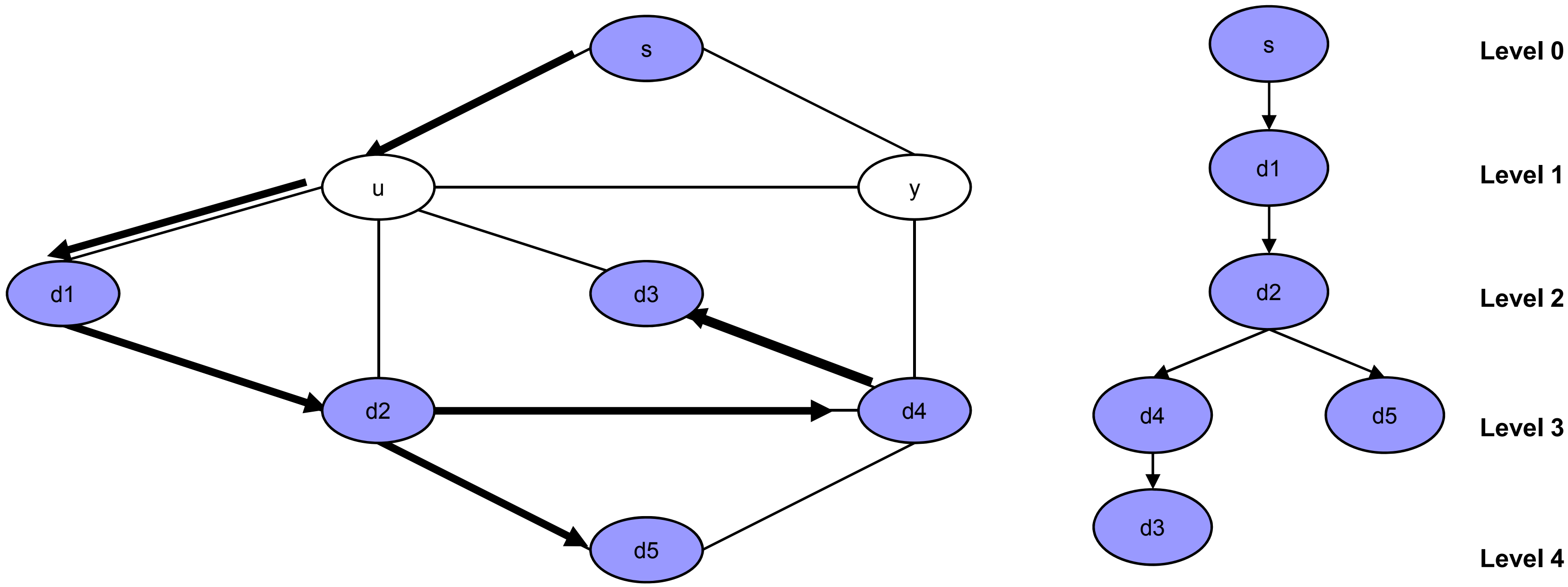
- Protection techniques are used for the restoration of traffic in case of a link failure.

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



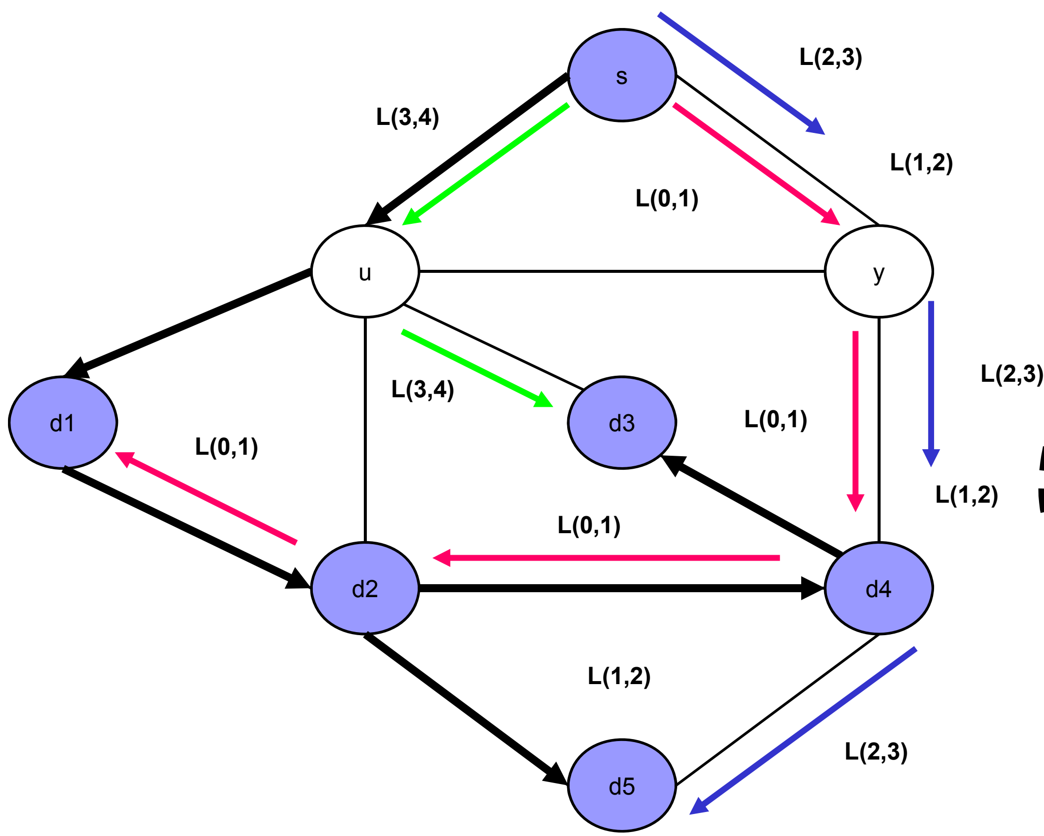
- A fiber cut (link failure) may jeopardize the entire multicast session

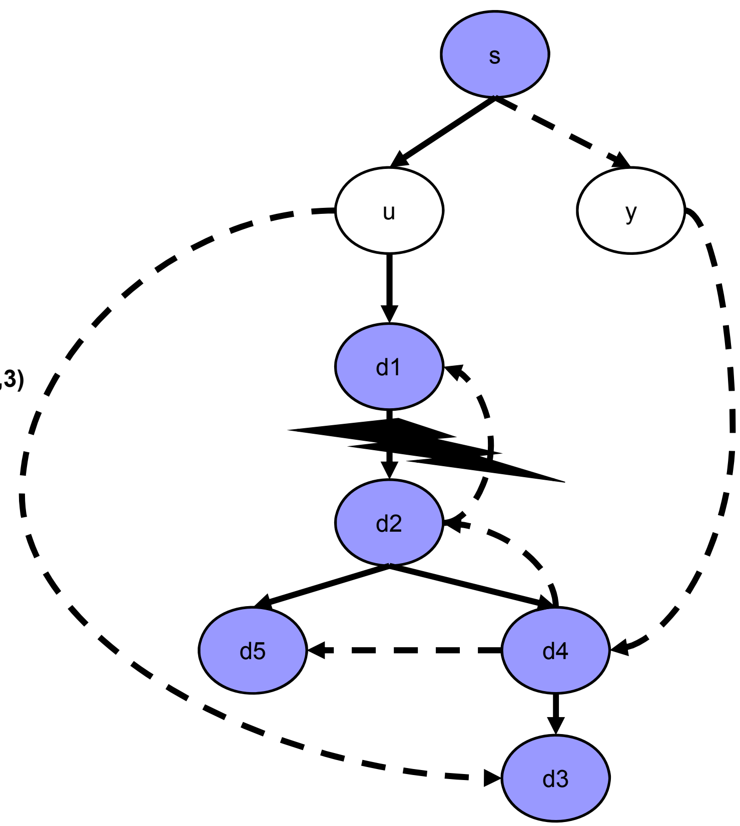
LPA Algorithm



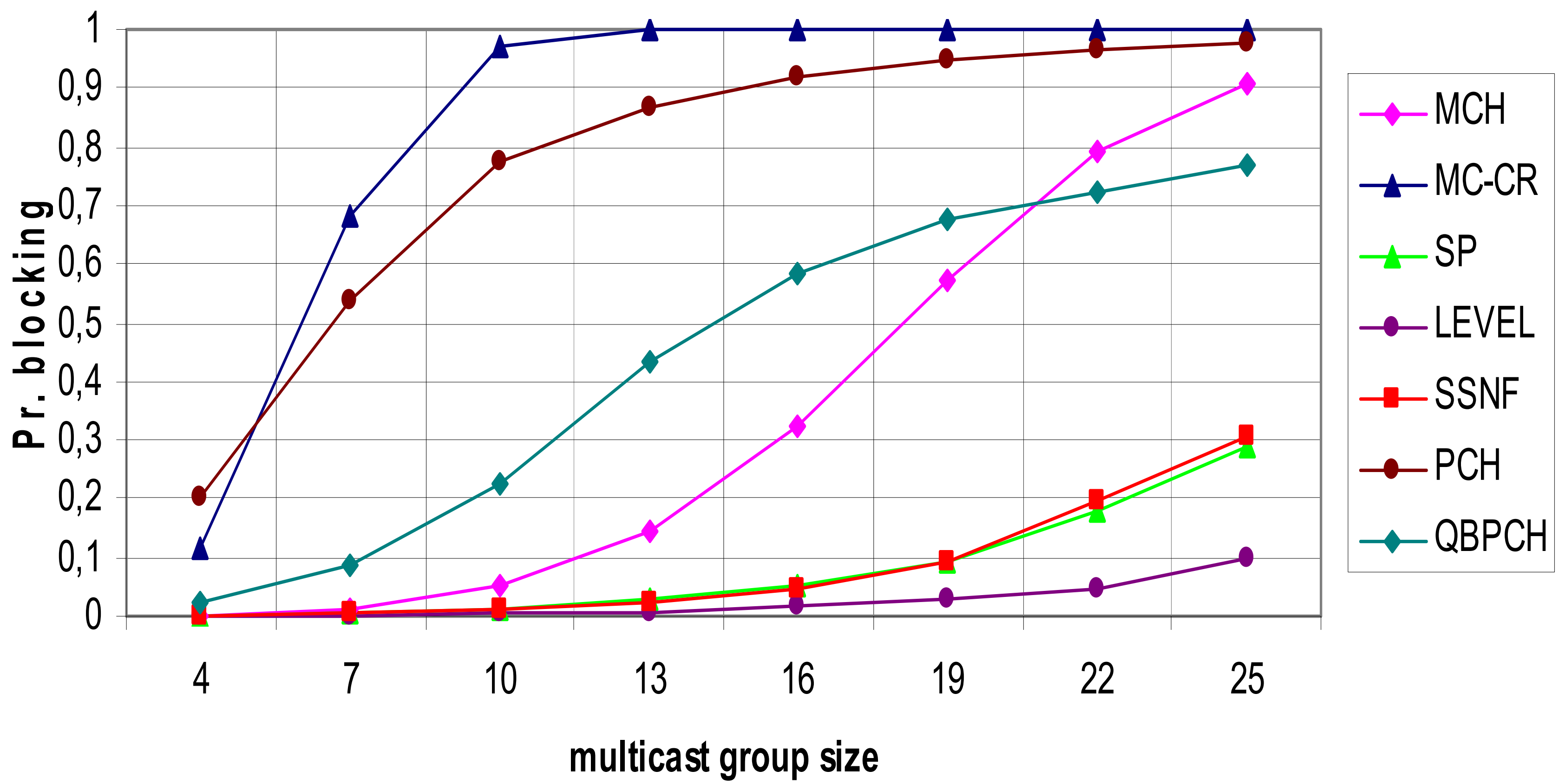
Segmentation nodes, levels and level segments are identified

