Virtual Network Embedding with Path-based Latency Guarantees in Elastic Optical Networks

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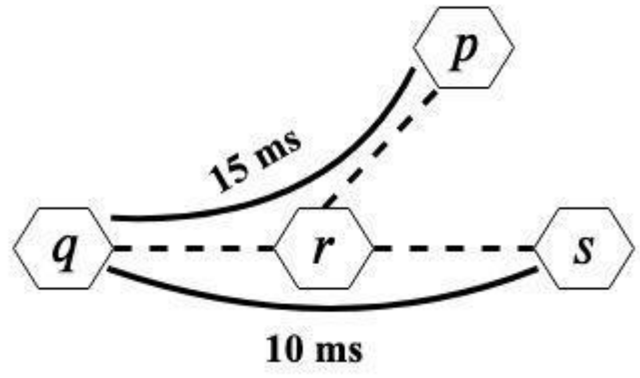
Outline

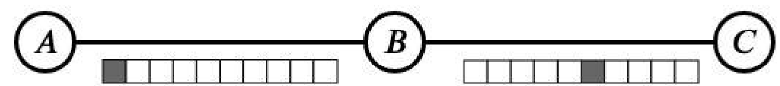
- Introduction
  - Elastic Optical Networks (EONs)
  - Key Contribution
  - Latency Model
- Problem Statement
- Integer Linear Program (ILP) Formulation
  - Constraints
  - Objective
- Heuristic Algorithm
- Evaluation
- Conclusion & Future Work

Introduction

- Many emerging applications have diverse latency requirements
  - Intelligent transportation, Industry automation, Online gaming, High-frequency trading
- An enabling technology to support latency-sensitive applications is **network virtualization**
  - Facilitates deployment of multiple virtual networks (VNs) with varying latency requirements on the same substrate network
  - Virtual network embedding maps VN nodes and links to substrate resources while guaranteeing latency constraints
- We focus on **transport network** as our substrate that connects Point of Presence (PoP) nodes
  - Optical network is the dominant technology due to its high-bandwidth and low-latency
  - Create lightpaths to embed virtual links



Virtual Network



Substrate Network

Elastic Optical Networks (EON)

- Traditional fixed-grid technology allocates spectrum in coarse-grained fashion
  - **Inefficient** - supports only 50 or 100 GHz wavelength grids
  - **Rigid** - allows limited transmission configurations for each data rate
- Elastic Optical Networks (EONs) are emerging to overcome the limitations
  - Enables **finer granularity** (12.5GHz) with arbitrary number of spectrum slices based on customer demand
  - Facilitates **tuning** of transmission configurations as per the need

Transmission configurations

Data Rate (Gbps)	Modulation format	FEC (%)	Spectrum bandwidth (GHz)	Reach (km)
100	QPSK	25	50	2000
200	QPSK	25	100	1000

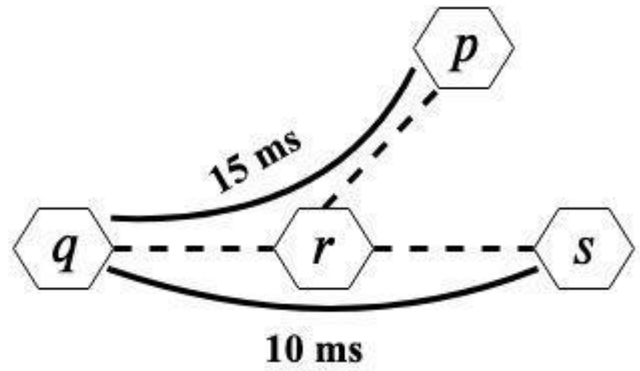
Traditional Optical Network

Data Rate (Gbps)	Modulation format	FEC (%)	Spectrum bandwidth (GHz)	Reach (km)
100	QPSK	25	50	2000
	16QAM	20	25	1250
200	QPSK	25	75	1000
	32QAM	20	37.5	400

Elastic Optical Network

Key contribution

- Existing literature represents latency requirements on **virtual links** (VLinks)
  - Cannot provide end-to-end latency guarantees
- We propose **path-based** latency requirements on virtual networks, called as VPath
  - Latency constraint is enforced along an entire path between PoPs
  - More flexibility in selecting substrate paths and transmission configurations for embedding VLinks
- How to distribute latency budgets to VLinks without violating path-based latency requirements?



VN request with path-based latency requirements

Latency model for a lightpath

- Node processing latency:
  - Transponders: ≈ 30 ns
  - FEC processing: ≈ 10 μs (standard) or ≈ 150 μs (super)

$$L_{node} = 2 \times (L_{transponder} + L_{FEC})$$

- Path latency
  - Fiber propagation: **4.9 μs/km**
  - Amplifiers: 150 ns
  - ROADMs: O(nano seconds)

$$L_{path} = len(p) \times L_{prop} + n_{amp} \times L_{amp} + (|p| + 1) \times L_{roadm}$$

- Zero queueing delay
  - By allocating dedicated resource on source and destination nodes
  - On intermediate nodes, data is optically switched - no queue buildup

Problem statement

Inputs:

