Multicast Routing under Optical Network Constraints

Bernard Cousin[1], Miklós Molnár[2], Fen Zhou[3]

(1) IRISA - Univ. of Rennes I (2) LIRMM - Univ. of Montpellier II (3) Telecom Bretagne

Colloque *Réseaux à large bande et Internet rapide*, Beyrouth, March 2011

AOMR

- Wavelength-routed WDM network $G(V, E, W)$
- One-to-many communication $ms(s, D)$
- Routing path: Light-structure (a set of light-trees !)
- Sparse splitting

Sparse Splitting: only few nodes equipped with light splitters (MC)

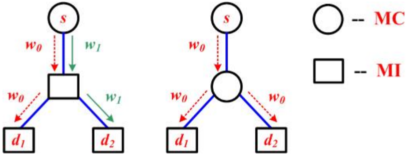


Figure: Multicast Incapable Node (MI) and Multicast Capable Node (MC)

Assumptions:

- No wavelength conversion
- Sparse splitting (density of light splitters normally below 50%).
- At least, two optical fibers between any two adjacent nodes

Optical Constraints:

- Wavelength Continuity Constraint.
- Distinct Wavelength Constraint.
- Limited Number of Wavelengths.

Challenge of AOMR:
Minimizing the cost of the multicast routes for $ms(s, D)$ is NP-Complete in WDM mesh networks.

Structure	Lightpath	Light-trail	Light-tree
No splitting	✓	✓Optimal	
Sparse Splitting			✓**Optimal ?**
Full splitting			✓Optimal

Light-tree is cost-optimal for AOMR with full splitting.

Is light-tree also cost-optimal for AOMR with sparse splitting?
NO!

Organization

- Cross Pair Switching
- Light-Hierarchy
- Cost-Optimality

- A pair of optical fibers between two adjacent nodes
- Input and output port pair
- MI node —> Special branching node

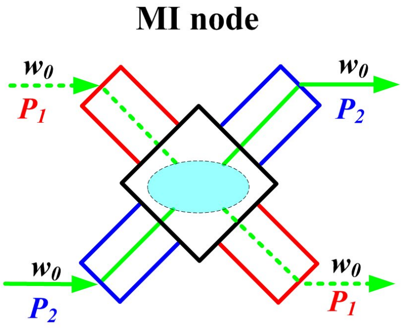


Figure: Cross Pair Switching of an MI node

Light-hierarchy: cycles are allowed!

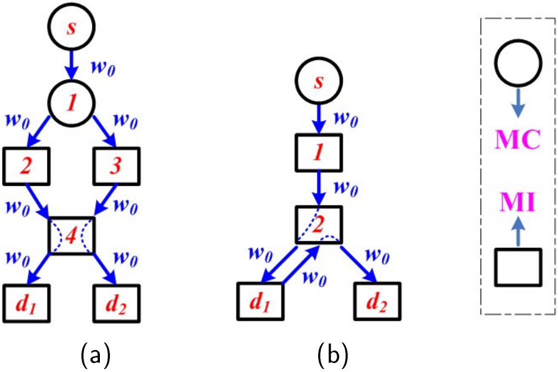


Figure: Two typical light-hierarchies with Cross Pair Switching

Definition of Light-hierarchy

A light-hierarchy is a set of consecutive and directed optical channels using the same wavelength, which is rooted from the source and terminated at the destinations. Different from a light-tree, light-hierarchy is free of the repetition of nodes while it forbids the duplicate of the same optical channel (same wavelength over the same link). A light-hierarchy has the following characters:

- Each directed link only used once.
- One predecessor link for each link except that from the source
- Permitting cycle.
- Using one wavelength.
- At most two optical fibers between a pair of nodes.
- Non-leaf MI nodes: No. of input links = No. output links.
- MC nodes: one input link

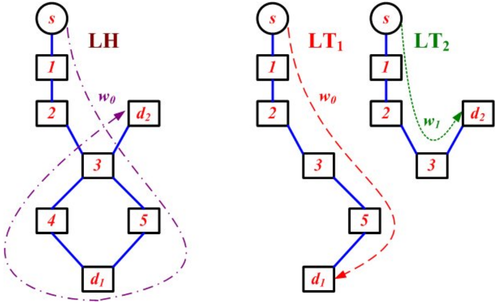
Light-tree: a special case of light-hierarchy!

Cost Optimality of Light-tree

Theorem

In a WDM network with sparse splitting, the light-tree structure is not cost-optimal for AOMR.