LPA Algorithm





Simulation Results



Work Package 5

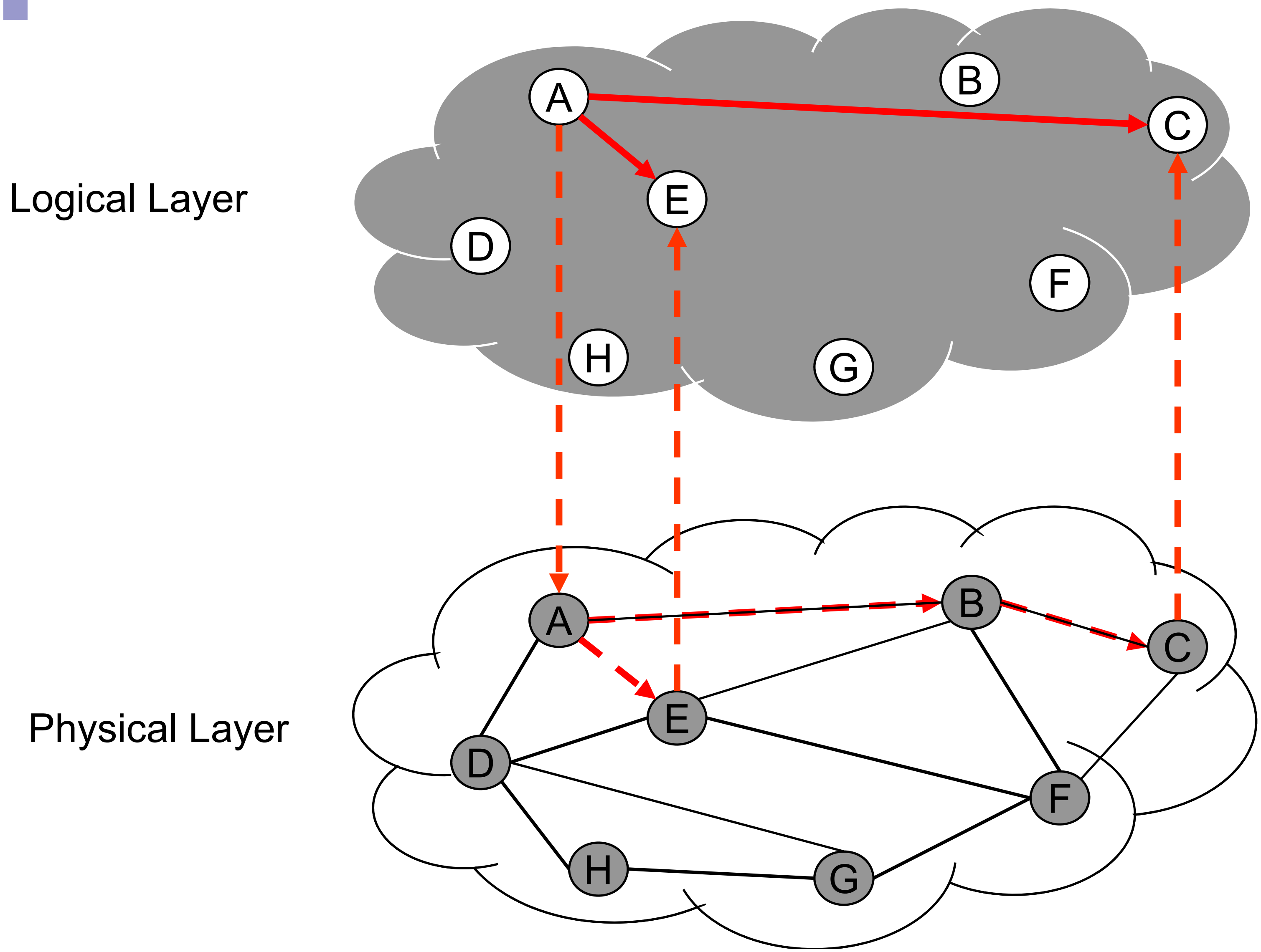
RWA with grooming under PLIs

- Development of three simulation codes that perform the routing/grooming and wavelength assignment under physical layer constraints.
  - Logical First Hybrid Routing (LFHR)
  - Physical First Sequential Routing (PFSR)
  - Routing on Hybrid Graph (RHG)
- Development of novel traffic grooming techniques for multicast connections:
  - Grooming with Maximum Overlapped Lightpath (GMOL) heuristic (for LFHR and PFSR simulation codes).
  - Minimum free Capacity First (MCF) heuristic (for RHG).
  - Maximum Overlapping Light-Tree First (MXOLF) heuristic (for RHG).

Introduction to Grooming

- Grooming Techniques increase the bandwidth of the network.
- 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.
- Example: If we have a wavelength with capacity 100Mbps, then two connections with capacity 50Mbps can be groomed onto the same wavelength.
- Routing/Grooming of the new multicast requests can be divided into to categories:
  - Logical Routing
  - Physical Routing