- EON substrate Network
    - K-shortest path between each pair of nodes
- A set of transmission configurations
- VN request:
    - VLinks have bandwidth demand in Gbps
    - Path-based latency constraints
    - Given node mapping

Approach:

- Embedding a VLink by splitting its demand into multiple substrate paths
    - One path can be used more than once

Outputs:

- To embed each VLink, select
    - A set of substrate paths and appropriate transmission configurations
    - Spectrum slice allocation

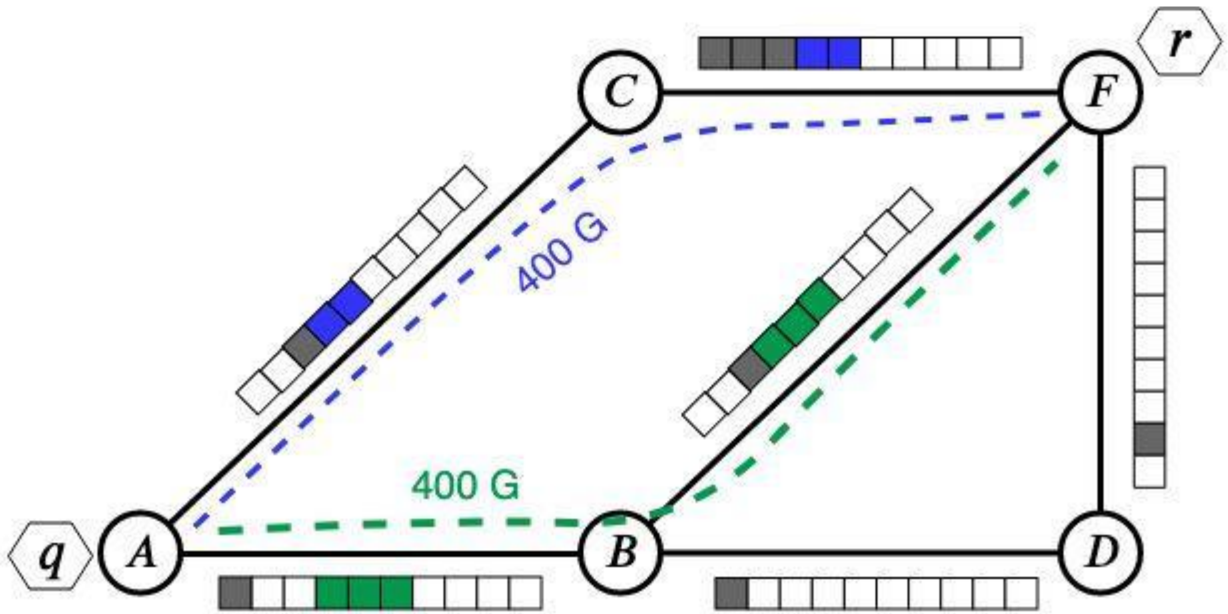
Objective:

- Minimize total spectrum resource allocation for the VN embedding (Primary)
- Minimize the total number of splits, i.e., transponders (Secondary)

Problem Formulation: Constraints

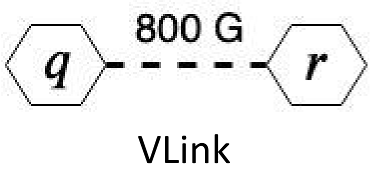
- An spectrum slice on a fiber link can be allocated to at most one split
- Each VLink demand is provisioned using up to a maximum (***q***) splits
    - Each split is realized using a transmission configuration satisfying its optical reach
    - Sum of the data rates carried by the splits is equal to the VLink demand