Proof.



(a)Topology and Light-hierarchy (b)Light-trees

$ms(s, (d_1, d_2))$	Light-hierarchy	Light-trees
Cost	8	9
Wavelengths	1	2

Cost optimality of Light-hierarchy

Theorem

In WDM networks with sparse splitting, the cost optimal structure for AOMR is a set of light-hierarchies (at least one).

Proof.

Refer to [1] for detailed proof. □

[1] F. Zhou, M. Molnar, B. Cousin. Is Light-tree Structure Optimal for Multicast Routing in WDM Mesh Networks?. 18th IEEE International Conference on Computer Communications and Networks, 2009.

Network Parameters

W	: The set of wavelengths supported per fiber.
Δ	: An integer big enough such that $\Delta > \|W\|$.
λ	: A wavelength, $\lambda \in W$.
$In(m)$	: The set of nodes which has an outgoing link leading to m.
$Out(m)$	: The set of nodes which can be reached from node m.
$Deg(m)$	: The in (or out) degree of node m in G, where $Deg^{-}(m) = Deg^{+}(m) = Deg(m)$.
$link(m, n)$	: The directed link from node m to node n.
$e(m, n)$	: The edge connecting nodes m and n in G. It consists of $link(m, n)$ and $link(n, m)$.
$c_{m,n}$	: The cost of the link from node m to node n.
MC_SET	: The set of MC nodes in G.
MI_SET	: The set of MI nodes in G.

ILP Variables

The objective function is subject to a set of variables/constraints:

$L_{m,n}(\lambda)$: Binary variable. Equals to 1 if multicast request $ms(s, D)$ uses wavelength λ on $link(m, n)$, equals to 0 otherwise.

$F_{m,n}(\lambda)$: Commodity flow. Denotes the number of destinations served by $link(m, n)$ on λ.

$w(\lambda)$: Binary variable. Equals to 1 if λ is used by the light-hierarchies, equals to 0 otherwise.

Why ILP: NP-complete!

Objective: Minimize the total cost, then the number of wavelengths used

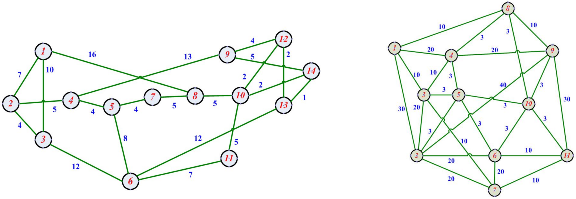
$$Minimize : \Delta \cdot \sum_{\lambda \in W} \sum_{m \in V} \sum_{n \in In(m)} c_{n,m} \cdot L_{n,m}(\lambda) + \sum_{\lambda \in W} w(\lambda) \qquad (1)$$

where $\Delta > |W|$.

Refer to [2] for detailed description of ILP formulation.

[2] F. Zhou, M. Molnar, B. Cousin. Light-hierarchy: the Optimal Structure for Multicast Routing in WDM Mesh Networks. IEEE Symposium on Computer and Communications, 2010.

- Light-Hierarchy vs Light-Tree
- ILP formulations using Cplex
- 100 multicast sessions for a group size $|D|$
- Uniform distribution
- NSF network and European Cost-239 network



(a) (b)

Figure: (a) NSF Network (b) European Cost-239 Network

LH vs LT in USA NSF Network

- $\searrow$: Percentage of reduced cost by Light-Hierarchy
- R(CPS): Number of Cross Pairs Switching used in 100 Samples

Configuration: nodes 5 and 8 are splitters (MC nodes)						
Size	Total Cost			Wavelengths		LH
$\lvert D \rvert$	LH	LT	$\searrow$	LH	LT	R(CPS)
2	2059	2079	0.96%	103	106	10/100
6	4096	4247	3.56%	107	114	35/100
9	5025	5213	3.61%	115	147	57/100
13	6237	6330	1.47%	121	156	67/100

Light-hierarchy outperforms light-tree for AOMR with sparse splitting!

LH vs LT in European Cost-239 Network

- $\searrow$: Percentage of reduced cost by Light-Hierarchy
- R(CPS): Number of Cross Pairs Switching used in 100 Samples

Configuration: nodes 3 and 9 are splitters (MC nodes)						
Size	Total Cost			Wavelengths		LH
$\|D\|$	LH	LT	$\searrow$	LH	LT	R(CPS)
2	1329	1344	1.12%	100	108	16/100
5	2685	2863	6.22%	102	183	82/100
7	3580	3747	4.46%	100	223	93/100
10	5204	5280	1.44%	100	272	100/100

Light-hierarchy is better than light-tree for AOMR with sparse splitting!

