# Reconfigurable MPLS/WDM Networks


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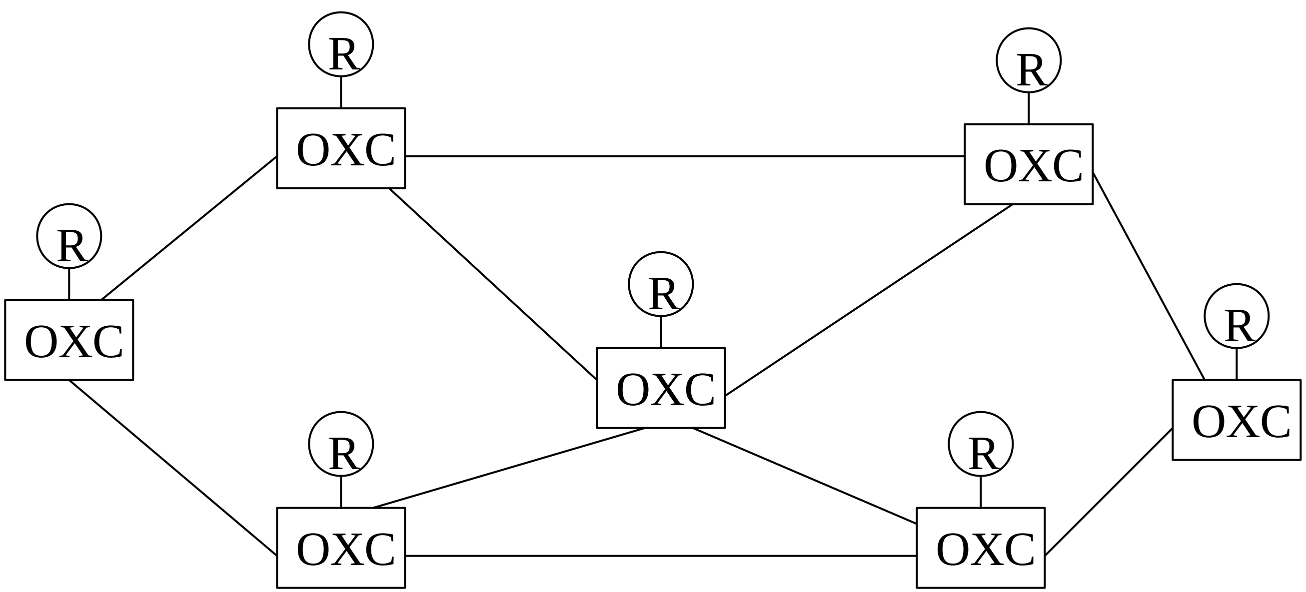
# Overview

- If IP is implemented over a reconfigurable WDM network, the logical links between routers can be changed in response to changes in traffic demands
- Traffic engineering in an MPLS/WDM network requires both logical topology design and LSP routing and provisioning
  - can be formulated as Mixed Integer Linear Program (MILP) (NP-complete)
- Standard approach
  - use heuristic for logical topology design
  - apply routing algorithm to map traffic demands onto logical topology
- New approach: Integrate LSP routing and provisioning into logical topology design

# Reconfigurable Optical Network

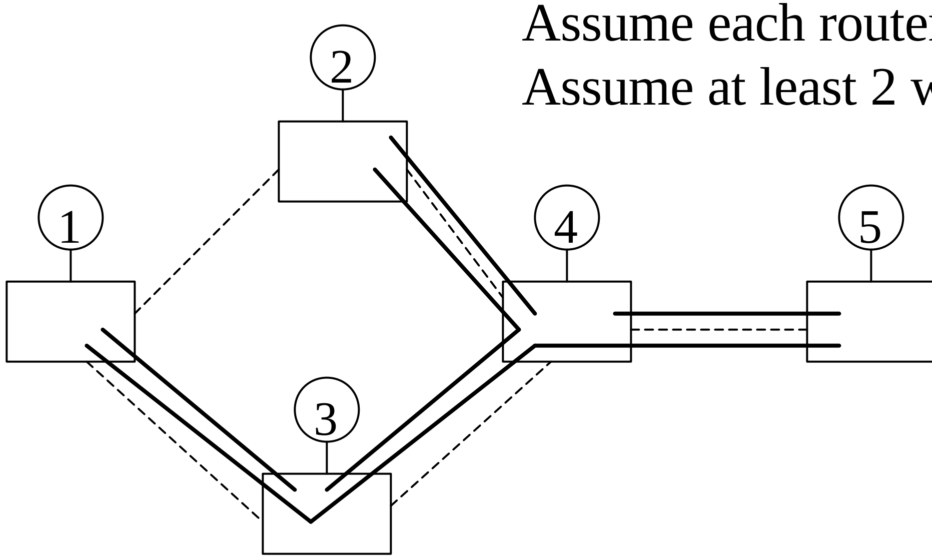
- Each node consists of router (LSR) together with optical crossconnect
- LSR has interfaces (transmitters and receivers) that each terminate one wavelength
- OXCs are interconnected by optical fibers that carry multiple wavelengths
- OXC can be configured to switch a wavelength on an input port to a wavelength on any output port, possibly with wavelength conversion



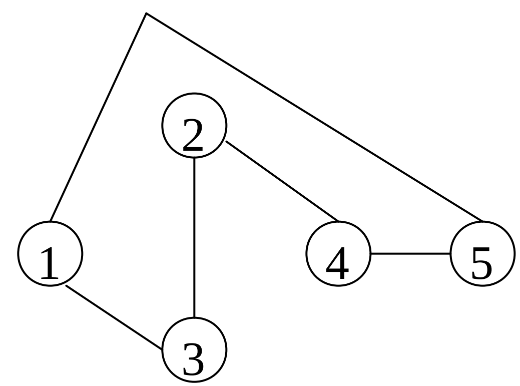
# Logical Topology Design

- Logical link between a pair of routers is formed by creating a lightpath between the nodes
  - Consists of sequence of fiber links together with selection of a wavelength in each fiber (RWA problem)
  - If no wavelength conversion, then RWA problem is subject to wavelength continuity constraint

Assume each router has 2 pairs of interfaces
Assume at least 2 wavelengths per fiber




Lightpaths




Logical topology

# Timescales

- Slowest: optical network reconfiguration
- Moderate: LSP reconfiguration (routing and bandwidth provisioning)
- Fast: balancing traffic among parallel LSPs
- Dynamic traffic engineering problem for MPLS/WDM can be formulated as <u>Multi-timescale Markov Decision Process</u>
- <u>Reference</u>
  - H.S. Chang, P. Fard, S.I. Marcus and M.A. Shayman, "Multi-timescale Markov Decision Processes," to appear in *IEEE Transactions on Automatic Control.*
- Observation: each optical network reconfiguration must be accompanied by LSP reconfiguration

# Traffic Engineering Issues

- Optical network reconfiguration includes
  - Logical topology design
    - Selection of logical neighbors and links
  - RWA (Routing and Wavelength Assignment)
    - Allocation of optical (physical) resources
    - Wavelength continuity, optical impairments
  - Traffic Grooming for multi-hop traffic
    - Integrating low rate traffic into high rate traffic streams
    - Mapping of traffic demand onto logical topology
    - Equivalent to routing of LSPs and mapping of traffic demand onto LSPs (if multiple LSPs for ingress-egress pair)

# LTD and TG Problem

- Given traffic demand matrix, physical topology and router interface constraints, construct the logical topology and route each traffic demand in order to minimize the average weighted delay and to maximize throughput

Minimize: $$\frac{\sum T_{s,d} \times d_{s,d}}{\sum T_{s,d}}$$ Maximize: $$\sum a_{s,d} \times T_{s,d}$$

where $\alpha_{sd} \in \{0,1\}$1 if a path for $t_{sd}$ is provisioned

- Contribution: new algorithms for integrated LTD & TG that outperform existing algorithms
- Reference: K.I. Lee, L. Sudarsan and M.A. Shayman, Integrated Logical Topology Design and Traffic Grooming in Reconfigurable WDM Networks, CISS'03.