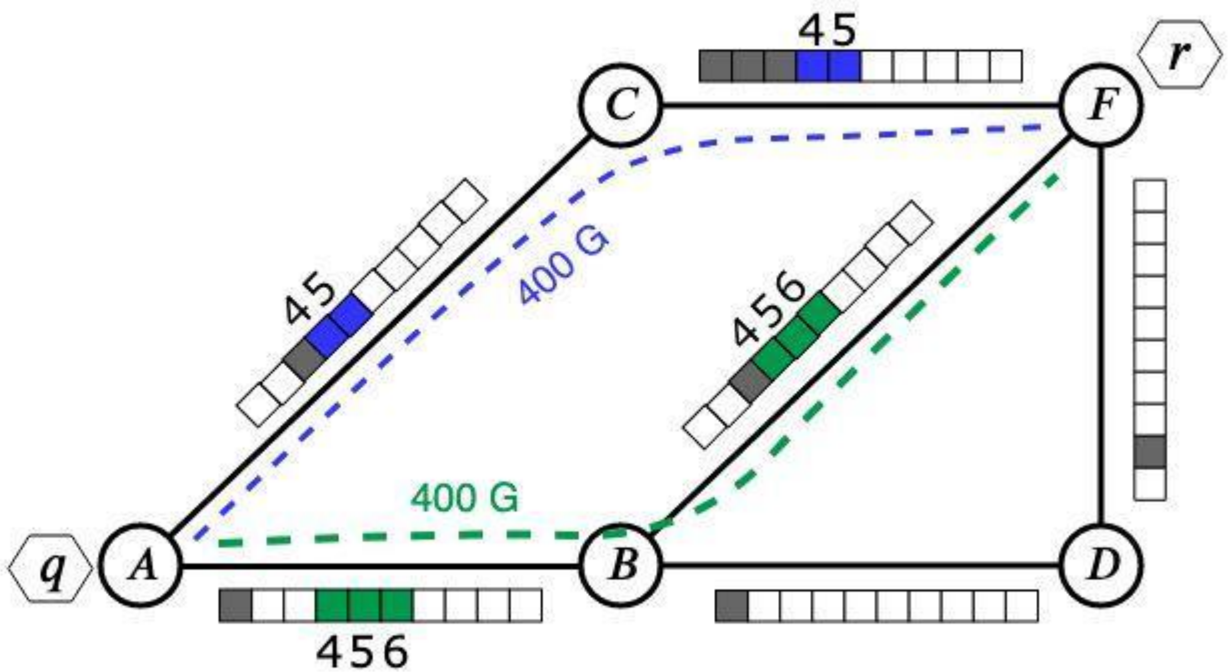
VLink



Constraints (Cont'd)

- Spectral contiguity and continuity:
  - Slices assigned to each split must be adjacent on each link of a substrate path (Contiguity)
  - Same set of slices should be assigned to each split along all links of a substrate path (Continuity)

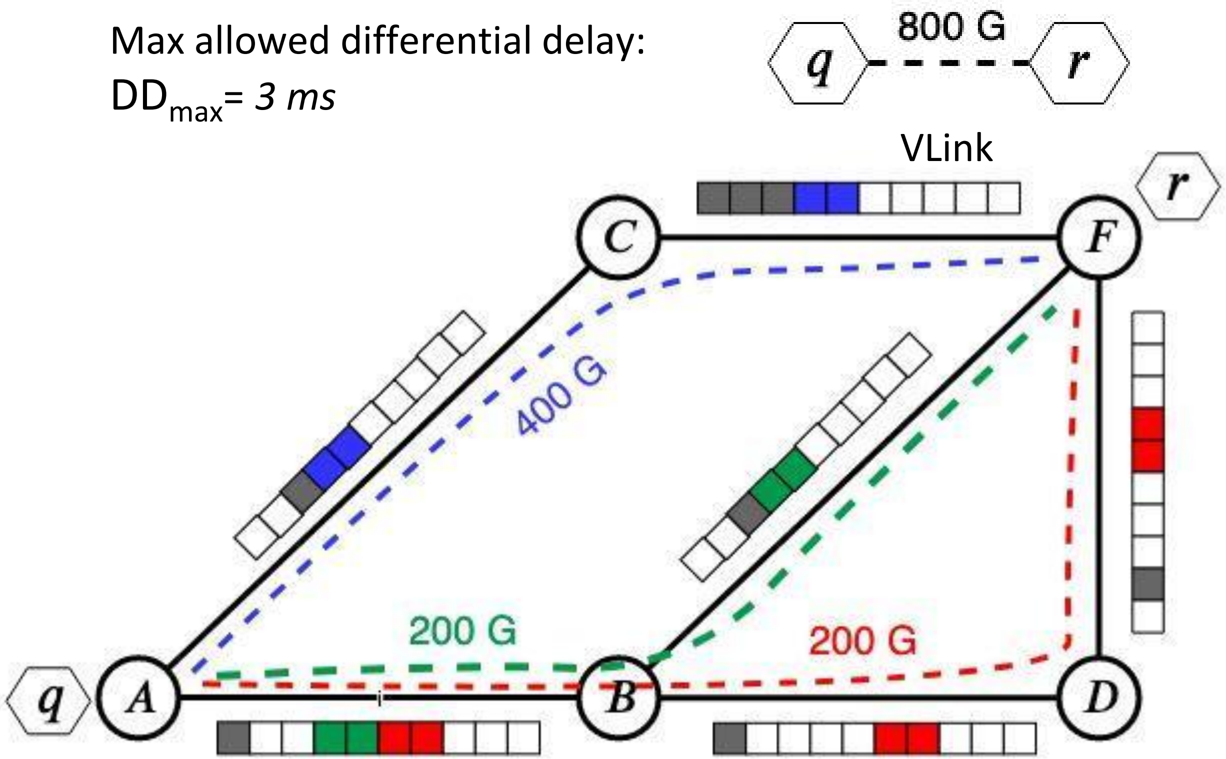




Constraints (Cont’d)

- Differential delay constraints:
  - The difference between the maximum and minimum latency of the splits provisioning a VLink should be less than DD_{max}