Definitions

- Multicast Capable Node (MC)
- Multicast Incapable Node (MI)

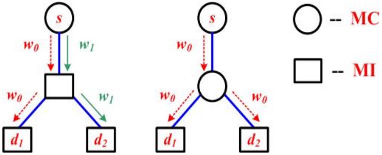


Figure: MI and MC nodes

In a light-tree *LT* under construction,

- MC_SET: source node, MC nodes and leaf MI nodes in *LT*
- MI_SET: non-leaf MI nodes in *LT*
- D: destinations not yet served

Related Work

- Reroute-to-Source algorithm (R2S)
- Reroute-to-Any algorithm (R2A)
- Member-First algorithm (MF)
- Member-Only algorithm (MO)

Table: Comparison of Multicast Routing Algorithms

	R2S	R2A	MF	MO
Link Stress	Very high	High	Average	Best
Total Cost	Very big	Big	Average	Best
Average Delay	Optimal	Average	Average	Very big
Diameter	Optimal	Average	Average	Very large

Need Improvement!

Member-Only Algorithm

1. The shortest path of all pairs of network nodes are computed and stored in a table.
2. $LT = \{s\}$, $MC\_SET = \{s\}$, $MI\_SET = \phi$.
3. Try to find the shortest path $SP(d,c)$ from destination $d \in D$ to MC_SET of light-tree LT such that $SP(d,c)$ does not involve any nodes in MI_SET of LT.
4. Add $SP(d,c)$ to LT and remove d from D
5. Update MC_SET and MI_SET of the new LT
6. Goto step2 until no $SP(d,c)$ can be found
7. Construct a new light-tree on another wavelength until $D = \phi$

Three Heuristics

1. **Hypo-Steiner Light-tree Heuristic**
   Delete the non-leaf MI nodes of LT from the network G, compute the nearest destination d to LT in the modified graph.
2. **Light-Hierarchy Heuristic**
   4-degree (or above) MI nodes can be crosswise used twice to switch the light signal from the same source node to two different destinations while employing the same wavelength.
   It could be a method to compute the light-hierarchies by deleting the used links from the network.
3. **In Tree Distance Priority Heuristic**
   A destination d is preferred to be connected to LT via the connector node nearest to source s in LT, if there are several connector nodes in LT with the same cost distance to d.

Hypo-Steiner Light-tree Heuristic

Improvement I:

Hypo-Steiner Heuristic enumerates all the possible shortest paths which are able to connect a destination to the light-tree while respecting constraints.

Example 1: ms_1={s: 8 | d: 4, 6}, MC: {8}; MI: {the other nodes}

Stress[MO]=2, Stress[HS]=1, Cost[MO] = Cost[HS]=6

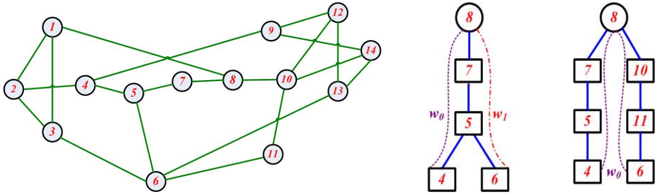


Figure: (a) NSF Network (b) Improvement I

Hypo-Steiner Light-tree Heuristic

Improvement II:

Hypo-Steiner Heuristic tries to find the shortest constraint-satisfied path to connect a destination to the light-tree, in case that the shortest path does not work.

Example 2: ms_2={s: 8 | d: 9-11}, MC: {8}; MI: {the other nodes}

Stress[MO]=2, Stress[HS]=1, Cost[MO] = 5, Cost[HS]=6

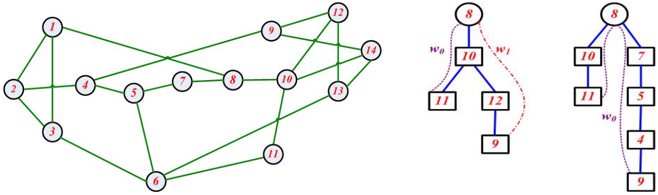


Figure: (a) NSF Network (b) Improvement II

Three Heuristics

1. **Hypo-Steiner Light-tree Heuristic**
   Delete the non-leaf MI nodes of LT from the network G, compute the nearest destination d to LT in the modified graph.
2. **Light-Hierarchy Heuristic**
   4-degree (or above) MI nodes can be crosswise used twice to switch the light signal from the same source node to two different destinations while employing the same wavelength.
   It could be a method to compute the light-hierarchies by deleting the used links from the network.
3. **In Tree Distance Priority Heuristic**
   A destination d is preferred to be connected to LT via the connector node nearest to source s in LT, if there are several connector nodes in LT with the same cost distance to d.