Introduction to Grooming

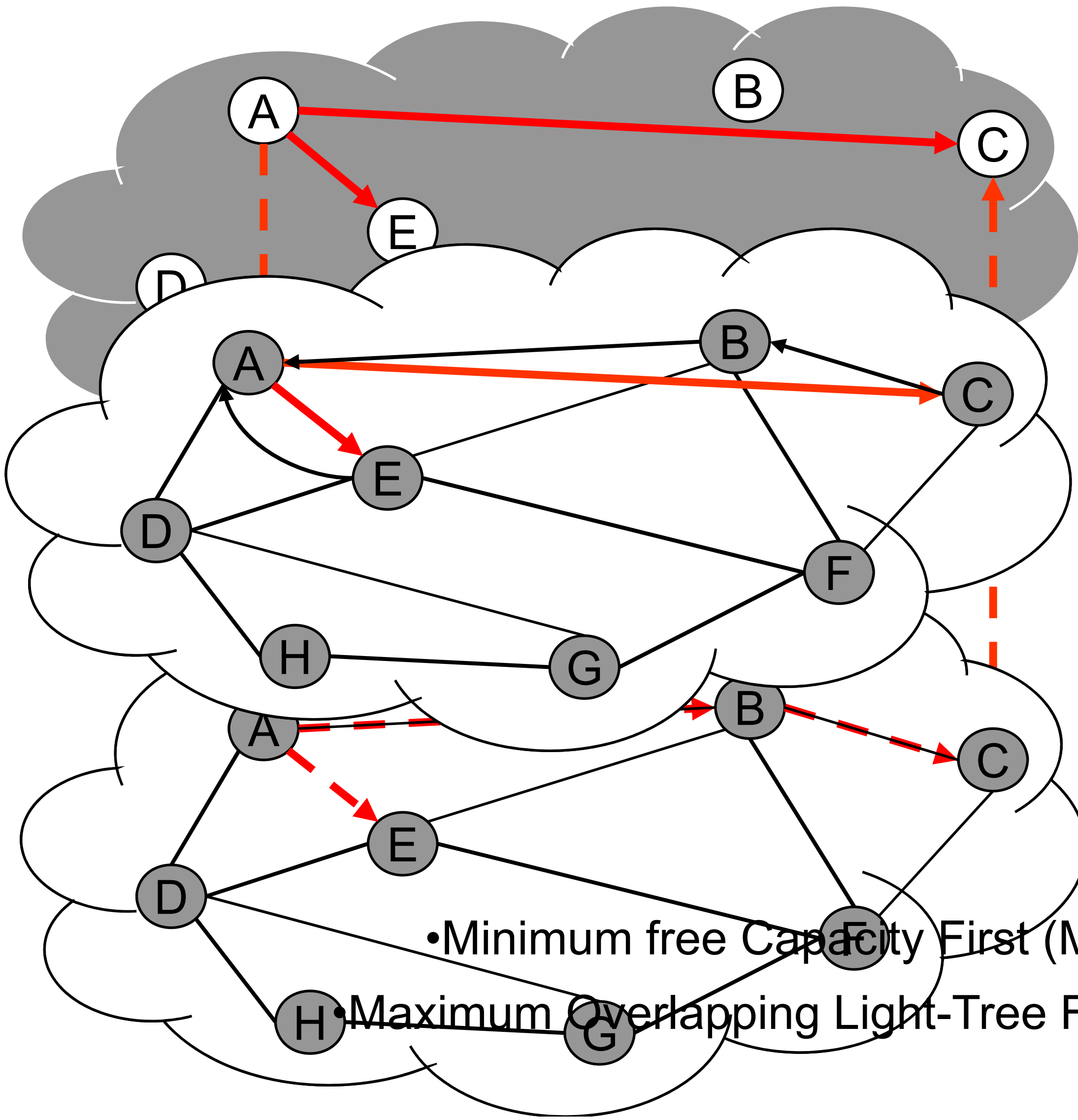


Introduction to Grooming

Logical Layer

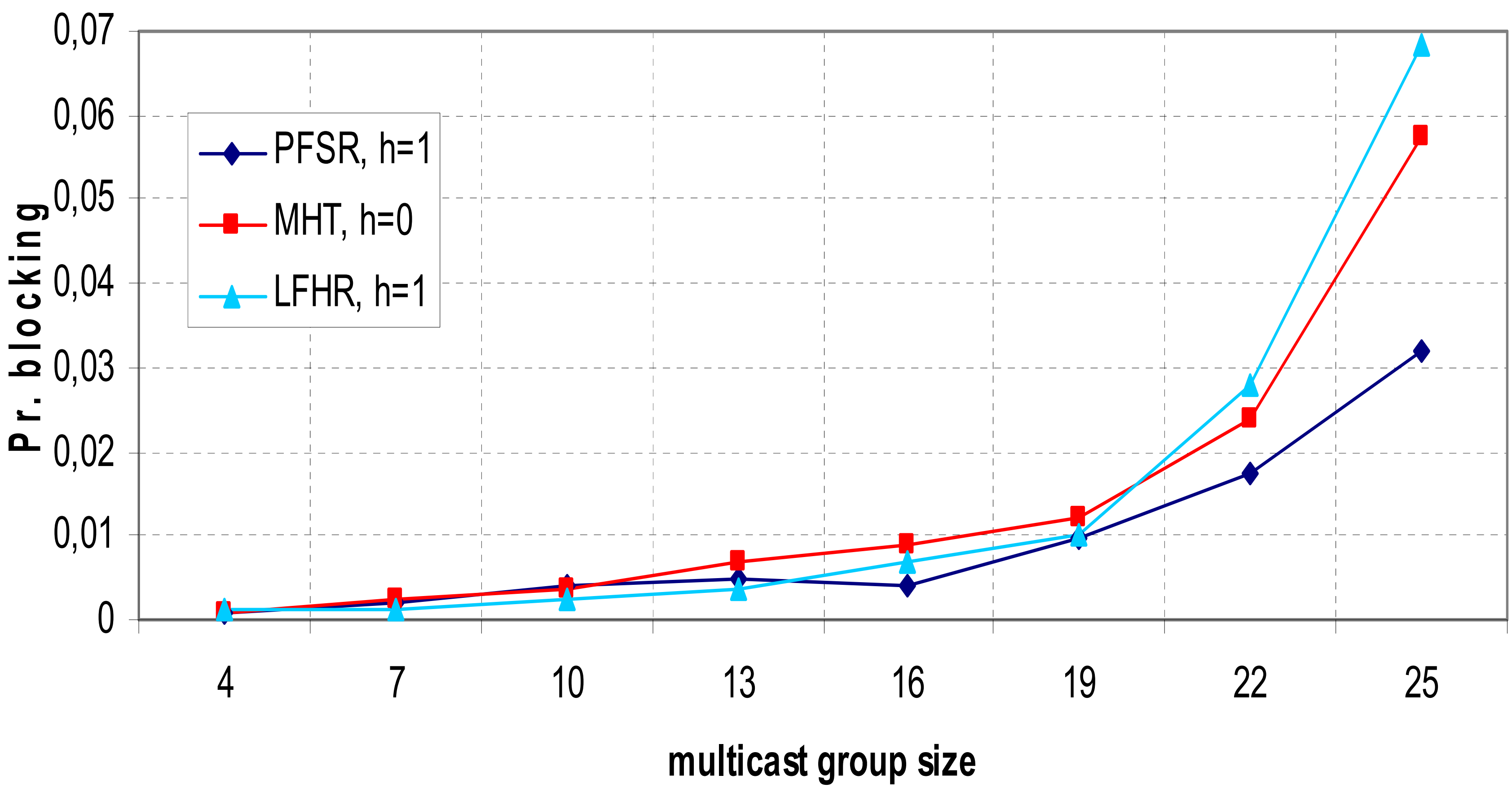
Hybrid Graph

Physical Layer

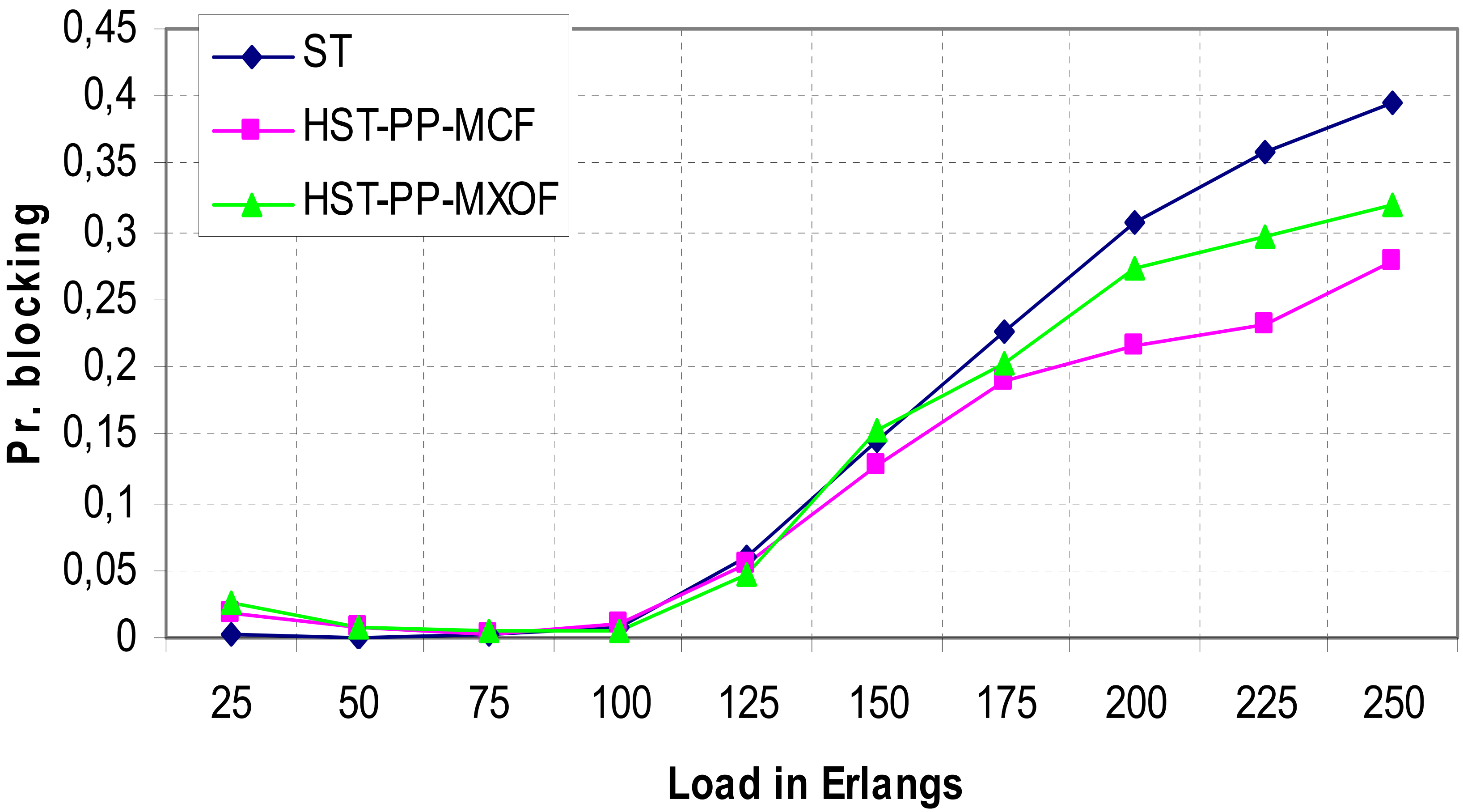


- Minimum free Capacity First (MCF).
- Maximum Overlapping Light-Tree First (MXOLF) .

Simulation Results



Simulation Results



Work Package 6

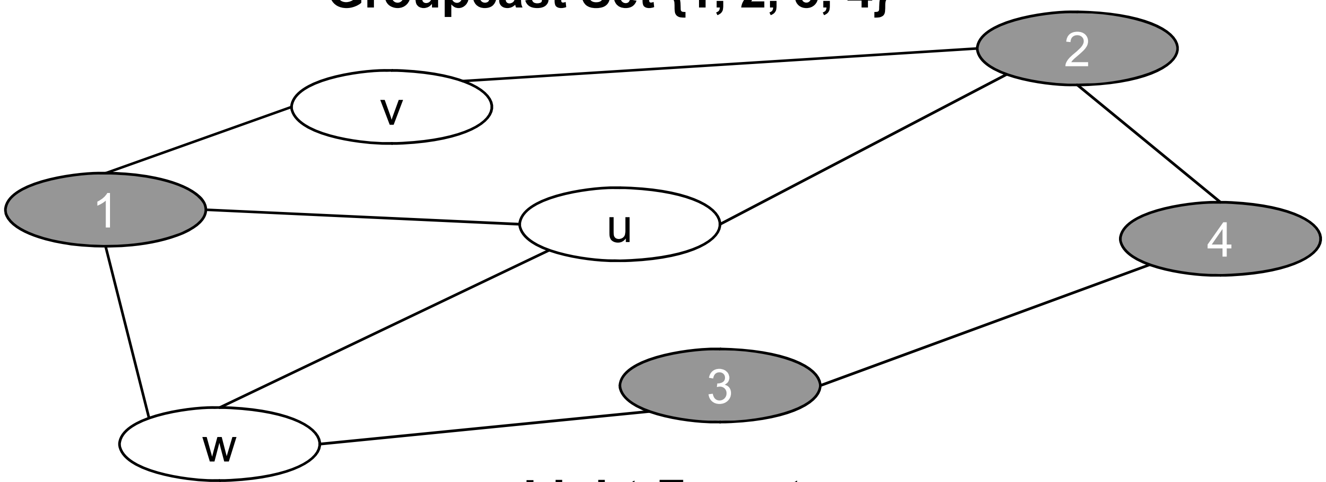
RWA for GC connections with PLIs

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

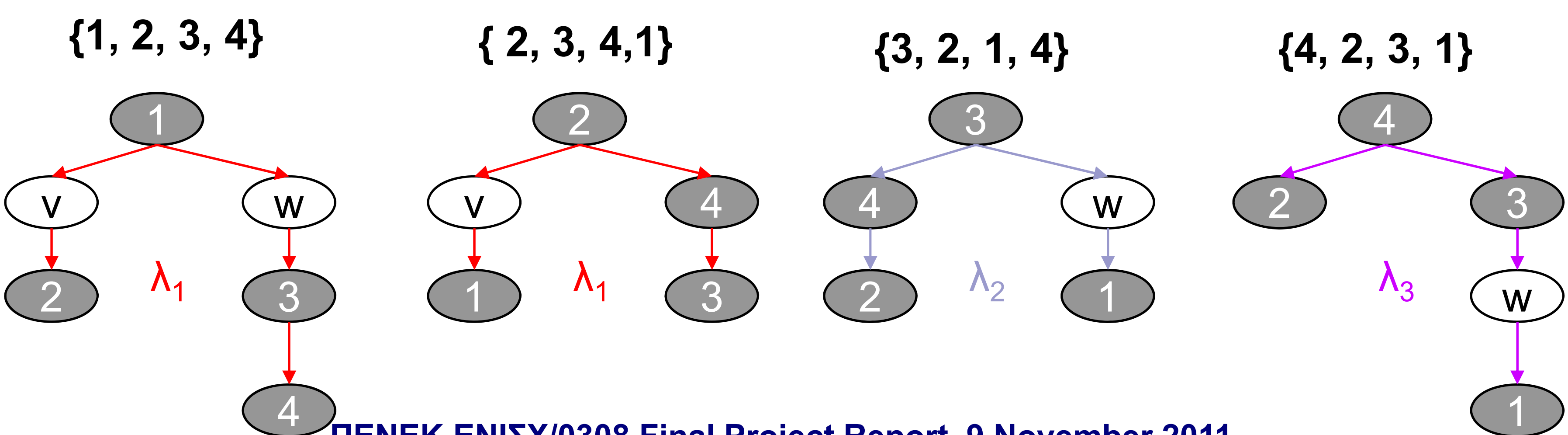
- Development of three groupcast routing algorithms:
  - Light-Trees heuristic
  - Light-Paths heuristic
  - Linear Light-Trees heuristic

Introduction in Groupcasting

Groupcast Set {1, 2, 3, 4}

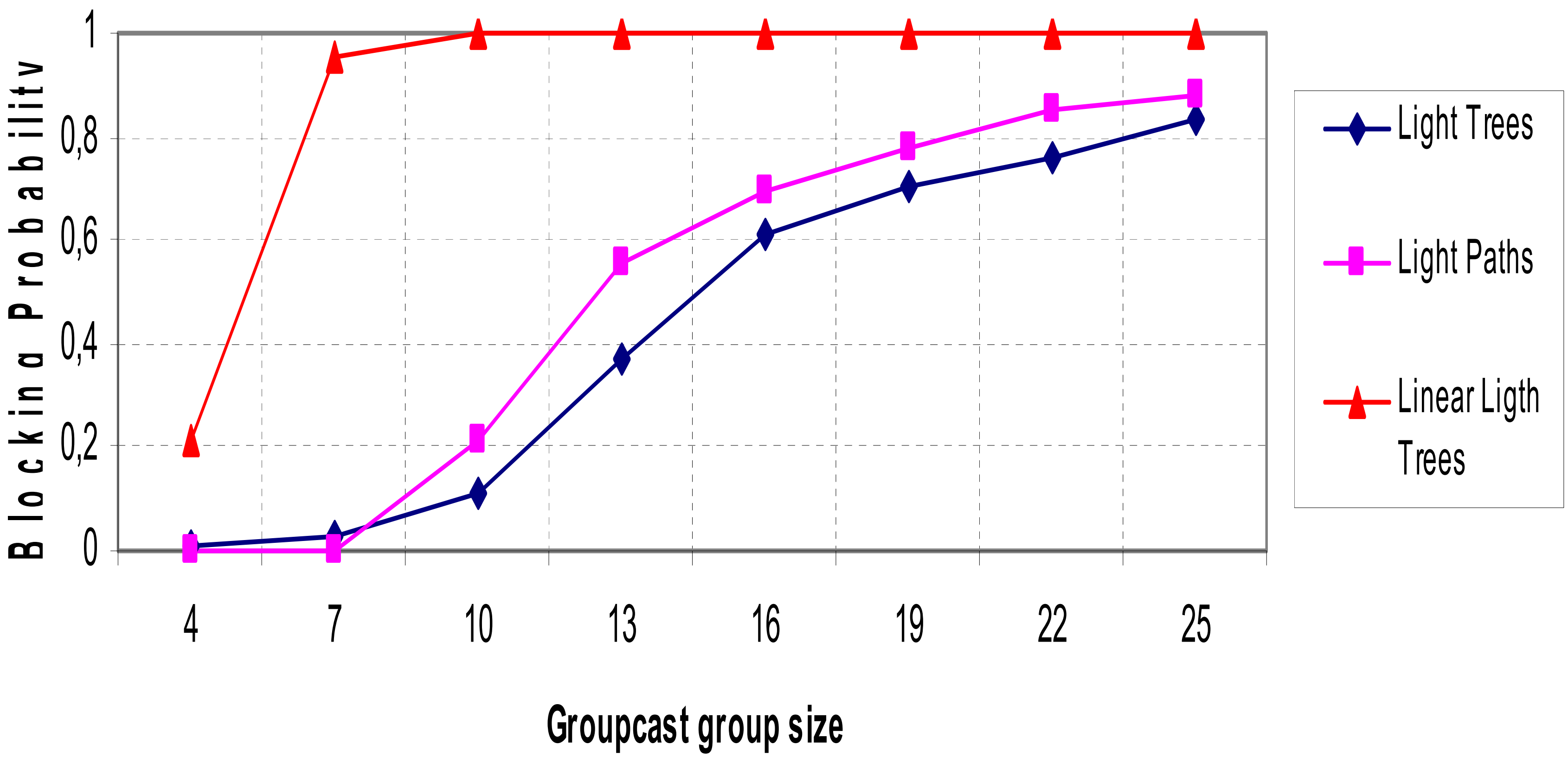


Light-Forest



Simulation Results

- With PLIs



Work Package 7

RWA of protected GC connections with PLIs

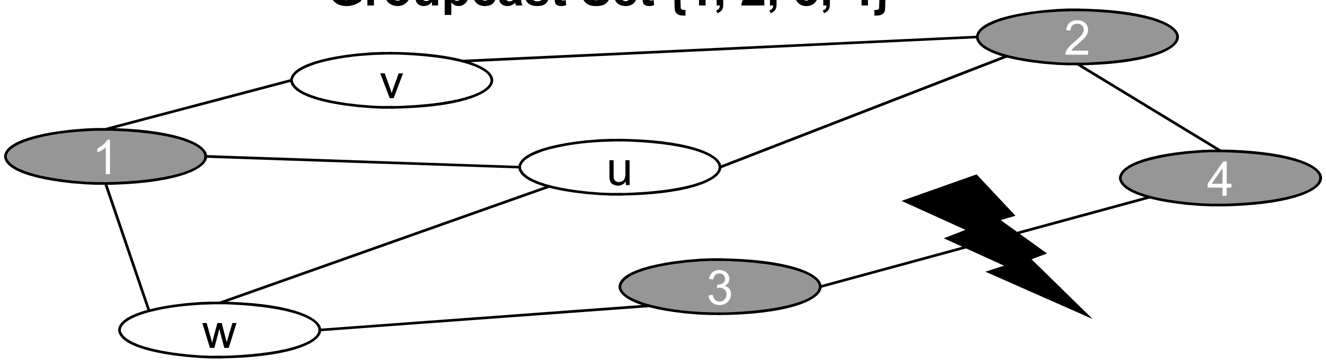
- Development of a simulation code that performs the routing/protection and wavelength assignment under physical layer constraints.