Max allowed differential delay:
$DD_{max} = 3\ ms$



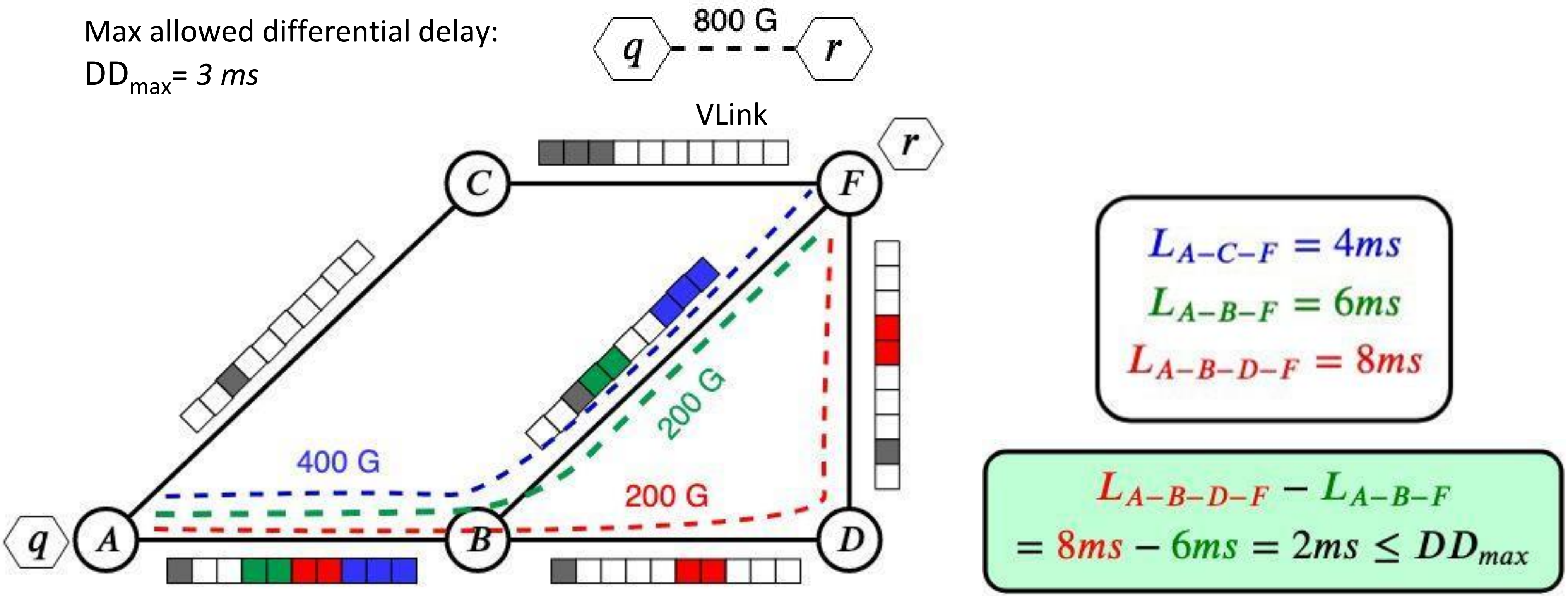
$$L_{A-C-F} = 4ms$$
$$L_{A-B-F} = 6ms$$
$$L_{A-B-D-F} = 8ms$$

$$L_{A-B-D-F} - L_{A-C-F} = 8ms - 4ms = 4ms \geq DD_{max}$$

Constraints (Cont'd)

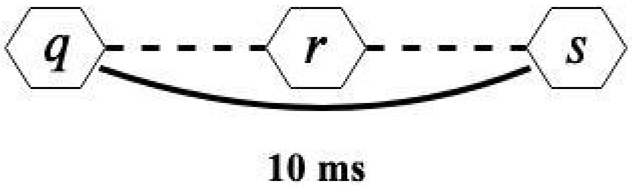
- Differential delay constraints:
  - The difference between the maximum and minimum latency of the splits provisioning a VLink should be less than DD_{max}

Max allowed differential delay:
DD_{max}= *3 ms*

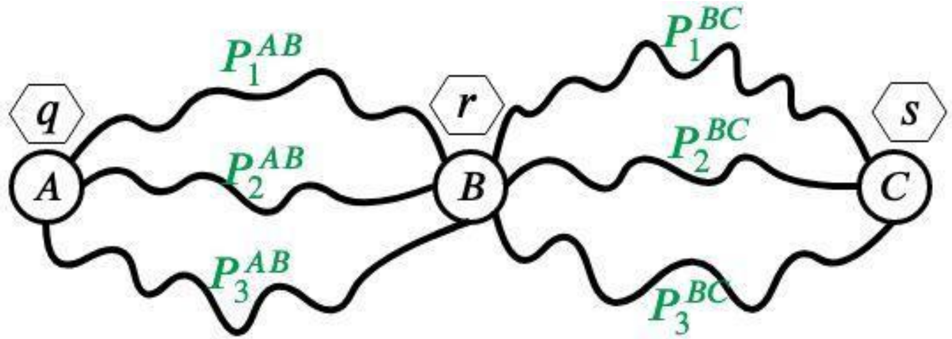


Constraints (Cont’d)

- Latency constraints for VPath:
  - The latency of each VLink embedding is equal to the maximum latency among its splits
  - The sum of the latencies of the VLinks on a VPath should satisfy the latency constraint



VN Request



$$L_{P_1^{AB}} = 3ms$$
$$L_{P_2^{AB}} = 4ms$$
$$L_{P_3^{AB}} = 5ms$$

$$L_{P_1^{BC}} = 4ms$$
$$L_{P_2^{BC}} = 6ms$$
$$L_{P_3^{BC}} = 8ms$$

Constraints (Cont'd)