Light-Hierarchy Heuristic

Advantages:

- Overcome the inherent drawback of light-tree structure
- Span as many destinations as possible in one light-hierarchy

Example 3: ms_3={s: 8 | d: 3, 6, 10, 11, 13, 14} MC: {8}
Stress[MO]=Stress[HS]=2, Stress[LH]=1; Cost[MO]=Cost[HS]=7, Cost[LH]=9

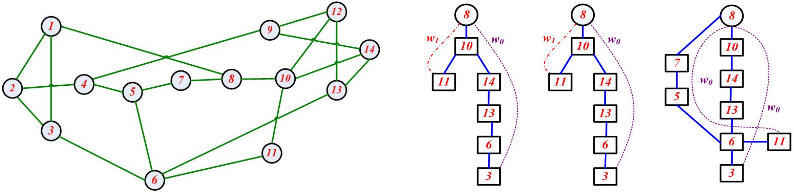


Figure: (a) NSF Network (b) Light-Hierarchy Heuristic

Three Heuristics

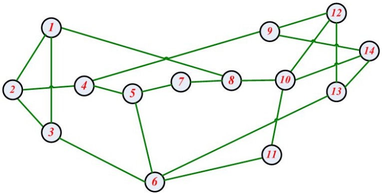
1. **Hypo-Steiner Light-tree Heuristic**
   Delete the non-leaf MI nodes of LT from the network G, compute the nearest destination d to LT in the modified graph.
2. **Light-Hierarchy Heuristic**
   4-degree (or above) MI nodes can be crosswise used twice to switch the light signal from the same source node to two different destinations while employing the same wavelength.
   It could be a method to compute the light-hierarchies by deleting the used links from the network.
3. **In Tree Distance Priority Heuristic**
   A destination d is preferred to be connected to LT via the connector node nearest to source s in LT, if there are several connector nodes in LT with the same cost distance to d.

In Tree Distance Priority Heuristic

Functions:

- Reduce Average Delay
- Reduce Diameter

Example 4: ms_4={s: 1 | d: 2-5}, MC: {1}; MI: {the other nodes}
AvDelay[C1] = 7/4, AvDelay[C2] = 10/4
Diameter[C1] = 3, Diameter[C2] = 4,



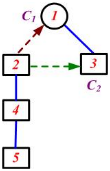


Figure: (a) NSF Network (b) In Tree Distance Priority Heuristic

Overview of the Proposed Algorithms

An equal cost function of *1 unit hop-count cost* is assumed on all the links.

1. **Hypo-Steiner Heuristic & Member-Only**
   - Cost Bound: $|D| \leq c(ms) \leq \frac{N^2}{4}$
   - Time Complexity: $|D| \times \big(N \log(N) + M\big)$, where N denotes the number of nodes in the network, and M is the number of edges in the network
2. **Light-Hierarchy Heuristic**
   - Time Complexity: $|D| \times \big(N \log(N) + M\big)$

Simulation Configuration

Metrics

1. Link Stress: the number of wavelengths required per fiber / per multicast session.
2. Total Cost: the number of fiber channels used per multicast session.
3. Average Delay: the average hop counts from destinations to source.
4. Diameter of Tree: the maximum hop counts from destinations to source.
5. Network Throughput: The number of accepted multicast sessions, given the number of wavelengths supported per fiber link.

Simulation Configuration

An equal cost of 1 $hop - count\ cost$ is applied on all the fiber links. MC and MI nodes are distributed independently through the network. 10000 random multicast sessions are generated for each network configuration.