- Development of a novel protection technique for groupcast connections taking into account the physical layer constraints:
  - LEVEL protection heuristic

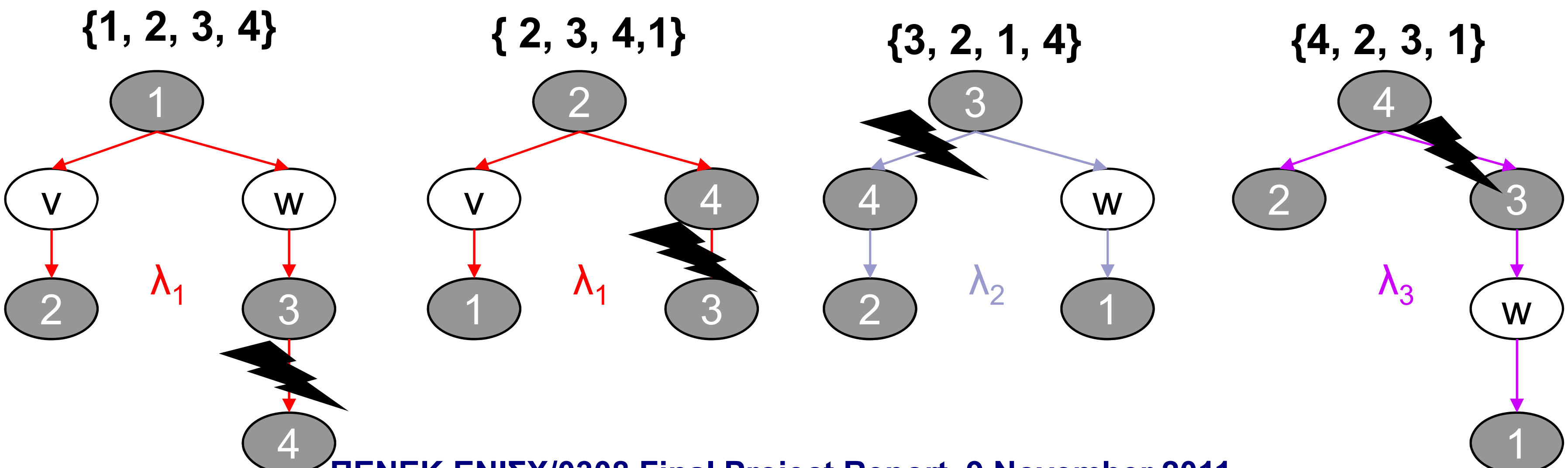
- And compared with existing protection techniques
  - Segment Protection Heuristic
  - SSNF heuristic

Introduction

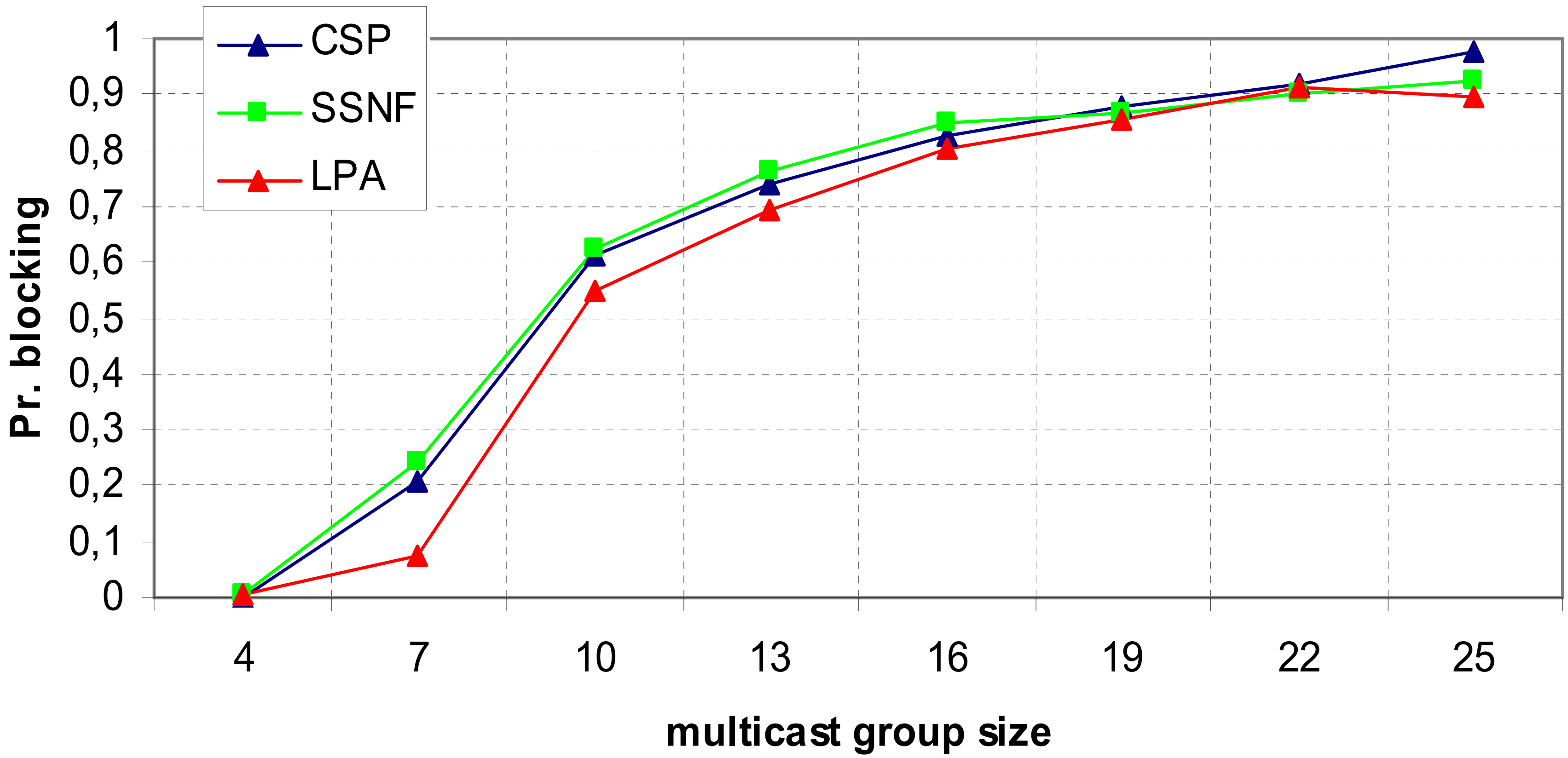
Groupcast Set {1, 2, 3, 4}



Light-Forest



Simulation Results



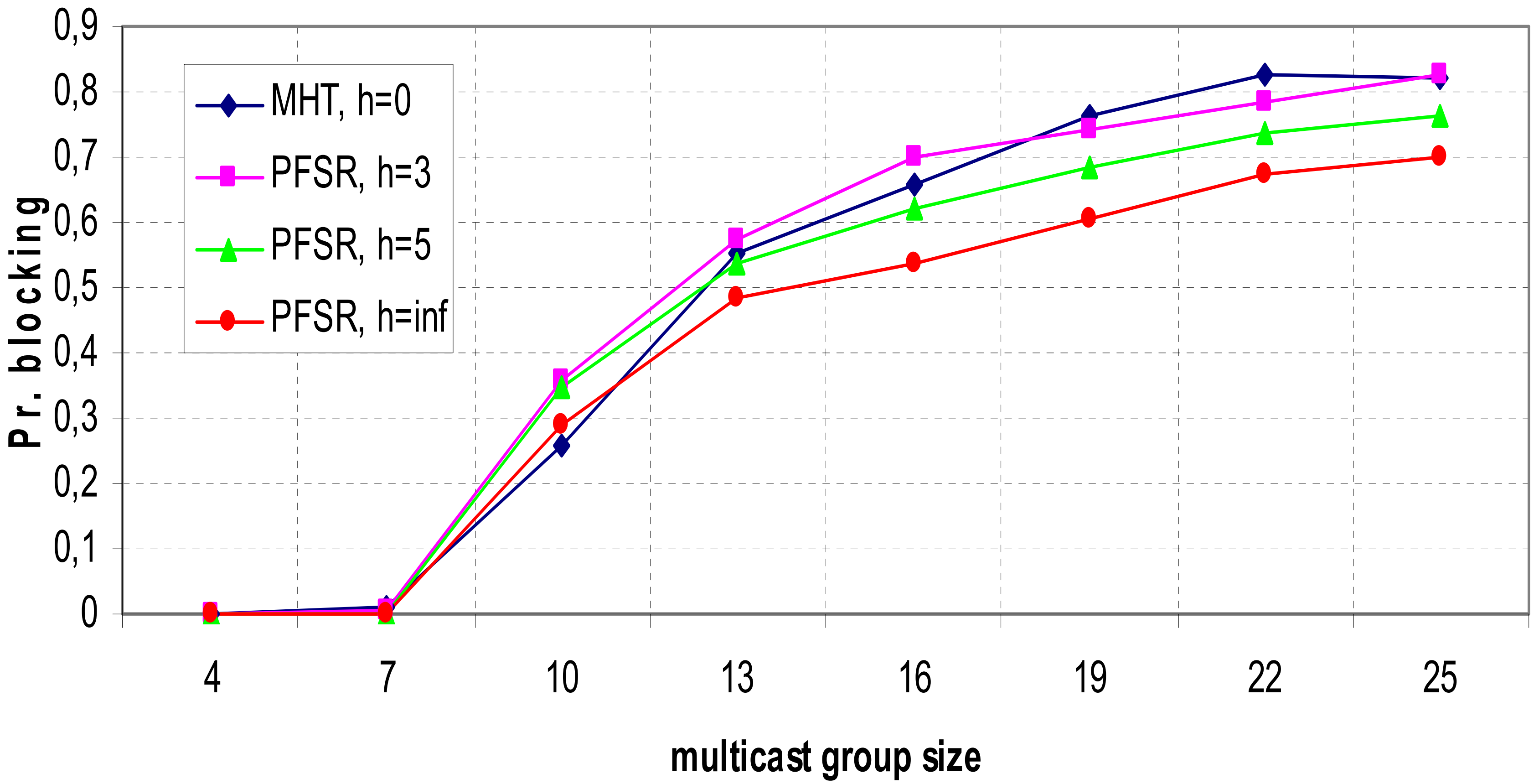
Work Package 8

Routing/Grooming and WA of GC connections with PLIs

- Development of a simulation code that performs the routing/grooming and wavelength assignment under physical layer constraints.
  - Physical First Sequential Routing (PFSR)