- Latency constraints for VPath:
  - The latency of each VLink embedding is equal to the maximum latency among its splits
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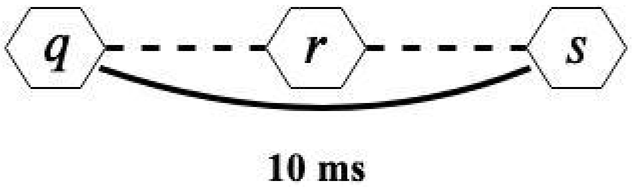
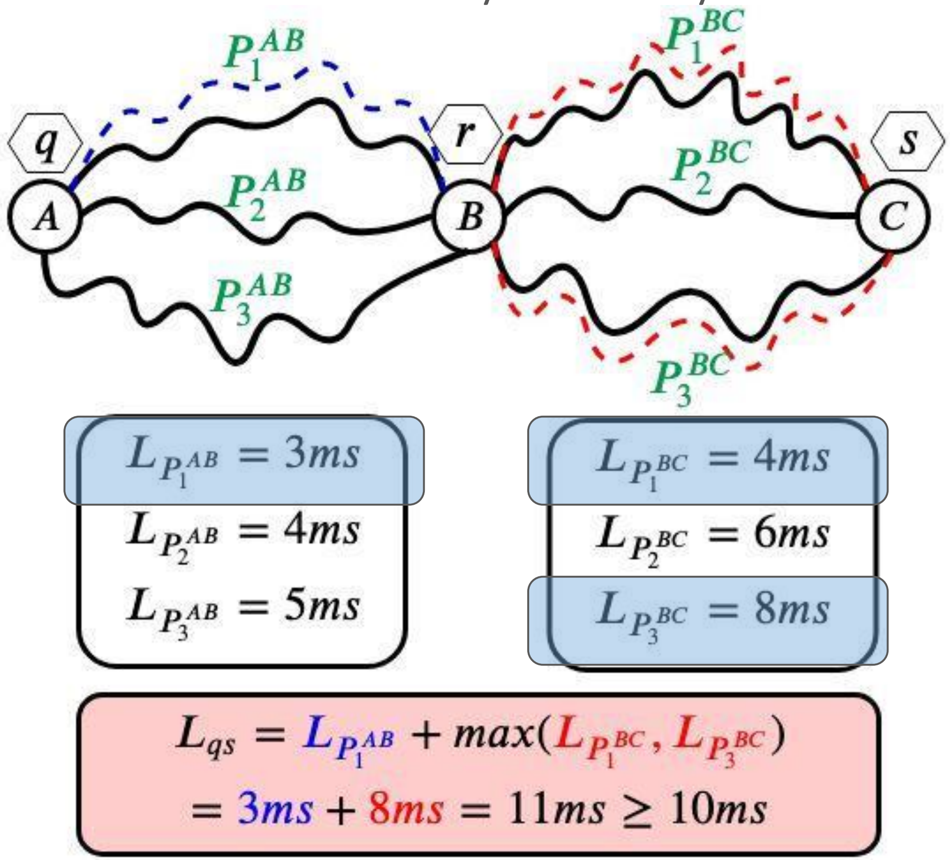


VN Request



Constraints (Cont’d)

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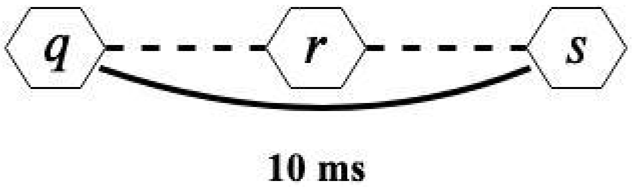
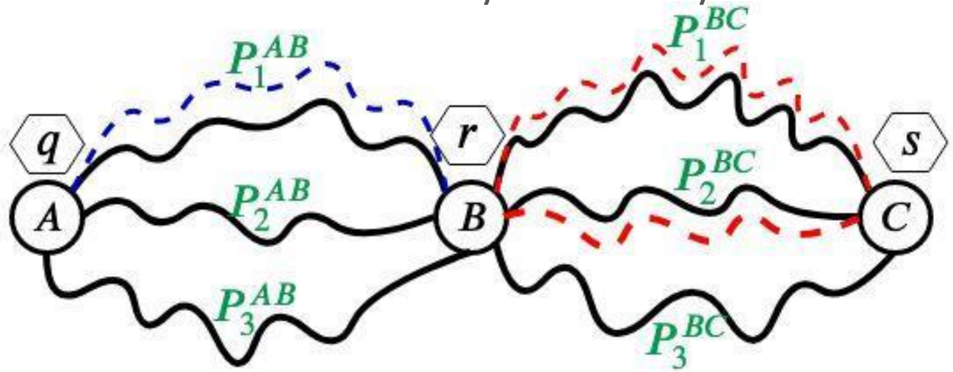