# LTD Algorithms - HLDA

- Heuristic Logical Topology Design
- Multiple lightpaths for same s-d pair
- Algorithm

```
Procedure HLDA (void)
    While (not done)
        Find s and d such that t_sd = MAX t_ij for all i,j
        If ((free transmitter available at s) AND (free receiver available at d) AND
                (free wavelength available in any optical path from s to d))
                Establish lightpath between s and d
                t_sd = t_sd - C
        Endif
    Endwhile
```

# LTD Algorithms - MRU

- Maximizing Resource Utilization
- Use <u>physical</u> (optical) hop distance $H_{sd}$
- Algorithm

```
Procedure MRU(void)
    Compute H_sd ∀s,d
    While (not done)
          Find s and d such that [t_sd /H_sd ]= MAX [t_ij /H_ij] for all i,j
          If ((free transmitter available at s) AND  (free receiver available at d) AND
                      (free wavelength available in any optical path from s to d))
                   establish lightpath between s and d
          Endif
    Endwhile
```

# LTD Algorithms - MMHA

- Maximizing Multi-Hop Algorithm
- Use <u>logical</u> hop distance $H_{sd}$
- Algorithm

Procedure MMHA(void)

While (not done)

Compute $H_{sd}$ $\forall s,d$

Find s and d such that $t_{sd}$ ($H_{sd}$-1)= MAX $t_{ij}$ ($H_{ij}$ -1) for all i,j

If ((free transmitter available at s) AND (free receiver available at d) AND

(free wavelength available in any optical path from s to d))

establish lightpath between s and d

endif

endwhile

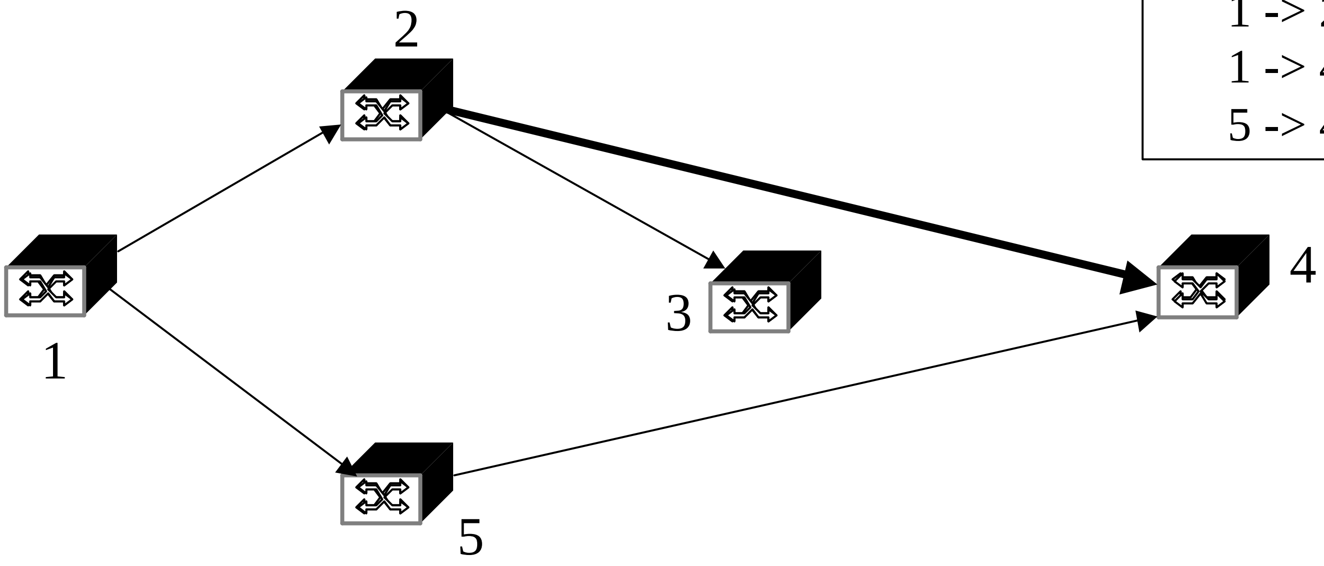
<u>Note</u>: If i and j are in different connected components, set $H_{ij}$ to infinity and rank such pairs based on $t_{ij}$

# Integrated LTD & Traffic Grooming

- Motivation
  - Provide multihop lightpath setup mechanism for multihop traffic
    - Typical algorithms only consider multihop traffic for routing, not for logical topology design
  - Determination of logical topology and traffic grooming simultaneously
- Approaches & Algorithms
  - Case 1 : when either source or destination has no free interface (Integrated LTD+TG)
  - Case 2 : when both source and destination have no free interface (ELH)
  - Case 3 : when a single path is not enough for traffic demands (MPELH)

# Algorithm 1 : Forward Multihop Lightpath Setup

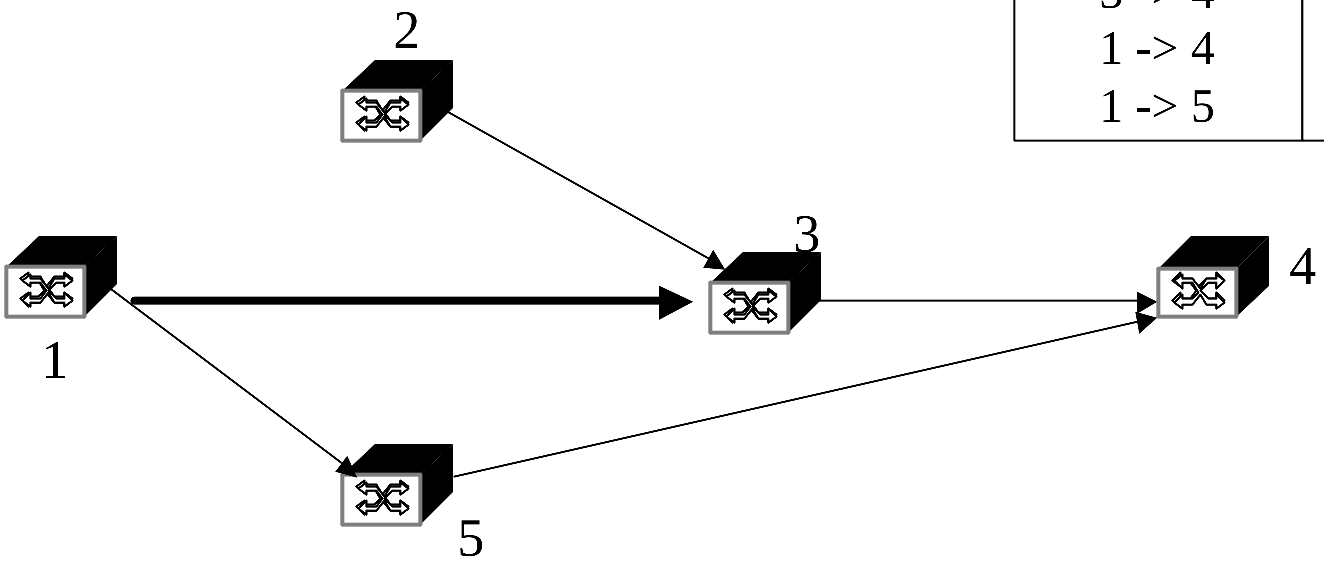
| Traffic Matrix | |
|---|---|
| 1-> 5 | 6 |
| 2 -> 3 | 5 |
| 1 -> 2 | 4 |
| 1 -> 4 | 4 |
| 5 -> 4 | 3 |