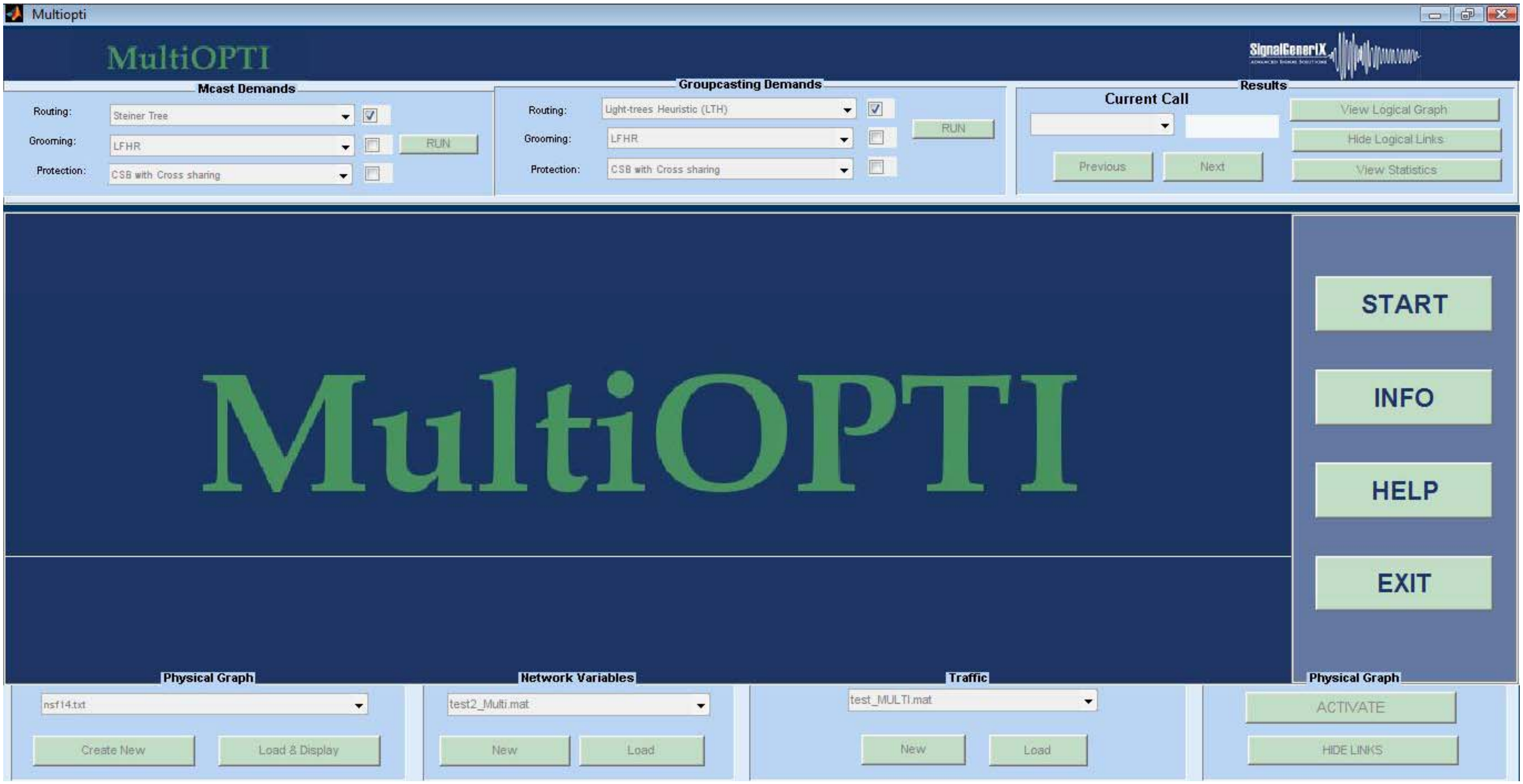
- Development of novel traffic grooming techniques for groupcast connections:
  - Grooming with Maximum Overlapped Lightpath (GMOL) heuristic.
  - GMOL heuristic with constraints on the number of hops.