VN Request



$L_{P_1^{AB}} = 3ms$

$L_{P_2^{AB}} = 4ms$

$L_{P_3^{AB}} = 5ms$

$L_{P_1^{BC}} = 4ms$

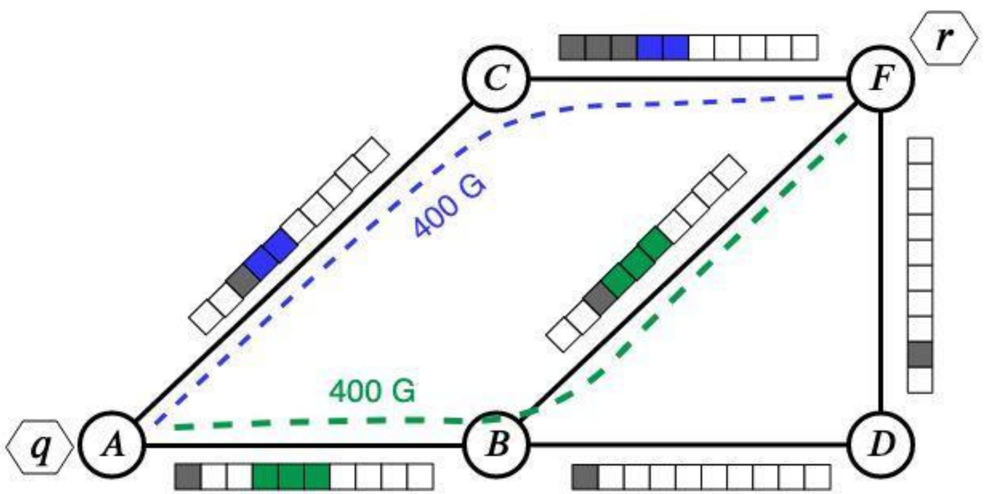
$L_{P_2^{BC}} = 6ms$

$L_{P_3^{BC}} = 8ms$

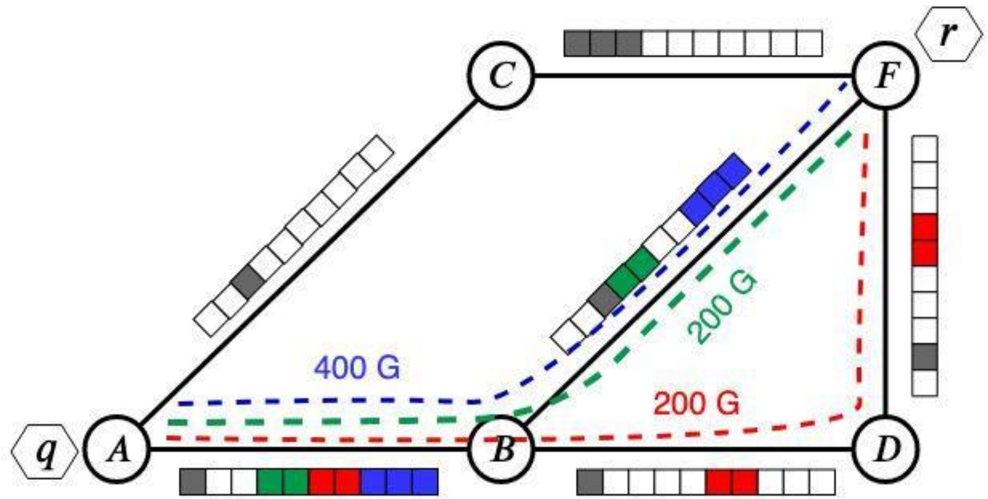
$$L_{qs} = L_{P_2^{AB}} + max(L_{P_1^{BC}}, L_{P_2^{BC}})$$
$$= 3ms + 6ms = 9ms \leq 10ms$$

Objective

- Minimize total spectrum resource allocation for the VN embedding (Primary)
- Minimize the total number of splits (Secondary)



Primary obj: 4 + 6 = 10 slices
Secondary obj = 2 splits



Primary obj: 6 + 4 + 6 = 16 slices
Secondary obj = 3 splits

Heuristic Algorithm

- Composed of 2 main steps
- Step 1: Choosing a VLink to be embedded next and computing an estimation of the latency budget for the VLink in terms of the candidate substrate paths
  - Most constrained VLink in terms of spectrum slice availability and latency
- Step 2: Finding an optimal embedding for the chosen VLink
  - Splits the VLink demand among multiple candidate paths
  - Uses the most spectrally efficient transmission configuration for each of the selected paths
  - Allocates spectrum slices on each link of the path
  - Finds the actual latency of the VLink based on the selected paths to help determine the latency of a VPath in step 1