Each router has 2 pairs of interfaces
Link capacity is 9
No interface available at source

# Algorithm 1 : Backward Multihop Lightpath Setup

| Traffic Matrix | |
|---|---|
| 5-> 4 | 6 |
| 2 -> 3 | 5 |
| 3 -> 4 | 4 |
| 1 -> 4 | 4 |
| 1 -> 5 | 3 |

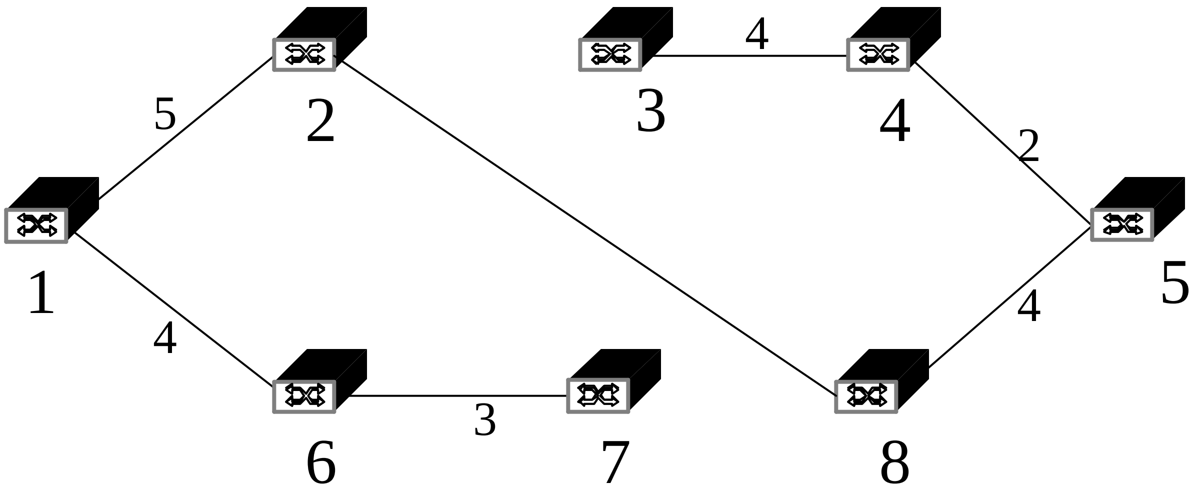



No interface available at destination

# Sketch of Algorithm 1

- Consider traffic demands $t_{ik}$ in decreasing order.
- When $t_{sd}$ is considered, if s has an available transmitter and d an available receiver, and if there is a physical path from s to d with an available wavelength, create a lightpath from s to d and set up 1-hop LSP.
- If s has available transmitter but d has no available receiver, and if d has a logical neighbor d' such that available BW on link d'd is at least $t_{sd}$ create lightpath from s to d' and set up 2-hop LSP.
  - Consider multihop neighbors of d if necessary.
- If d has available receiver but s has no available transmitter, and if s has a logical neighbor s' such that available BW on link ss' is at least $t_{sd}$ create lightpath from s' to d and set up 2-hop LSP.
  - Consider multihop neighbors of s if necessary.
- Use constrained shortest path routing to route LSPs for remaining traffic demands in decreasing order of demands.

# Algorithm 2 : Example




Consider $t_{15}$ for logical topology design

LTD(1,5,2) = 3 and TG (1,5,2) = ∞,

so we choose path 1-2-8-5 with a new lightpath from node 2 to node 8

Consider $t_{24}$ for logical topology design

LTD(2,4,1) = 5 and TG (2,4,1) = 3

so we choose path 2-8-5-4 without new lightpath setup

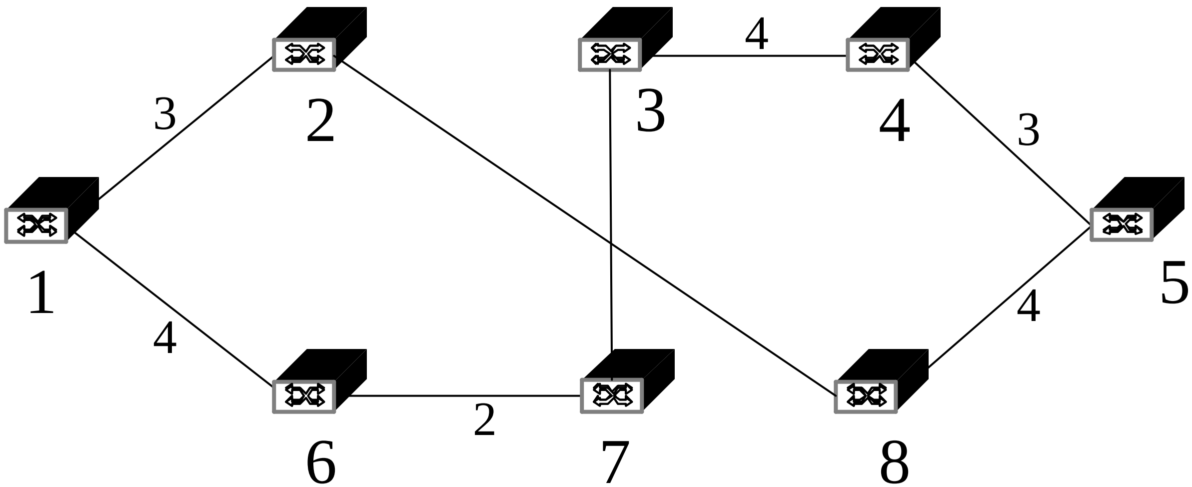
# Algorithm 2 : Description

- ELH : Estimated Logical Hop
  - $LTD(s,d,t_{sd})$ : length of shortest path with sufficient BW where one new lightpath is created
  - $TG(s,d,t_{sd})$ : the length of shortest TG path with sufficient BW composed of existing links
  - $ELH = MIN\ [LTD(s,d,\ t_{sd}),TG(s,d,\ t_{sd})]$
- <u>*Theorem 1*</u>
  - $ELH(s,d,t_{sd})$ is equal to the number of hops in the locally optimal path from s to d with bandwidth $t_{sd}$. Any path that may be constructed from existing links and newly created links has at least length $ELH(s,d,t_{sd})$
- ELH Algorithms : the order of traffic matrix
  - ELH-MTD : $Max[t_{sd}]$
  - ELH-REF : $Max\ [t_{sd}\ /\ ELH(s,d,t_{sd})]$