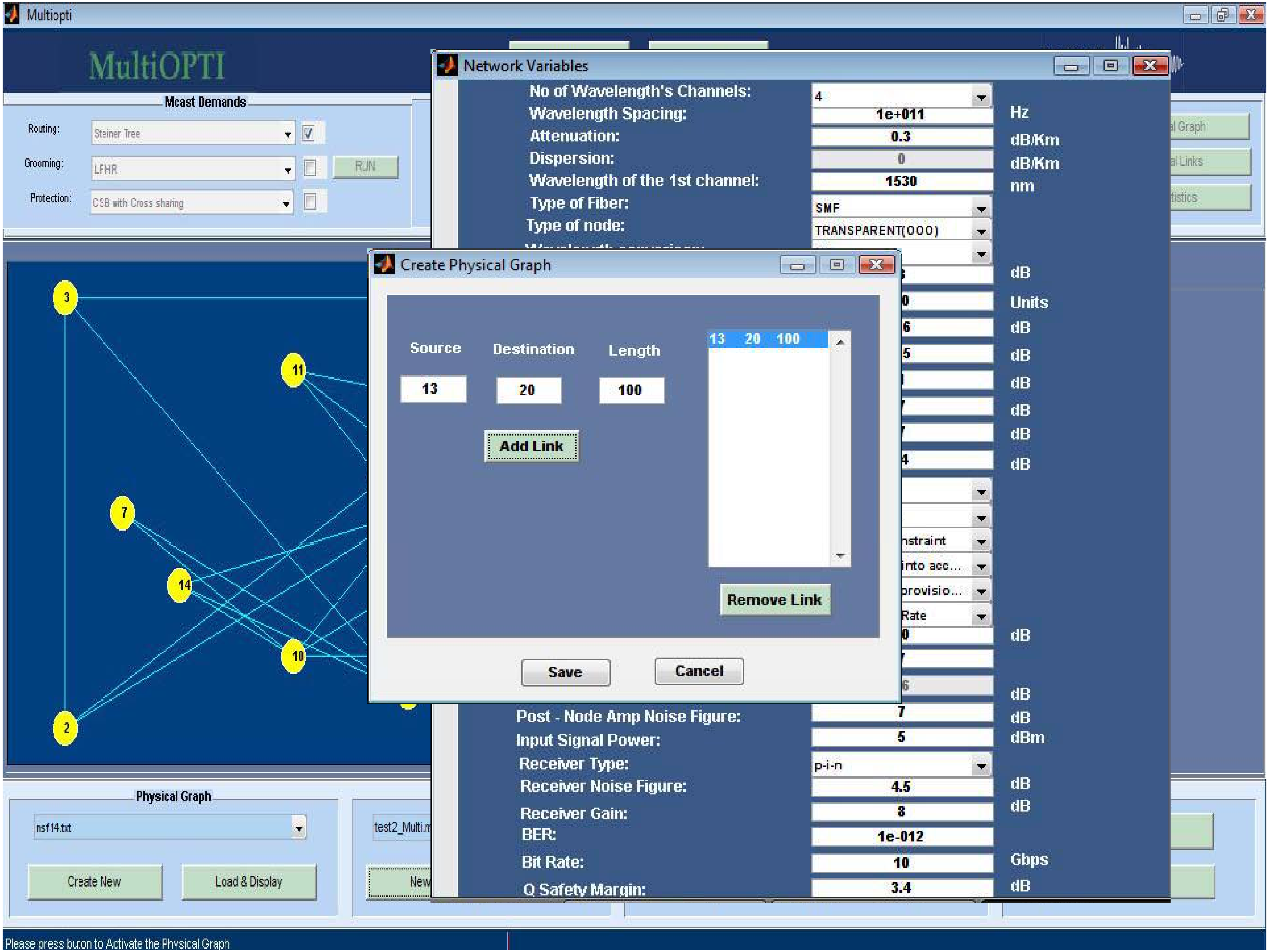
Simulation Results

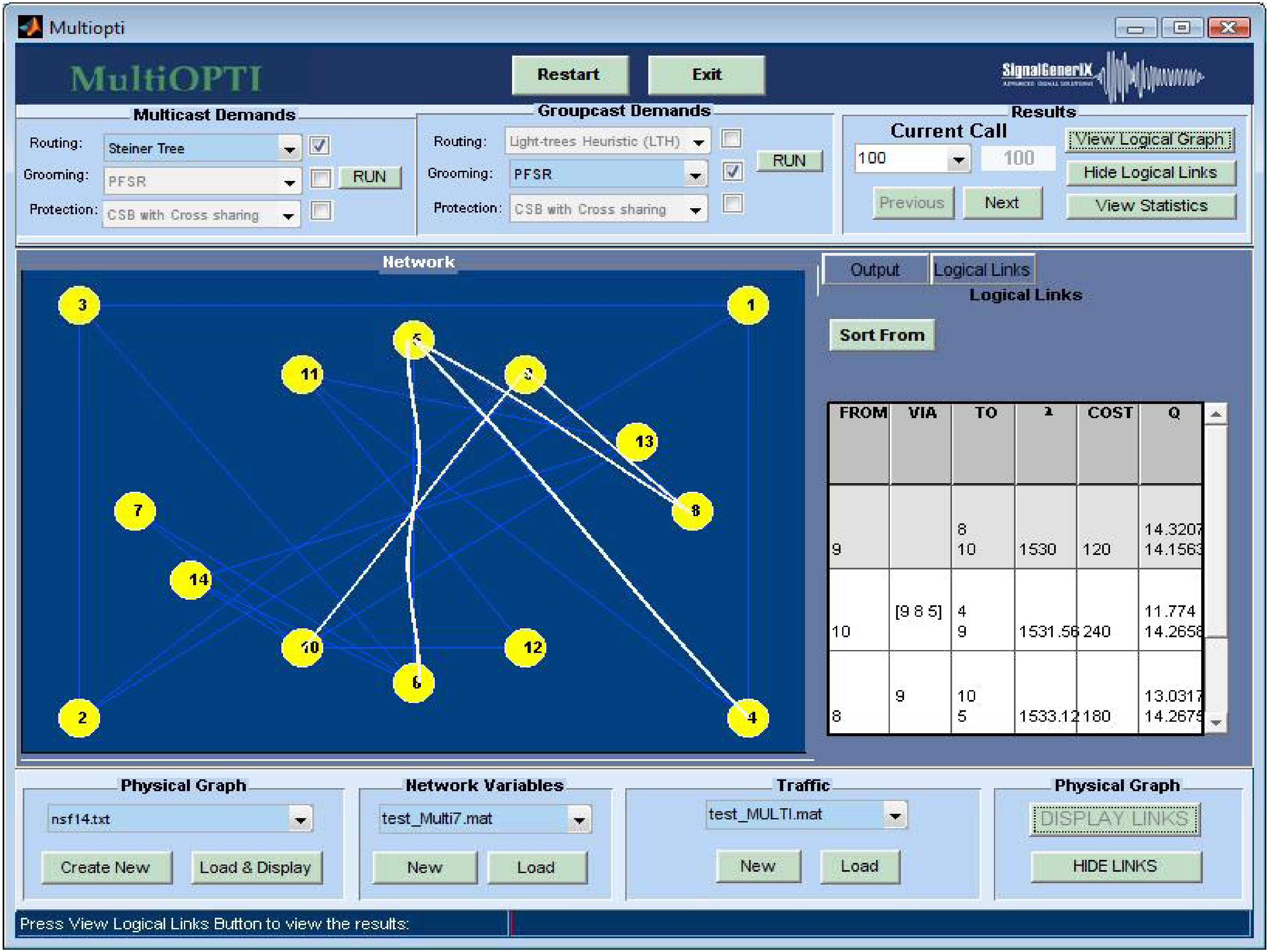


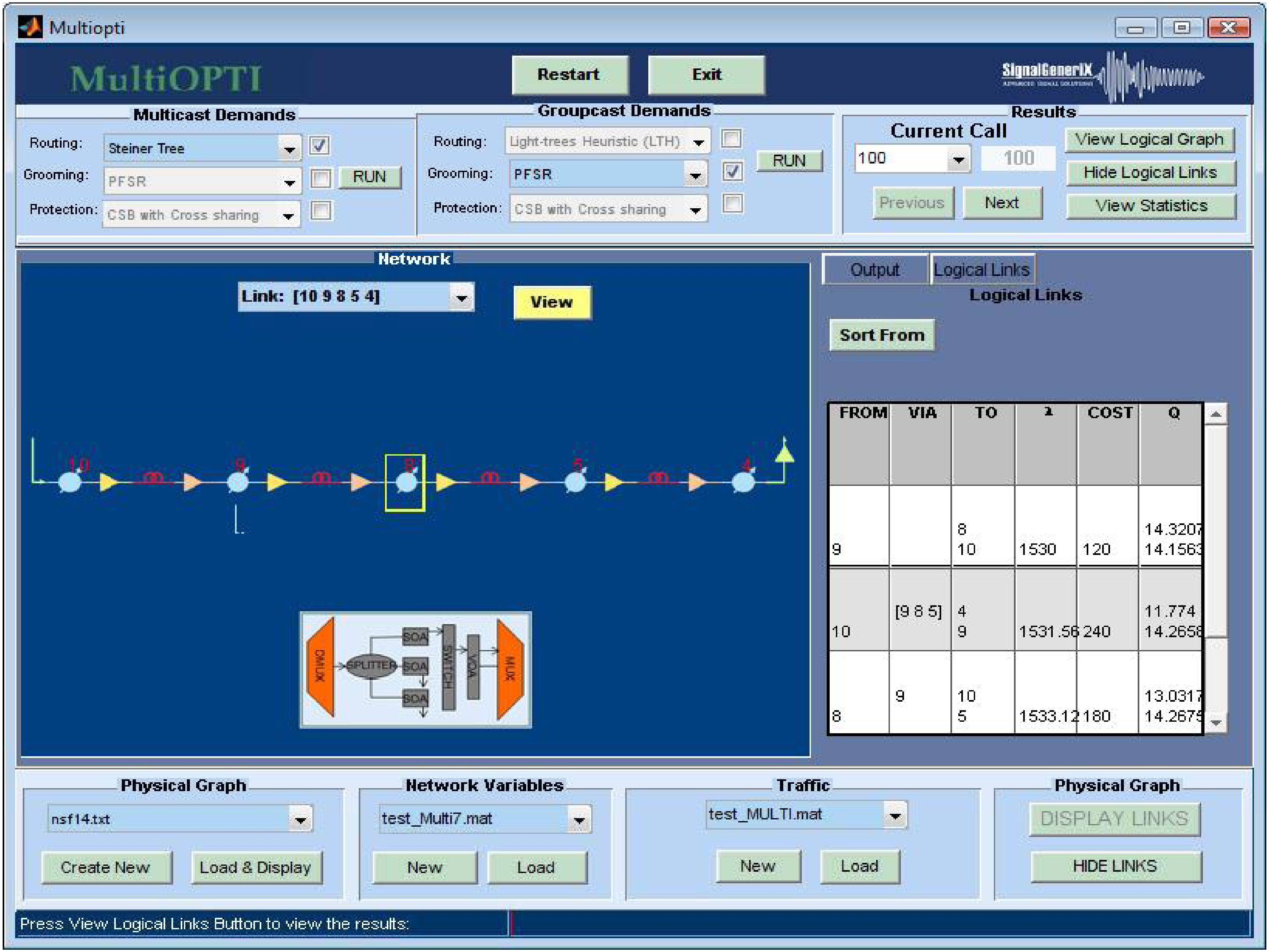
Work Package 9

- Development of the MULTIOPTI software simulation tool that incorporates multicast and groupcast connections




Multiopti
MultiOPTI
Mcast Demands
Routing: Steiner Tree
Grooming: LFHR
Protection: CSB with Cross sharing
RUN
Network Variables
No of Wavelength's Channels: 4
Wavelength Spacing: 1e+011 Hz
Attenuation: 0.3 dB/Km
Dispersion: 0 dB/Km
Wavelength of the 1st channel: 1530 nm
Type of Fiber: SMF
Type of node: TRANSPARENT(OOO)
Create Physical Graph
Source
Destination
Length
13
20
100
13 20 100
Add Link
Remove Link
Save
Cancel
Post - Node Amp Noise Figure: 7 dB
Input Signal Power: 5 dBm
Receiver Type: p-i-n
Receiver Noise Figure: 4.5 dB
Receiver Gain: 8 dB
BER: 1e-012
Bit Rate: 10 Gbps
Q Safety Margin: 3.4 dB
Physical Graph
nsf14.txt
Create New
Load & Display
test2_Multi.m
Please press buton to Activate the Physical Graph


Multiopti
MultiOPTI
Restart
Exit
SignalGenerIX
Multicast Demands
Routing: Steiner Tree
Grooming: PFSR
Protection: CSB with Cross sharing
RUN
Groupcast Demands
Routing: Light-trees Heuristic (LTH)
Grooming: PFSR
Protection: CSB with Cross sharing
RUN
Results
Current Call
100
100
Previous
Next
View Logical Graph
Hide Logical Links
View Statistics
Network
3
1
5
11
9
13
7
8
14
10
12
6
2
4
Output
Logical Links
Logical Links
Sort From
FROM VIA TO λ COST Q
9 8 10 1530 120 14.3207 14.1563
10 [9 8 5] 4 9 1531.56 240 11.774 14.2658
8 9 10 5 1533.12 180 13.0317 14.2675
Physical Graph
nsf14.txt
Create New
Load & Display
Network Variables
test_Multi7.mat
New
Load
Traffic
test_MULTI.mat
New
Load
Physical Graph
DISPLAY LINKS
HIDE LINKS
Press View Logical Links Button to view the results:


Multiopti
MultiOPTI
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Exit
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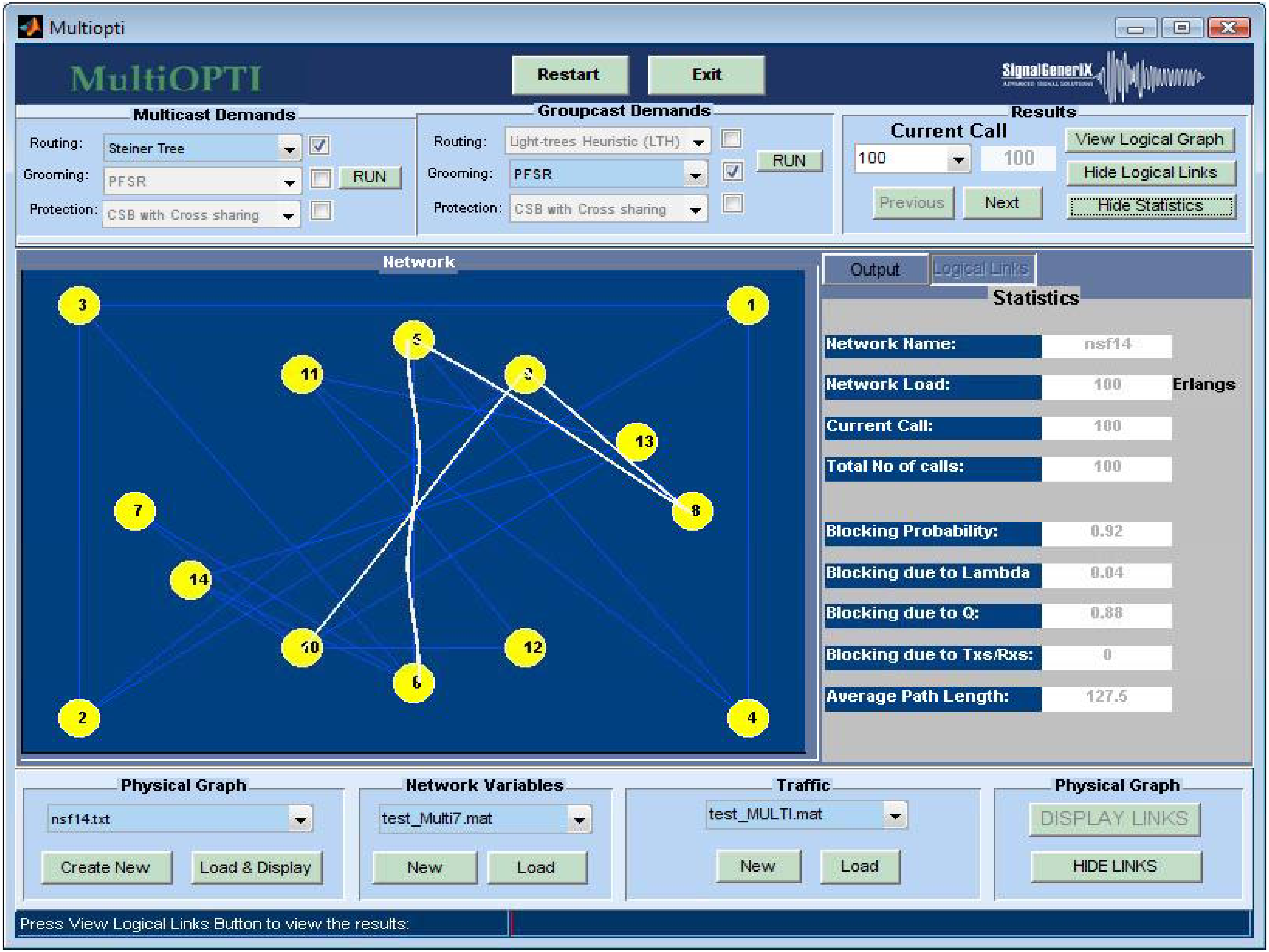
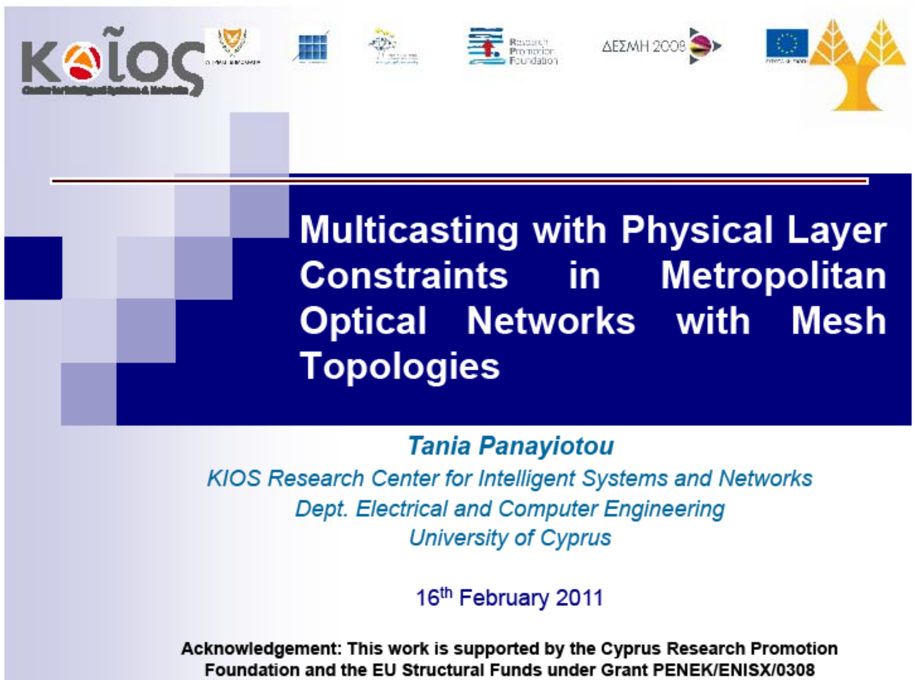
Multicast Demands
Routing: Steiner Tree
Grooming: PFSR
Protection: CSB with Cross sharing
RUN
Groupcast Demands
Routing: Light-trees Heuristic (LTH)
Grooming: PFSR
Protection: CSB with Cross sharing
RUN
Results
Current Call
100
100
Previous
Next
View Logical Graph
Hide Logical Links
View Statistics
Network
Link: [10 9 8 5 4]
View
10
9
8
5
4
DMUX
SPLITTER
SOA
SOA
SOA
SWITCH
VOA
MUX
Output
Logical Links
Logical Links
Sort From
FROM
VIA
TO
λ
COST
Q
9
8
10
1530
120
14.3207
14.1563
10
[9 8 5]
4
9
1531.56
240
11.774
14.2658
8
9
10
5
1533.12
180
13.0317
14.2675
Physical Graph
nsf14.txt
Create New
Load & Display
Network Variables
test_Multi7.mat
New
Load
Traffic
test_MULTI.mat
New
Load
Physical Graph
DISPLAY LINKS
HIDE LINKS
Press View Logical Links Button to view the results:


Multiopti
MultiOPTI
Restart
Exit
SignalGenerIX
Multicast Demands
Routing:
Steiner Tree
Grooming:
PFSR
RUN
Protection:
CSB with Cross sharing
Groupcast Demands
Routing:
Light-trees Heuristic (LTH)
Grooming:
PFSR
RUN
Protection:
CSB with Cross sharing
Results
Current Call
100
100
View Logical Graph
Hide Logical Links
Previous
Next
Hide Statistics
Network
Output
Logical Links
Statistics
Network Name:
nsf14
Network Load:
100
Erlangs
Current Call:
100
Total No of calls:
100
Blocking Probability:
0.92
Blocking due to Lambda
0.04
Blocking due to Q:
0.88
Blocking due to Txs/Rxs:
0
Average Path Length:
127.5
Physical Graph
nsf14.txt
Create New
Load & Display
Network Variables
test_Multi7.mat
New
Load
Traffic
test_MULTI.mat
New
Load
Physical Graph
DISPLAY LINKS
HIDE LINKS
Press View Logical Links Button to view the results:

Summary

- Several novel and noteworthy results were obtained during the implementation of WPs 3-9 including:
  - Novel QoT-Based MC/GC-RWA algorithms
  - Novel node design and network engineering approaches
  - Novel QoT-based protection techniques for MC/GC connections
  - Novel QoT-based grooming techniques for MC/GC connections
- No major problems were observed during the implementation of the entire project
- No deviation from the original timetable was experienced
- Extensive dissemination of project results
- Currently under discussions with a telecom company for the utilization of the software tool

Seminars



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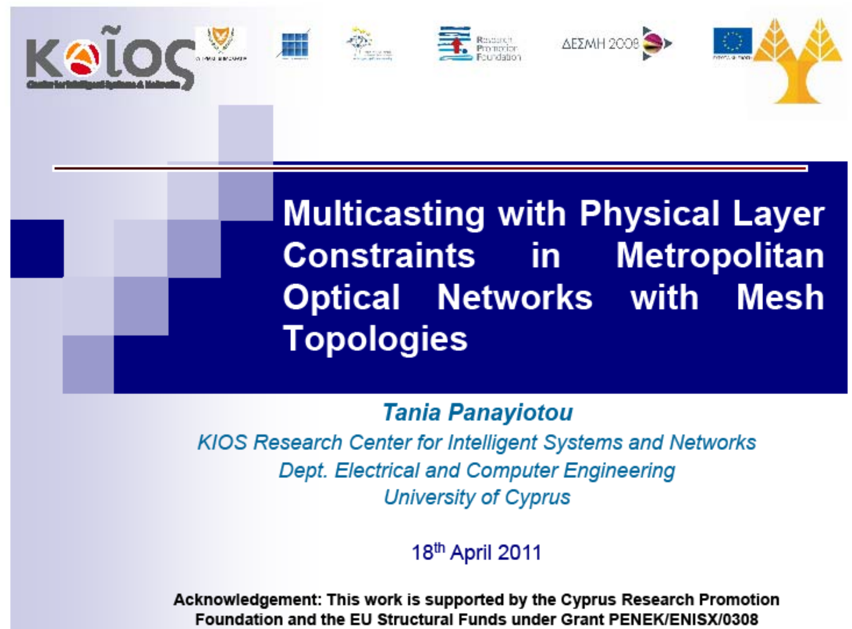

Multicasting with Physical Layer Constraints in Metropolitan Optical Networks with Mesh Topologies
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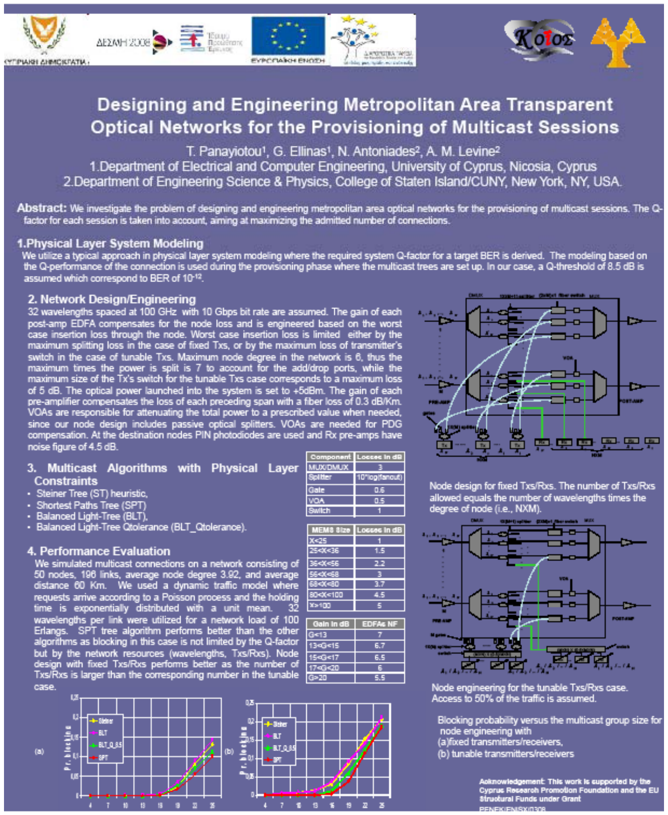
Designing and Engineering Metropolitan Area Transparent Optical Networks for the Provisioning of Multicast Sessions

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Abstract: We investigate the problem of designing and engineering metropolitan area optical networks for the provisioning of multicast sessions. The Q-factor for each session is taken into account, aiming at maximizing the admitted number of connections.

1.Physical Layer System Modeling
We utilize a typical approach in physical layer system modeling where the required system Q-factor for a target BER is derived. The modeling based on the Q-performance of the connection is used during the provisioning phase where the multicast trees are set up. In our case, a Q-threshold of 8.5 dB is assumed which correspond to BER of 10^{-12}.

2. Network Design/Engineering
32 wavelengths spaced at 100 GHz with 10 Gbps bit rate are assumed. The gain of each post-amp EDFA compensates for the node loss and is engineered based on the worst case insertion loss through the node. Worst case insertion loss is limited either by the maximum splitting loss in the case of fixed Txs, or by the maximum loss of transmitter's switch in the case of tunable Txs. Maximum node degree in the network is 6, thus the maximum times the power is split is 7 to account for the add/drop ports, while the maximum size of the Tx's switch for the tunable Txs case corresponds to a maximum loss of 5 dB. The optical power launched into the system is set to +5dBm. The gain of each pre-amplifier compensates the loss of each preceding span with a fiber loss of 0.3 dB/Km. VOAs are responsible for attenuating the total power to a prescribed value when needed, since our node design includes passive optical splitters. VOAs are needed for PDG compensation. At the destination nodes PIN photodiodes are used and Rx pre-amps have noise figure of 4.5 dB.

Component	Losses in dB
MUX/DMUX	3
Splitter	10*log(fanout)
Gate	0.6
VOA	0.5
Switch	1

MEMS Size	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

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

3. Multicast Algorithms with Physical Layer Constraints
- Steiner Tree (ST) heuristic,
- Shortest Paths Tree (SPT)
- Balanced Light-Tree (BLT),
- Balanced Light-Tree Qtolerance (BLT_Qtolerance).

4. Performance Evaluation
We simulated multicast connections on a network consisting of 50 nodes, 196 links, average node degree 3.92, and average distance 60 Km. We used a dynamic traffic model where requests arrive according to a Poisson process and the holding time is exponentially distributed with a unit mean. 32 wavelengths per link were utilized for a network load of 100 Erlangs. SPT tree algorithm performs better than the other algorithms as blocking in this case is not limited by the Q-factor but by the network resources (wavelengths, Txs/Rxs). Node design with fixed Txs/Rxs performs better as the number of Txs/Rxs is larger than the corresponding number in the tunable case.

Node design for fixed Txs/Rxs. The number of Txs/Rxs allowed equals the number of wavelengths times the degree of node (i.e., NXM).

Node engineering for the tunable Txs/Rxs case. Access to 50% of the traffic is assumed.

Blocking probability versus the multicast group size for node engineering with
(a)fixed transmitters/receivers,
(b) tunable transmitters/receivers

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Node Architecture Design and Network Engineering Impact on Optical Multicasting Based on Physical Layer Constraints

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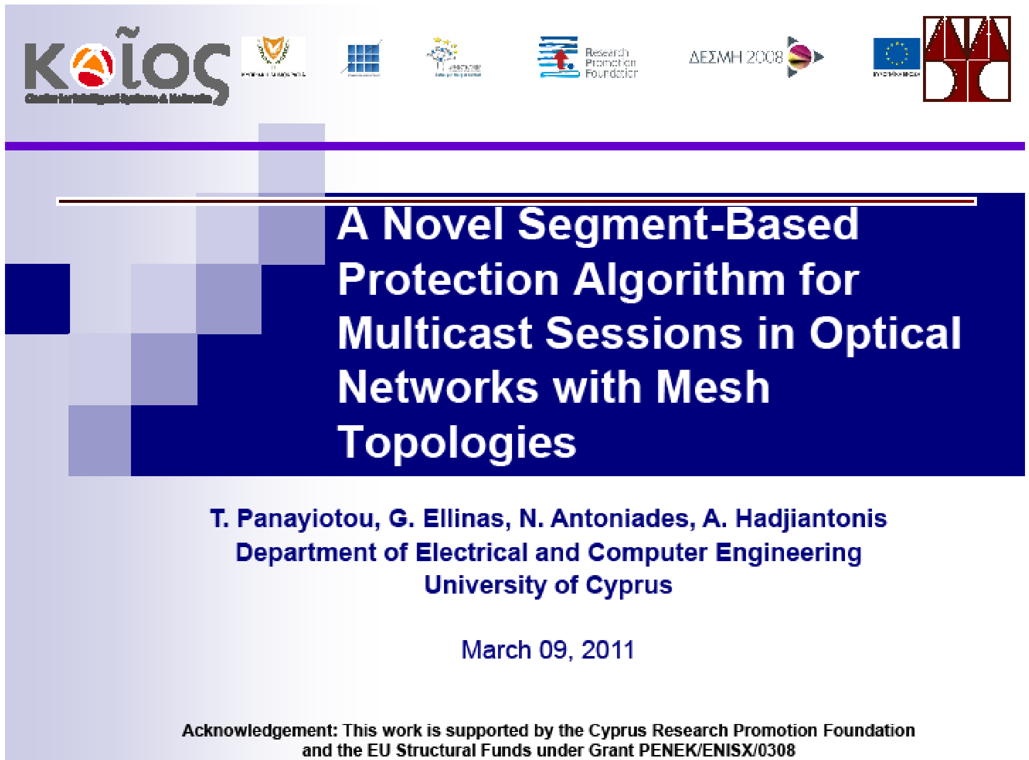

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Multicast Routing Algorithms Based on Q-Factor Physical-Layer Constraints in Metro

G. Ellinas *Senior Member IEEE*, N. Antoniades *Member IEEE*, T. Panayiotou, A. Hadjiantonis, and A. M. Levine

***Abstract*—We use novel "light-tree balancing techniques" to investigate the problem of provisioning multicast sessions in metropolitan all-optical networks. The Q-factor for every path of a derived light-tree is calculated taking into account several physical layer constraints in the network and using a Q-budgeting approach. Based on the above performance, tree balancing techniques are applied to maximize the number of multicast connections that can be admitted to the network.**

***Index Terms*—Multicasting, Q-factor, routing, impairments.**

I. Introduction

Multicasting has been investigated since the early days of optical networking [1,2], but has only recently received considerable attention from the service providers, mainly because now many applications exist that can utilize the multicasting feature. Bandwidth-intensive applications and rich multimedia and real-time services are becoming very popular in today's networks (e.g., video-conferencing, real-time online computer games, etc.) and unicast, multicast and groupcast traffic need to be supported. In these networks, optical splitters can be used to split the incoming signal to multiple output ports thus enabling a source node to establish connections with multiple destinations. In this case, a *light-tree* is created to serve a multicast request, which is a set of lightpaths from the source to all the destination nodes.

In this paper we present novel light-tree routing approaches that use physical layer constraints through the Q-factor. Apart from finding the minimum cost tree, our proposed techniques calculate the physical performance of the system by calculating Q-penalties for impairments and using a Q-budgeting approach [3], to investigate whether a multicast connection should be admitted to the network. The new routing approaches use "tree balancing techniques" for the multicast sessions, aiming at maximizing the multicast connections that can be admitted to the network. The work presented here expands the existing multicast routing techniques that use optical signal power as the main optical layer constraint [4]. We demonstrate that by taking into account the noise contributions in the network and calculating the Q-factor as opposed to just the optical power results in significantly improved blocking probability for multicast connections. A byproduct of the above is that different engineering of the physical layer produces different multicast group blocking, a strong indicator that a more refined interaction between physical and logical layer is needed for multicast connection provisioning.

II. Tree Balancing Algorithms with Physical Layer Impairments

Constructing cost-effective light-trees (known as the Steiner-tree problem) along with the wavelength assignment problem for these light-trees is an NP-complete problem [1]. Even though several heuristics exist for solving the multicast routing and wavelength assignment (MC-RWA) problem [2,5-7], these heuristics do not account for the physical layer impairments encountered by the multicast connections. Furthermore, when the physical layer constraints are introduced in solving the MC-RWA problem, only the power budget is considered [4,8]. This paper improves on these MC-RWA algorithms by also including physical layer constraints utilizing the Q-factor.