Step 1: Finding Next VLink Algorithm

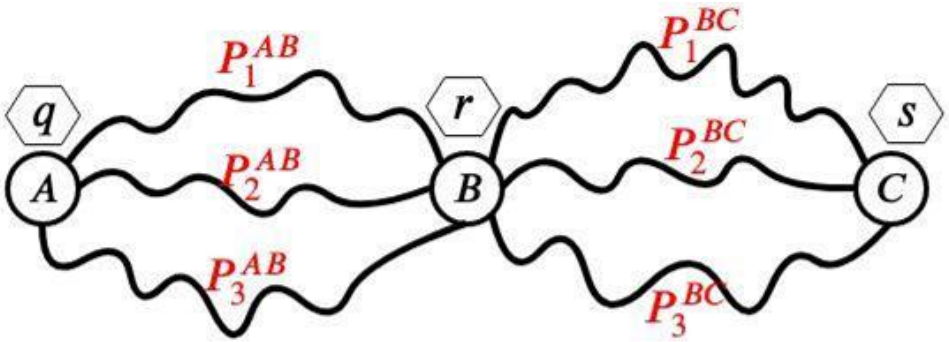
- Estimate latency budgets for all **VLinks** yet to be embedded
  - Assigned budgets do not violate any latency constraint
  - Determines the number of candidate paths to use for the VLinks
- The **number of available slices** on the candidate paths satisfying the assigned latency budget is maximized for the most constrained VLink
  - Spectrum resource availability is the bottleneck
  - Compute using binary search on the number of available spectrum slices
  - Check if the number of slices can be used without violating any latency constraint
- Return the VLink with the **minimum number of available slices** that does not violate the assigned latency budget

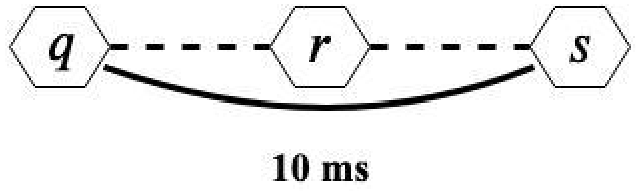
Step 1: Finding Next VLink Algorithm (Cont'd)

- Binary Search on the range of the number of available slices on the candidate paths
  - Finding the number of available slices on the candidate paths for each VLink
  - Get the minimum value of the number of available slices
  - Check if the number of slices can be used without violating any latency constraint
  - Do binary search
- Return the VLink with the **minimum number of available slices** that does not violate the assigned budget

Step 1: Finding Next VLink Algorithm (Cont'd)

Estimating a latency budget for each **VLink**





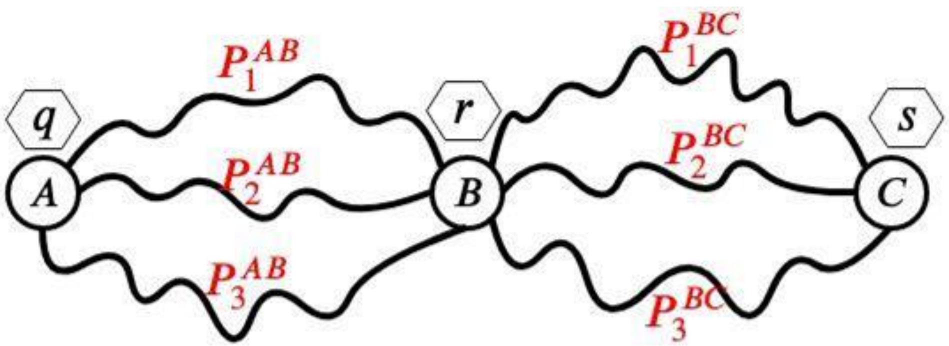
VN Request

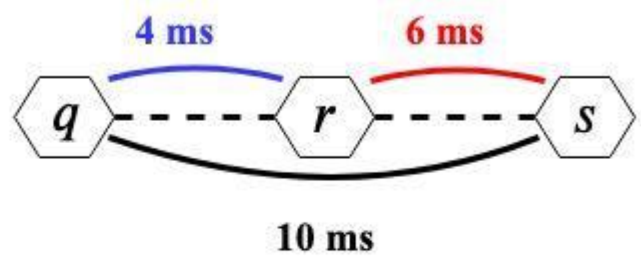
	L	Available slices
P_1^{AB}	$3ms$	4
P_2^{AB}	$4ms$	3
P_3^{AB}	$5ms$	1

	L	Available slices
P_1^{BC}	$4ms$	10
P_2^{BC}	$6ms$	4
P_3^{BC}	$8ms$	6

Step 1: Finding Next VLink Algorithm (Cont'd)

Estimating a latency budget for each **VLink**





VN Request

	L	Available slices
P_1^{AB}	$3ms$	4
P_2^{AB}	$4ms$	3
P_3^{AB}	$5ms$	1

7 Slices

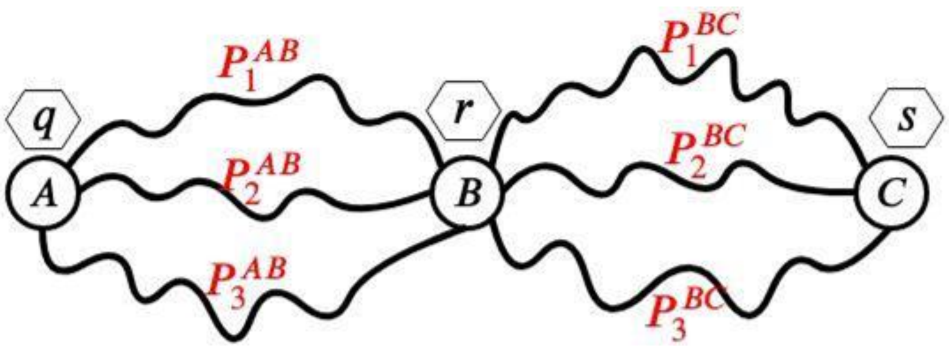
	L	Available slices
P_1^{BC}	$4ms$	10
P_2^{BC}	$6ms$	4
P_3^{BC}	$8ms$	6