# Sketch of Algorithm 2

- Consider all remaining traffic demands $t_{ik}$
- When $t_{sd}$ is considered, find node x starting from node s that has a free transmitter and find node y starting from node d that has an free receiver using constrained shortest path routing. Then, compute LTD(s,d,$t_{sd}$) with a path p(s,x,y,d,$t_{sd}$)
- Find a path with existing links from s to d using constrained shortest path routing. And, compute TG(s,d,$t_{sd}$)
- Compute ELH and REF = $t_{sd}$/ELH(s,d,$t_{sd}$)
- Find s-d pair with maximum REF
- Provision a path for s-d pair whose hop count is ELH(s,d,$t_{sd}$).
- If a path contains a potential lightpath, then set up that lightpath

# Algorithm 3 : Example




Consider $t_{15} = 5$ for logical topology design but no single path is available

LTD(1,5,*) = 3 and TG (1,5,*) = ∞,

so we choose path 1-2-8-5 with a new lightpath from node 2 to node 8 and assign 3 BU along the path

We reconsider $t'_{15} = 2$ for logical topology design

LTD(1,5,*) = 5 and TG (1,5,*) = ∞

so we choose path 1-6-7-3-4-5 with a new lightpath from node 7 to node 3

# Algorithm 3 : Description

- When there is no single path available to accommodate the traffic demands
- We extend ELH-REF algorithm for multipath
  - Shortest-widest path (MPELH-SW)
  - Widest-shortest path (MPELH-WS)
- ELH(s,d,*) = MIN [LTD(s,d,*),TG(s,d,*)]
  - LTD(s,d,*) : the length of LTD path using links with available link bandwidth > 0
  - TG(s,d,*) : the minimum number of hops of TG path using links with available link bandwidth > 0
  - B(s,d) : the bandwidth of ELH path ($B(s,d) \leq t_{sd}$)
- REF for multi-path ELH (MPELH)
  - B(s,d) / ELH(s,d,*)

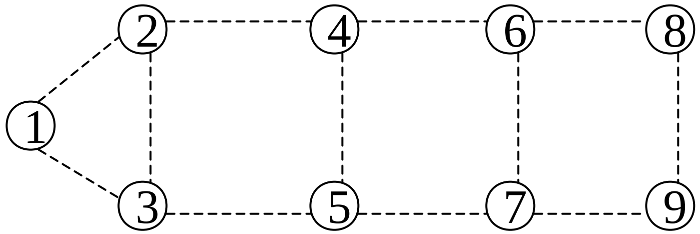
# Sketch of Algorithm 3

- Consider all remaining traffic demands $t_{ik}$
- Compute B(s,d) and ELH(s,d,*) for all s-d pair
- Compute REF using ELH such that REF = B(s,d)/ELH(s,d,*)
- Find s-d pair with maximum REF
- Provision a path for s-d pair whose hop count is ELH(s,d,*)
- If a path contains a potential lightpath, then set up that lightpath
- If B(s,d) is less than $t_{sd}$, $t'_{sd} = t_{sd} - B(s,d)$
- $T = T - \{t_{sd}\} + \{t'_{sd}\}$

# Example

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | * | 6 | 5 | 0 | 0 | 0 | 5 | 0 | 0 |
| 2 | | * | 0 | 3 | 0 | 0 | 0 | 1 | 0 |
| 3 | | | * | 0 | 0 | 0 | 1 | 0 | 1 |
| 4 | | | | * | 4 | 6 | 0 | 0 | 2 |
| 5 | | | | | * | 0 | 1 | 0 | 0 |
| 6 | | | | | | * | 4 | 6 | 2 |
| 7 | | | | | | | * | 0 | 6 |
| 8 | | | | | | | | * | 1 |
| 9 | | | | | | | | | * |

Traffic Matrix (symmetric)



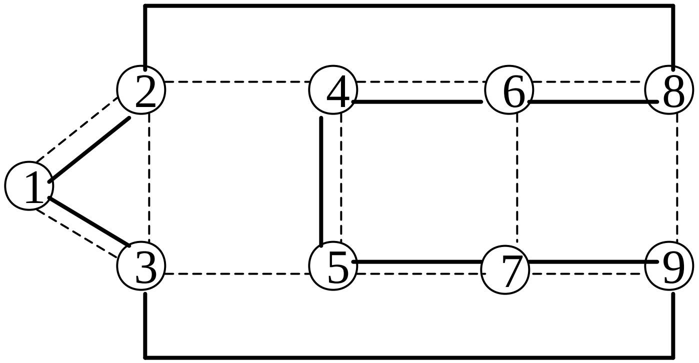

Physical Topology

Assume each lightpath has capacity 13 units.
Assume each router has 2 pairs of interfaces.

# Logical Topology: HLDA & MRU

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | * | 6 | 5 | 0 | 0 | 0 | 5 | 0 | 0 |
| 2 | | * | 0 | 3 | 0 | 0 | 0 | 1 | 0 |
| 3 | | | * | 0 | 0 | 0 | 1 | 0 | 1 |
| 4 | | | | * | 4 | 6 | 0 | 0 | 2 |
| 5 | | | | | * | 0 | 1 | 0 | 0 |
| 6 | | | | | | * | 4 | 6 | 2 |
| 7 | | | | | | | * | 0 | 6 |
| 8 | | | | | | | | * | 1 |
| 9 | | | | | | | | | * |

WHD = 1.615 (total)
= 1.596 ($t_{sd}$ >1)



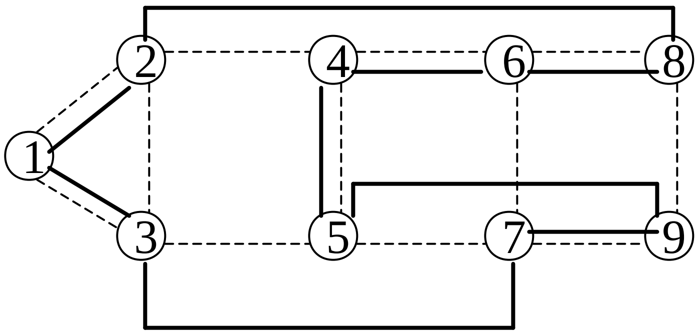

Large demands $t_{17}$, $t_{67}$, $t_{24}$, $t_{49}$ is not considered in logical topology design since no interfaces are available. Resulting hop distance for
Hop(1,7) = 3 , Hop(6,7) = 3, Hop (2,4) = 3, Hop(4,9) = 3

The $t_{69}$ is blocked since there is not enough bandwidth

# Logical Topology: Integrated LTD & TG

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | * | 6 | 5 | 0 | 0 | 0 | 5 | 0 | 0 |
| 2 | | * | 0 | 3 | 0 | 0 | 0 | 1 | 0 |
| 3 | | | * | 0 | 0 | 0 | 1 | 0 | 1 |
| 4 | | | | * | 4 | 6 | 0 | 0 | 2 |
| 5 | | | | | * | 0 | 1 | 0 | 0 |
| 6 | | | | | | * | 4 | 6 | 2 |
| 7 | | | | | | | * | 0 | 6 |
| 8 | | | | | | | | * | 1 |
| 9 | | | | | | | | | * |

WHD = 1.596 (total)
= 1.532 ($t_{sd}$ >1)