Initially, the algorithm finds a shortest-path light-tree T that spans the source and the destination nodes for each multicast group. This work then extends the *balanced light-tree* (BLT) approach for power budget constraints [4] by taking into account the Q-factor (*balanced light-tree_Q* [BLT_Q]). Consider a light-tree, and let u denote the node with the minimum Q-factor, and v denote the node with the maximum Q-factor. The idea behind BLT_Q is to delete node u from T, and add it back to the tree by connecting it to node v in the path from source s to node v. This results in an increase of the Q-factor of node u, but it also reduces the Q-factor of all nodes below node v in the tree. Therefore, this pair of delete/add operations is performed *only* if it does not reduce the Q-factor of any node beyond that of node u. Thus, after each iteration of BLT_Q, the Q-factor of the node with the minimum value is increased. The algorithm also ensures that while the Q-factor of some other node(s) is decreased, it does not decrease beyond the previous minimum value. As a result, the difference between the minimum and maximum Q-factor values also decreases with each iteration. The balancing part of the algorithm terminates after a certain number of iterations. Note that if more than a pair of nodes with the same maximum and minimum Q-factor exist, we let U denote the set of nodes with the minimum Q-factor and V denote the set of nodes with the maximum Q-factor. We then select the shortest path amongst all the shortest paths that may exist between any two nodes in sets U and V.

As the BLT_Q algorithm tends to create trees that have more breadth than depth, it decreases the attenuation loss and

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Designing and Engineering Metropolitan Area Transparent Optical Networks for the Provisioning of Multicast Sessions

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Abstract: We investigate the problem of designing and engineering metropolitan area optical networks for the provisioning of multicast sessions. The Q-factor for each session is taken into account, aiming at maximizing the admitted number of connections.

1. Introduction

Advances in optical WDM networking have made bandwidth-intensive multicast applications such as interactive distance learning, video-conferencing, distributed games, movie broadcasts from studios, etc., widely popular. Multicasting has been investigated in the research community since the early days of optical networking, but has only recently received considerable attention from the service providers, mainly because now many emerging applications can potentially utilize the optical multicasting feature. In WDM networks optical splitters can be used to split the incoming signal to multiple output ports thus enabling a source node to establish connections with multiple destinations. In this case, a light-tree is created to serve a multicast request. To investigate whether a multicast connection should be admitted to the network, apart from finding the minimum cost tree, this paper considers a Q-budgeting approach as a metric on the physical performance of the system. There exist several heuristics on finding these light-trees and this work presents "tree-balancing techniques" aiming at maximizing the multicast connections that can be admitted to the network. It is shown that different node design and engineering approaches as well as different system physical parameters produce different multicast group blocking results, a strong indicator that a better interaction between the physical and logical layers is needed for multicast connection provisioning in optical networks to be more effective. We focus on the metropolitan area network environment where such applications are currently gaining traction.

2. Physical Layer System Modeling

We utilize a typical approach in physical layer system modeling where the required system Q-factor for a target BER is derived using the equation below [1-2]:

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \quad \text{where } \sigma_i^2 = \sigma_{th}^2 + \sigma_{shot-i}^2 + \sigma_{ASE-ASE}^2 + \sigma_{s-ASE-i}^2 + \sigma_{RIN-i}^2 + \sigma_{ASE-shot}^2$$

The above equation assumes a baseline system that includes amplified spontaneous emission (ASE) noise from the optical amplifiers and incorporates the sum of the variances of the thermal noise, shot noise, various beat noise components, and RIN noise at the receiver in the form of σ_i. A Q-budgeting approach that calculates the Q penalty due to each introduced impairment is then used as described in detail in [2] and references therein that results in a lower system Q than the initial baseline. This approach provides a good trade-off between accuracy and computational complexity especially given the fact that thousands of connections are being routed in each iteration and interaction with the physical layer is needed in each one. In a real system this interaction happens during the provisioning phase to decide whether a multicast connection will be admitted to the network or rejected. The modeling based on the Q-performance of the connection is used during the provisioning phase where the multicast trees are being set up to decide whether a multicast connection will be admitted in the network. If the derived Q for any path on the calculated tree is below a pre-determined threshold, then the new call will be blocked. In our case, a Q-threshold of 8.5 dB is assumed which corresponds to BER of 10^{-12}. Budgeting for crosstalk, nonlinearites, PMD, filter concatenation and component aging is as described in [2].

3. Network Design/Engineering

This article expands on the work in [2], where the optical node was treated as a "black box", by examining different node architectures, including cases with fixed or tunable transmitters (Tx)/receivers (Rx) (the number of transmitters/receivers varies from being equal to the number of wavelengths to being equal to the number of wavelengths times the degree of the node). In this work passive splitters are used at each node (see Fig. 1) and power is split as many times as the fan-out of the node plus one to account for the add/drop ports. Controllable SOAs are used as gates to "cut-off" power at outputs where the signal is not destined for. All gates are controlled together in an intelligent manner in order to avoid clashing at the same output/same wavelength of the switch. The effects of the described node design and proper system engineering on the performance of multicast algorithms have not been studied before and provide a good insight into the interaction of physical and network layers in an optical network. Figure 1(a) shows the node design for the case of fixed Txs/Rxs, while Figure 1(b) shows the node design when tunable Txs/Rxs are assumed. For the latter, a switch is added at the add/drop ports respectively in order to allow for maximum flexibility for the multicast connections; its size depends on the

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Node Architecture Design and Network Engineering Impact on Optical Multicasting Based on Physical Layer Constraints

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Abstract: Different node design architectures and node engineering approaches are considered for fully-transparent metropolitan area optical networks for the provisioning of multicast sessions. A number of multicast routing approaches are considered that take into account the physical layer constraints. The goal of this work is to minimize the overall blocking probability in the network, while ensuring that the provisioned multicast connections meet a prescribed bit error rate.

1. Introduction

High-bandwidth multicast applications are becoming widely popular, further driving the requirement for next generation optical networks to support all types of traffic (unicast, multicast, groupcast) and all kinds of applications. Even though there is a large body of work on optical multicasting, this area is receiving renewed attention from the service providers, as the number of multicasting applications is constantly increasing. In these networks optical splitters can be used in network nodes to split the incoming signal to multiple outputs, thus enabling the establishment of connections with multiple destinations [1]. In transparent optical networks, a light-tree is created to serve a multicast request, which is a set of lightpaths from the source to all the destination nodes [2].

Recent work on the problem of routing and wavelength assignment (RWA) for provisioning multicast connections in transparent optical networks have included the inclusion of physical impairments to investigate whether a multicast connection should be admitted to the network, apart from finding the minimum cost tree. In our previous work a Q-budgeting approach is used as a metric of the physical performance of the system as described in [3]. In [4] the detailed design of the node architecture and the engineering of the nodes are presented, in order to study the impact of physical impairments on the provisioning of the connections. In this article, we expand on that work by investigating the node design and considering nodes with active or passive splitters, and nodes with various transmitter/receiver designs.

2. Physical Layer System Modeling

Modeling of the physical layer is based on the physical path Q factor that is subsequently used to calculate the Bit Error Rate (BER) of the system, a parameter that is difficult to evaluate upfront [3,5]. This approach assumes a baseline system with various receiver noise terms as well as Amplified Spontaneous Emission (ASE) noise. To include other common physical layer impairments such as crosstalk, fiber nonlinearities, distortion due to optical filter concatenation, and PMD among others, a simple Q-budgeting approach is used as described in [3]. We start from the Q-value for the baseline system and budget Q-penalties for the various physical layer impairments present. Thus, 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 without the computationally complex time-domain approach, thus enabling simulation repetitions that are needed for system engineering.

The Q penalty Q_{dB} associated with each physical layer impairment in a system is expressed in dB and is calculated as the Q_{dB} without the impairment in place minus the Q_{dB} with the impairment present. After the Q factor is evaluated, the BER can then be calculated [5]. In this work, 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 set threshold [6].

3. Node Architectures and Node Engineering Designs

In this section we present different node architectures and different node engineering designs and examine the physical performance of the network using the Q-budgeting approach. We

A Novel Segment-Based Protection Algorithm for Multicast Sessions in Optical Networks with Mesh Topologies

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Abstract: This work examines protection of multicast sessions in optical networks utilizing a novel segment-based algorithm called Level Protection. Our proposed scheme exhibits improved performance compared to other segment-based multicast protection schemes.

OCIS codes: (060.4250) Fiber optics and optical communications, Networks; (060.4255) Networks, multicast; (060.4261) Networks, protection and restoration.

1. Introduction

High-bandwidth multicast applications are becoming widely popular, further driving the requirement for next generation optical networks to support all types of traffic (unicast, multicast, and groupcast) and all kinds of applications. Multicasting has been investigated in the research community since the early days of optical networking, but has only recently received considerable attention from the service providers, mainly because now many emerging applications can potentially utilize the optical multicasting feature. For such applications to be viable, it is important that the multicast traffic is not only routed efficiently through the optical network but it is also protected against any possible failures in the network.

In transparent optical networks, a light-tree is created to serve a multicast request [1]. In these networks, optical splitters can be used in network nodes to split the incoming signal to multiple outputs, thus enabling the establishment of connections with multiple destinations [2]. An effective solution to the multicast routing problem would be to calculate the Steiner Minimum Tree (SMT) between the source and destination nodes. However, as the SMT problem was proven to be NP-complete, heuristics were developed to compute a multicast tree [3,4]. Protecting a multicast session against a link failure requires finding alternate paths for all failure scenarios prior to the occurrence of the fault. Various approaches exist for multicast protection including path-, segment-, and cycle-based techniques. This work investigates the problem of segment-based protection of multicast connections in mesh optical networks, as segment-based protection schemes are reported to have better performance than other known schemes in terms of resource efficiency and blocking probability. The proposed algorithm is compared to segment-based protection algorithms described in the literature [5,6,7] and is shown to improve performance compared to previously published work. In order to improve the resource utilization ratio and reduce blocking probability, sharing techniques are also included in our algorithm (both self- and cross-sharing) as these are described in [8].

2. Multicast Protection

Several segment-based protection schemes proposed in the literature [5,6] are based on the Conventional Segment Protection (CSP) algorithm. Given a primary light-tree, CSP first identifies the segments on that light-tree and then attempts to derive a link-disjoint backup segment for each segment on the primary light-tree. Here, a segment in a primary light-tree is defined as the path between two segment points of the tree and segment points are defined as all the splitting nodes, the destination nodes, and the source node. In [7], a segment protection scheme called segment-based protection with sister node first (SSNF) is proposed and its basic idea is to protect a primary light-tree using a set of backup segments, with higher priority to protect the segments from a splitting node to its children. In this work, we propose a novel and efficient algorithm called *Level Protection Algorithm (LPA)* that differs from the other segment-based protection algorithms proposed in the literature in how the segments are identified.

2.1. Level Protection Algorithm Definitions

Segmentation nodes of a tree: Given a tree T, a vertex $n \in T$ is a *segmentation node* if it is the source or it is a destination node of the multicast request. In Figure 1(a), the segmentation nodes are nodes s, d_1, d_2, d_3, d_4, and d_5.
Segments of a tree: Given a tree T, a path between two segmentation nodes is said to be a *segment of the tree* if the path does not pass through any other segmentation nodes of the tree except the two end-nodes of the path. The primary light-tree given in Figure 1(a) is divided to five primary segments, that are $\{s, u, d_1\}$, $\{d_1, d_2\}$, $\{d_2, d_4\}$, $\{d_2, d_3\}$, $\{d_4, d_5\}$.

Web Site

Georgios Ellinas

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

General Project Description

This project investigates the problems of routing, grooming, and survivability for transparent optical networks that support unicast, multicast, as well as groupcast applications. In these transparent networks, where the signal stays in the optical domain for the entire path, efficient routing and wavelength assignment of multicast and groupcast connections becomes extremely important especially in light of the multiple splits that the signal undergoes and the physical layer impairments (crosstalk, dispersion, etc) that the optical signal encounters. In the design of the algorithms the physical layer impairments will be taken into consideration during the provisioning of each application. The algorithms designed will be incorporated in a software simulation tool that can be utilized by network designers and researchers to design and evaluate the performance of metropolitan optical networks when such applications are present. In this way, more efficient networks can be deployed, thus lowering the cost of the network operation and the cost of the services offered to the clients of the telecommunications carriers and service providers.

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