Testbed

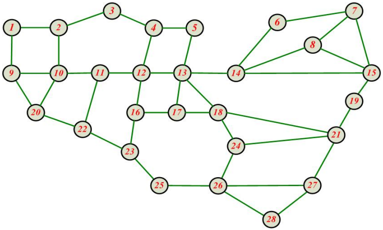


Figure: USA Longhaul Network

Link Stress

1. M=|D|+1: denotes the multicast session groupsize.
2. GRDP-LT: Hypo-Steiner Heuristic + Distance Priority
3. GRDP-LH: Light-Hierarchy + Distance Priority

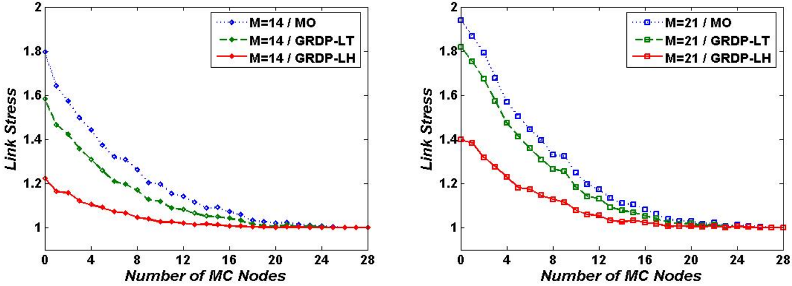


Figure: Comparison of Link Stress

Total Cost

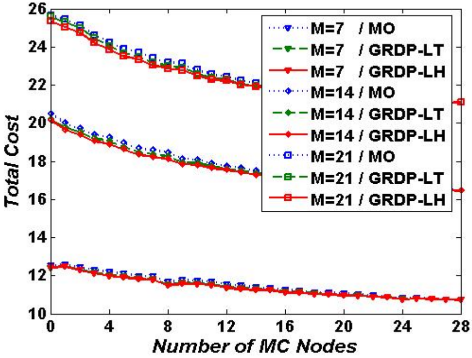
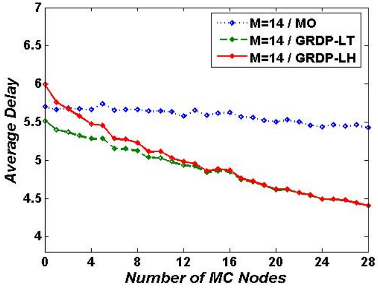


Figure: Comparison of Total Cost

Average Delay



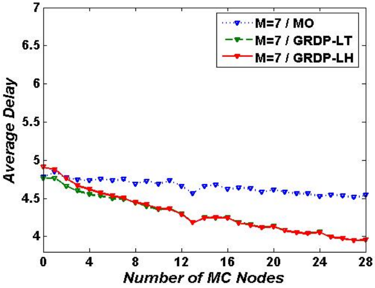


Figure: Comparison of Average Delay

Diameter

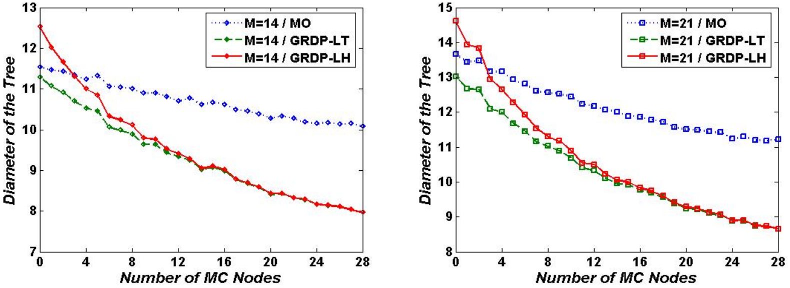


Figure: Comparison of Diameter

Network Throughput

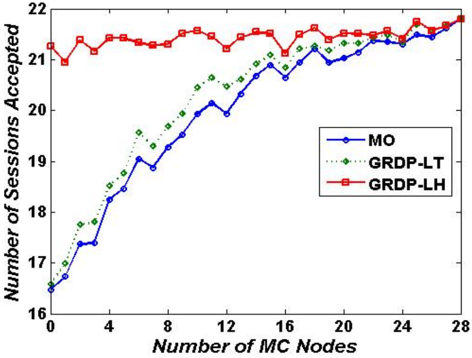


Figure: Comparison of Network Throughput

1. **Summary**
   - Cross pair switching of MI nodes
   - Light-hierarchy: cost-optimal AOMR structure
   - ILP formulation
   - Time efficient AOMR heuristic using light-hierarchies [1]

[1] F. Zhou, M. Molnar, B. Cousin. Is Light-tree Structure Optimal for Multicast Routing in WDM Mesh Networks?. 18th IEEE International Conference on Computer Communications and Networks, 2009.

2. **Future Work**
   - Power budget consideration in AOMR (e.g., take account optical amplifier)

Thank you for your attention!