Large demands $t_{17}$, $t_{24}$,$t_{49}$ are considered to create multihop paths in logical topology design using ELH since no interfaces are available. Resulting hop distance for Hop(1,7) = 2 , Hop (2,4) = 3, Hop(4,9) = 2

However $t_{67}$ is not considered since there are no interfaces available at either nodes 6 or 7

Resulting hop distance for Hop (6,7) = 4

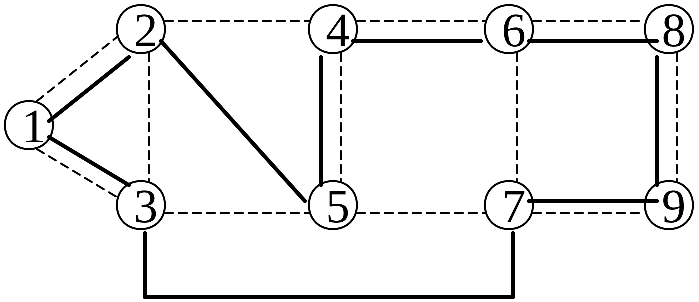
The demand $t_{69}$ is blocked since there is not enough bandwidth

# Logical Topology: ELH

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | * | 6 | 5 | 0 | 0 | 0 | 5 | 0 | 0 |
| 2 | | * | 0 | 3 | 0 | 0 | 0 | 1 | 0 |
| 3 | | | * | 0 | 0 | 0 | 1 | 0 | 1 |
| 4 | | | | * | 4 | 6 | 0 | 0 | 2 |
| 5 | | | | | * | 0 | 1 | 0 | 0 |
| 6 | | | | | | * | 4 | 6 | 2 |
| 7 | | | | | | | * | 0 | 6 |
| 8 | | | | | | | | * | 1 |
| 9 | | | | | | | | | * |

WHD = 1.519 (total)

= 1.426 ($t_{sd}$ >1)




Large demands $t_{17}$,$t_{67}$ ,$t_{24}$,$t_{49}$ are considered to create multihop paths in logical topology design using ELH. Resulting hop distances

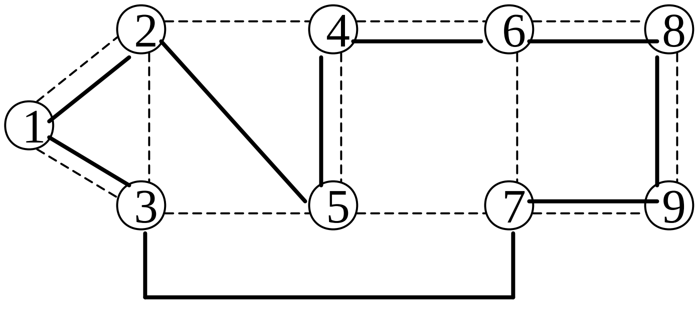
Hop(1,7) = 2 , Hop (6,7) = 3 ,Hop (2,4) = 2, Hop(4,9) = 4

But, still $t_{69}$ is blocked since there is not enough bandwidth

# Logical Topology: MPELH

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | * | 6 | 5 | 0 | 0 | 0 | 5 | 0 | 0 |
| 2 | | * | 0 | 3 | 0 | 0 | 0 | 1 | 0 |
| 3 | | | * | 0 | 0 | 0 | 1 | 0 | 1 |
| 4 | | | | * | 4 | 6 | 0 | 0 | 2 |
| 5 | | | | | * | 0 | 1 | 0 | 0 |
| 6 | | | | | | * | 4 | 6 | 2 |
| 7 | | | | | | | * | 0 | 6 |
| 8 | | | | | | | | * | 1 |
| 9 | | | | | | | | | * |

WHD = 1.648 (total)
= 1.538 ($T - \{t_{69}\}$)

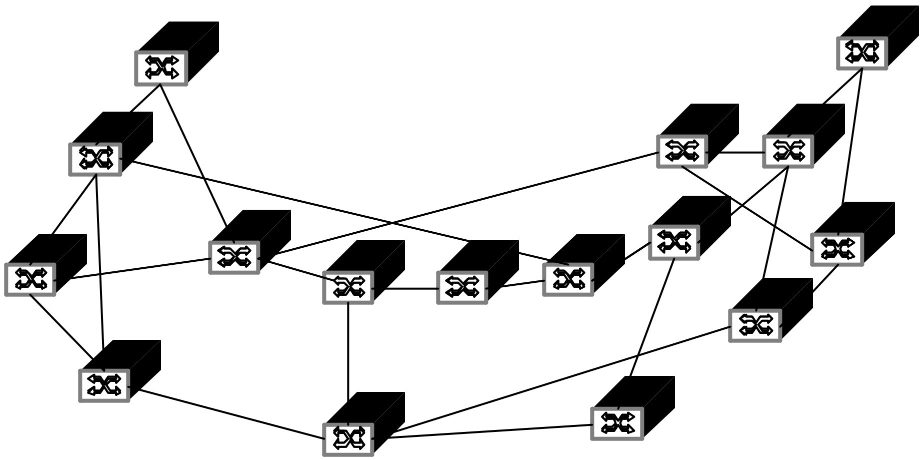



The logical topology is same as that of ELH. However, the demand $t_{69}$ is routed using two paths with $\{t'_{69} = 1\}$ : 6-8-9 and $\{t''_{69} = 1\}$ : 6-4-5-2-1-3-7-9

In this example, we can increase the throughput at the expense of greater WHD

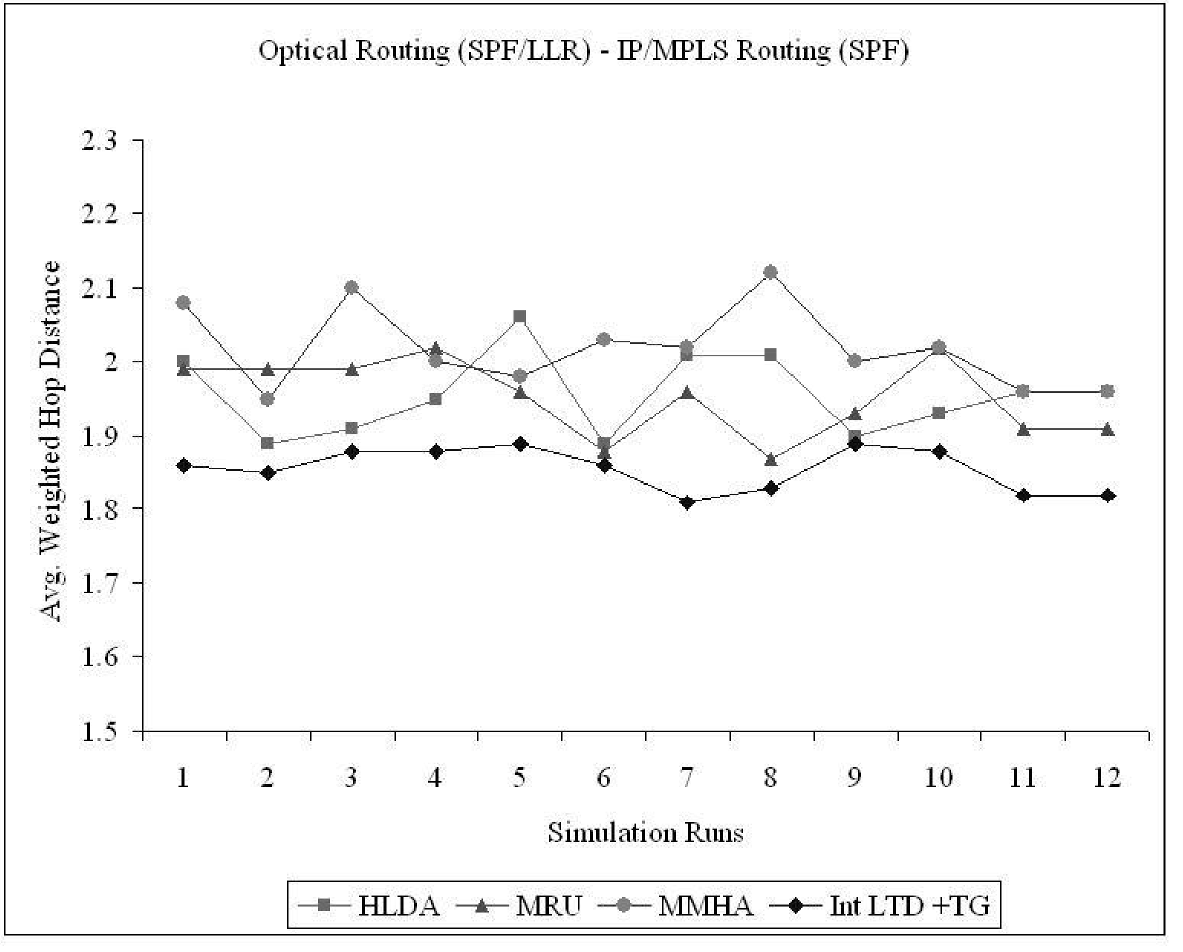
# Experimental Analysis

- Topology
  - Use 16 node NSFnet

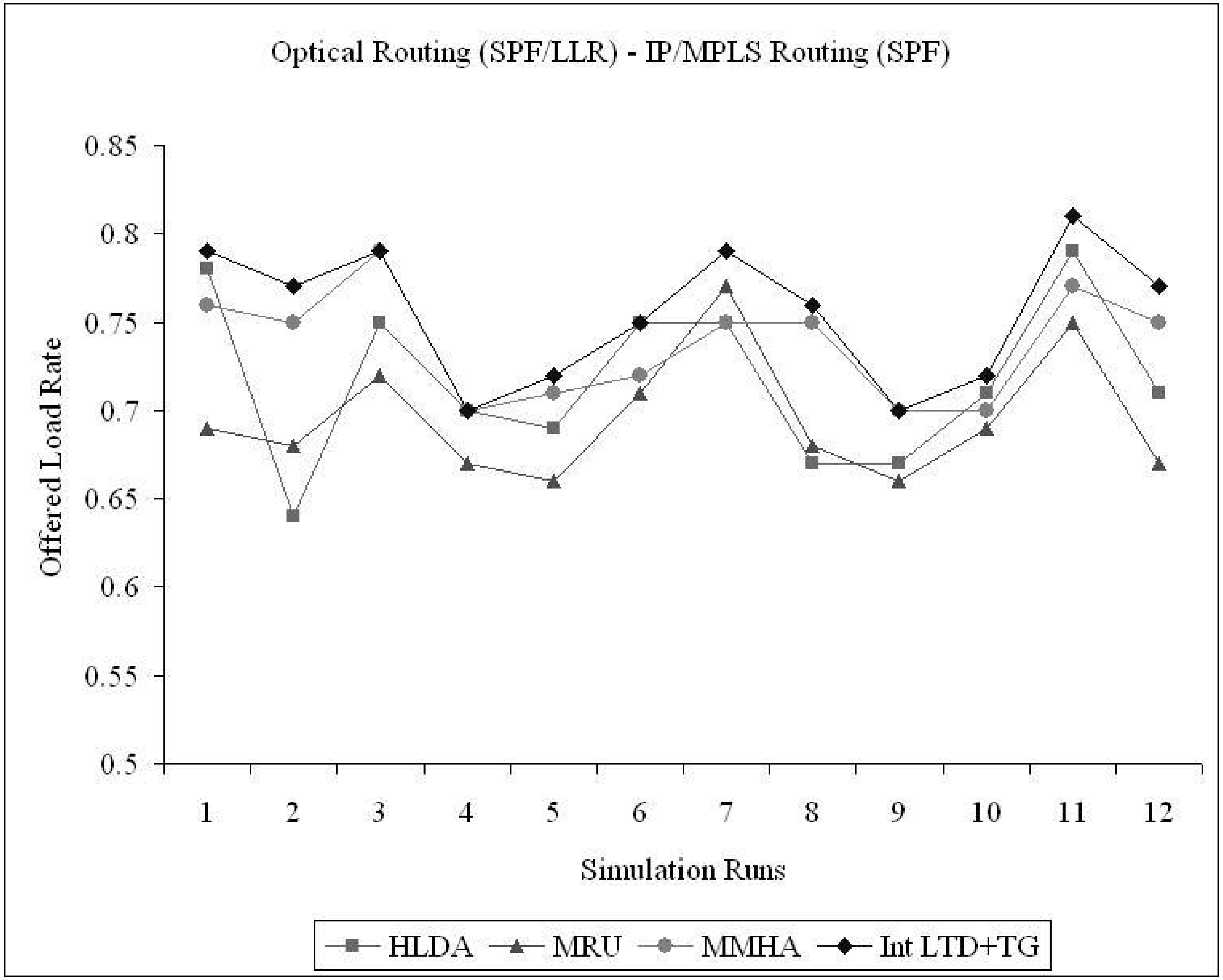


- Performance Metrics
  - Avg. weighted delay or hop count
  - Throughput = total traffic rate accommodated in the network

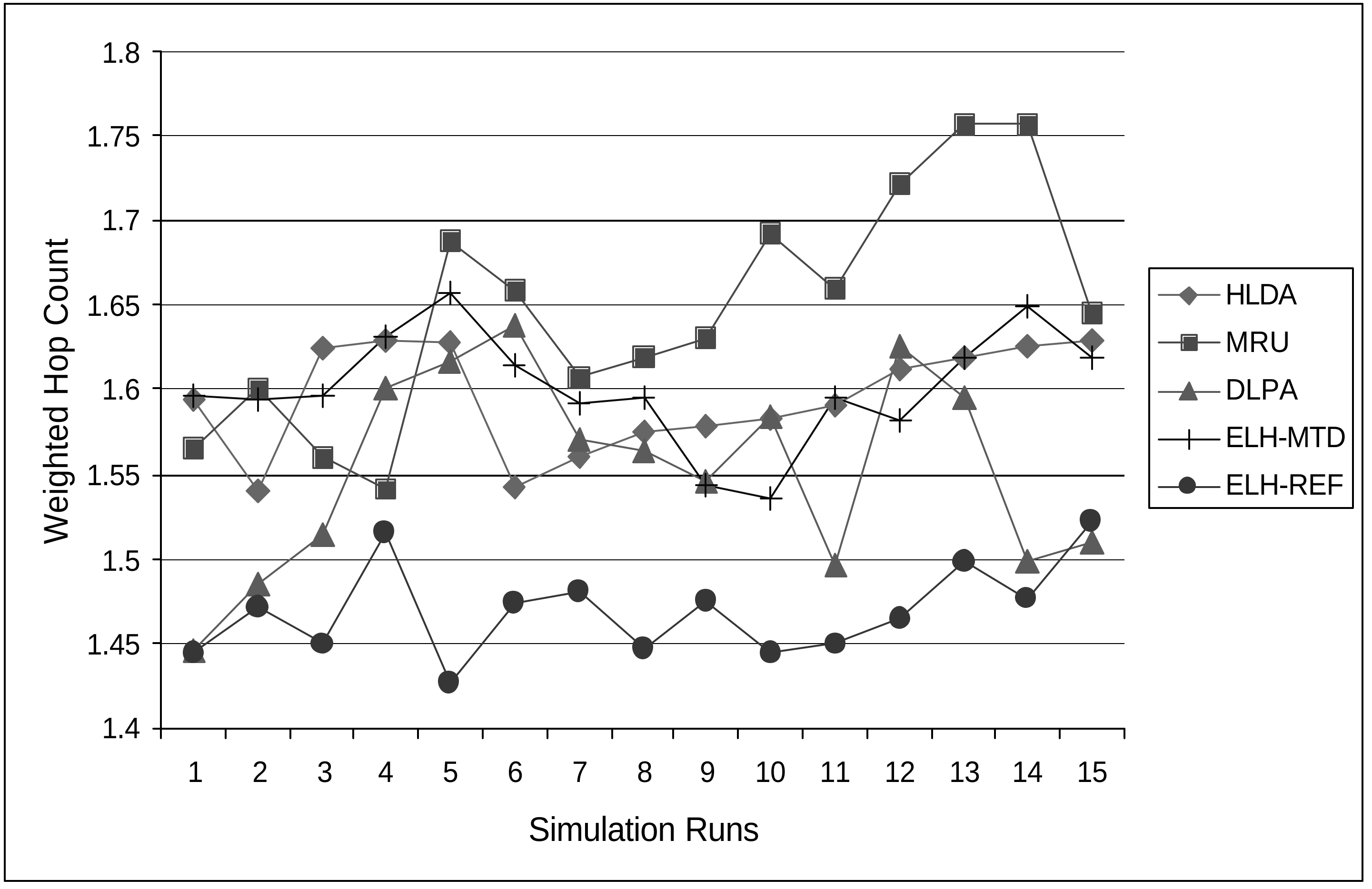
# Algorithm 1 : Weighted Hop Count



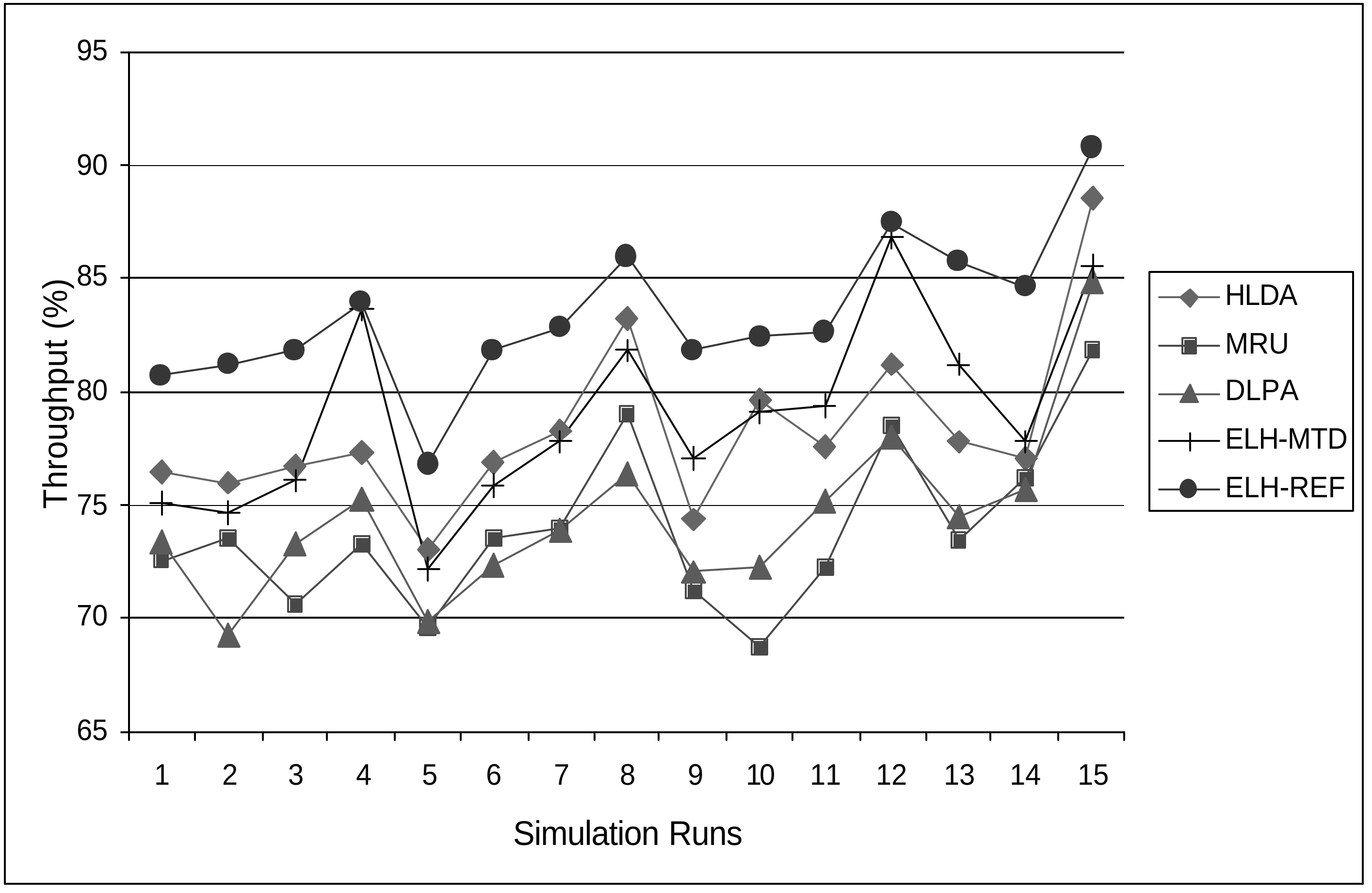
# Algorithm 1 : Throughput



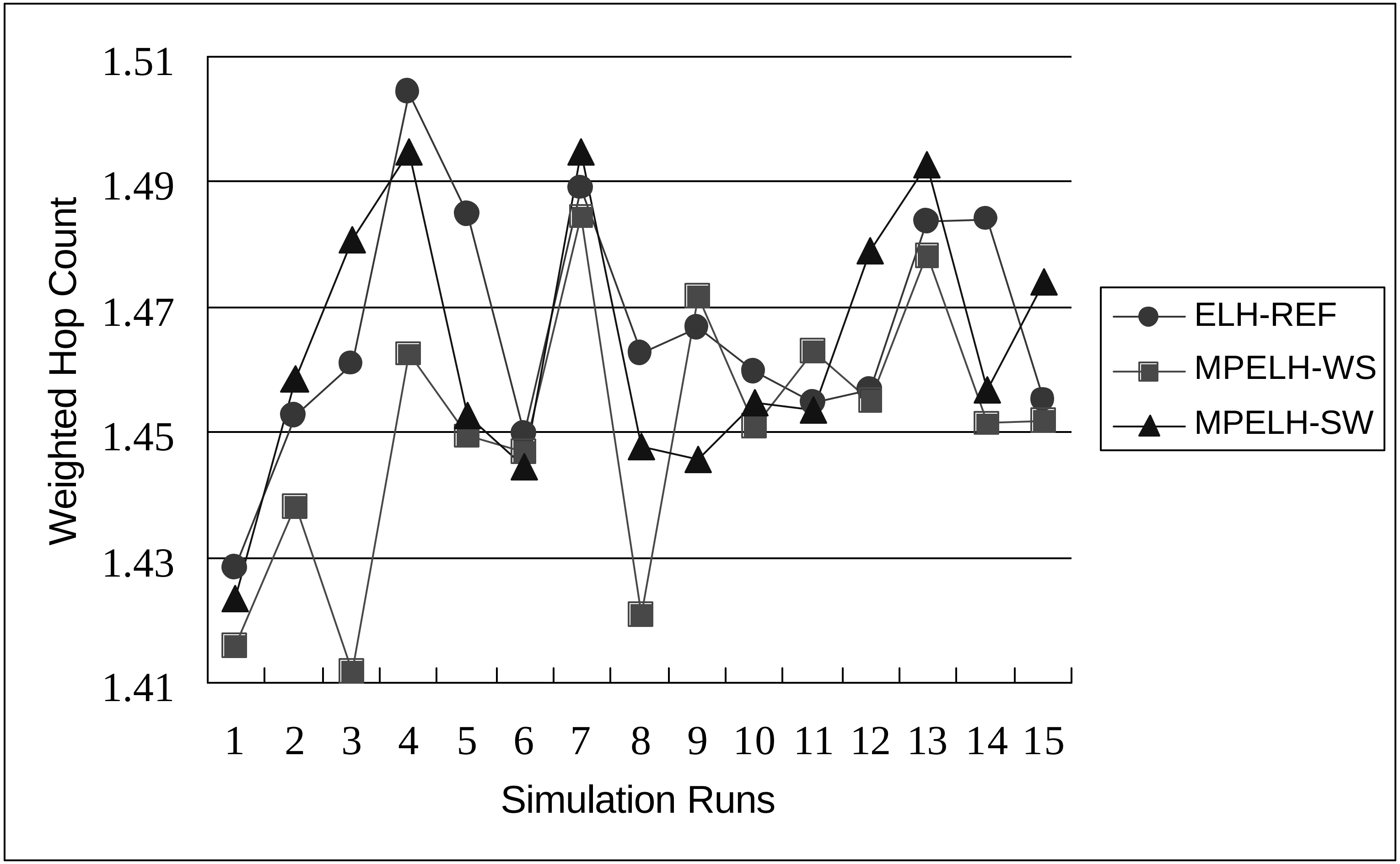
# Algorithm 2 : Weighted Hop Count



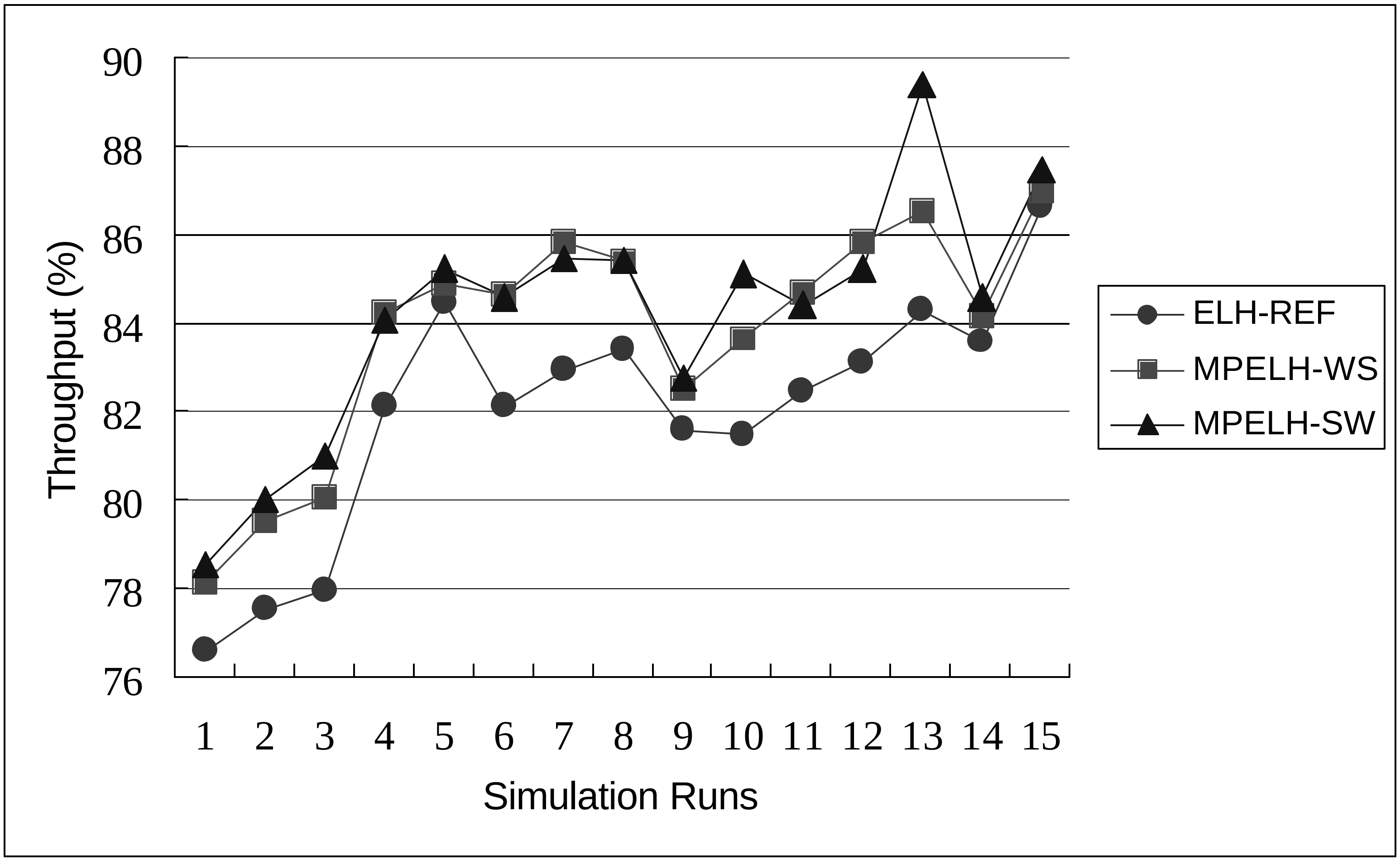
# Algorithm 2 : Throughput



# Algorithm 3 : Weighted Hop Count



# Algorithm 3 : Throughput



# Conclusions

- Integrated LTD & TG provides
  - Low delay (Avg. weighted hop distance)
  - High network throughput
- Work Done
  - Design ELH algorithm for LTD+TG
  - Multi-path support (MP-ELH)
  - Integration of our algorithm with GLASS/SSF
- Current & Future Work
  - Integrated solution for LTD,TG, and RWA problems
  - LTD and TG with optical constraints
    - wavelength continuity and optical impairments
  - Dynamically varying traffic demands