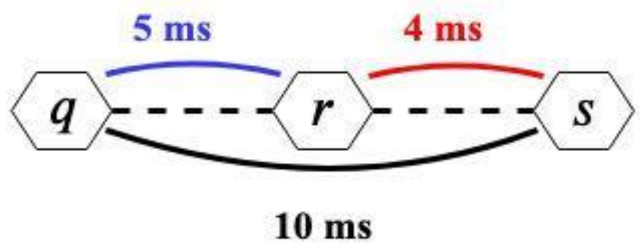
14 Slices

Goal: Maximize the number of slices for the VLink with minimum number of usable slices

Step 1: Finding Next VLink Algorithm (Cont’d)

Estimating a latency budget for each **VLink**





VN Request

	L	Available slices
P_1^{AB}	$3ms$	4
P_2^{AB}	$4ms$	3
P_3^{AB}	$5ms$	1

8 Slices

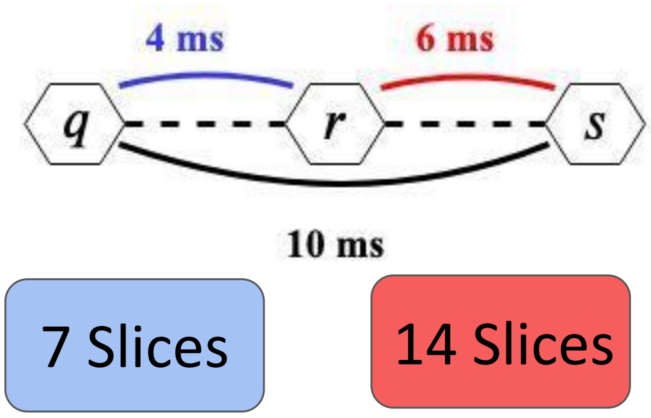
	L	Available slices
P_1^{BC}	$4ms$	10
P_2^{BC}	$6ms$	4
P_3^{BC}	$8ms$	6

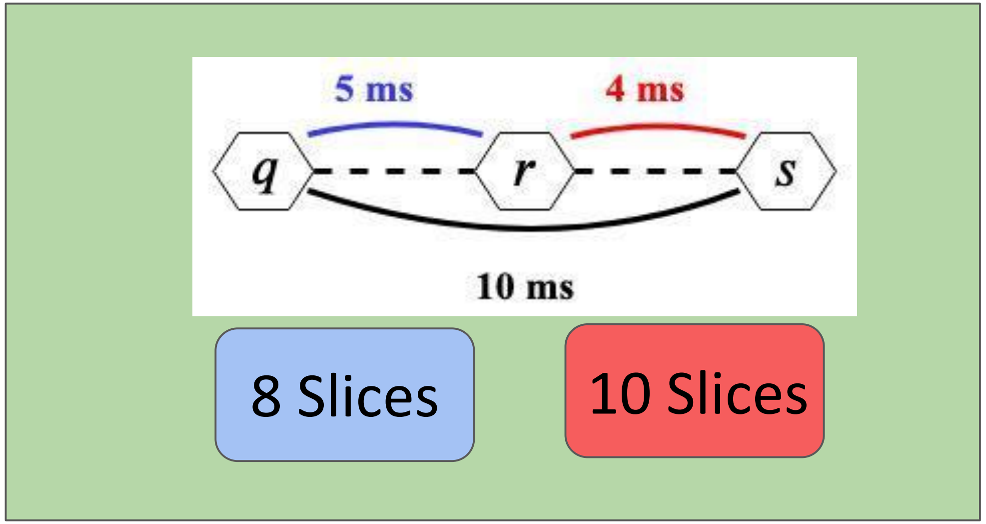
10 Slices

Goal: Maximize the number of slices for the VLink with minimum number of usable slices

Step 1: Finding Next VLink Algorithm (Cont'd)

Estimating a latency budget for each **VLink**





Goal: Maximize the number of slices for the VLink with minimum number of usable slices

Step 2: Optimal embedding for a VLink

- Compute link embedding using an exhaustive search considering all possible
  - Path selection (considering splitting)
    - All **multiset** of candidate paths with size <= q
    - Assigning **data rate** satisfying VLink demand

    } Specifying Splits
  - Transmission configuration selection
    - Choose a configuration supporting the **datarate** along the distance of a path in the multi-set
  - Spectrum slice assignment
    - **First-fit** slice allocation
- Select the combination of <path, transmission configuration, slice assignment> that minimizes the objective
  - Extends an algorithm published in [1]
- Additional pruning
  - Multi-sets of paths that violate differential delay constraint
  - Solutions requiring more slices than a lower bound computed using dynamic programming

1. Shahriar, Nashid et al. "Achieving a Fully-Flexible Virtual Network Embedding in Elastic Optical Networks." *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications* (2019): 1756-1764.

Step 2: Optimal embedding for a single VLink (Cont’d)

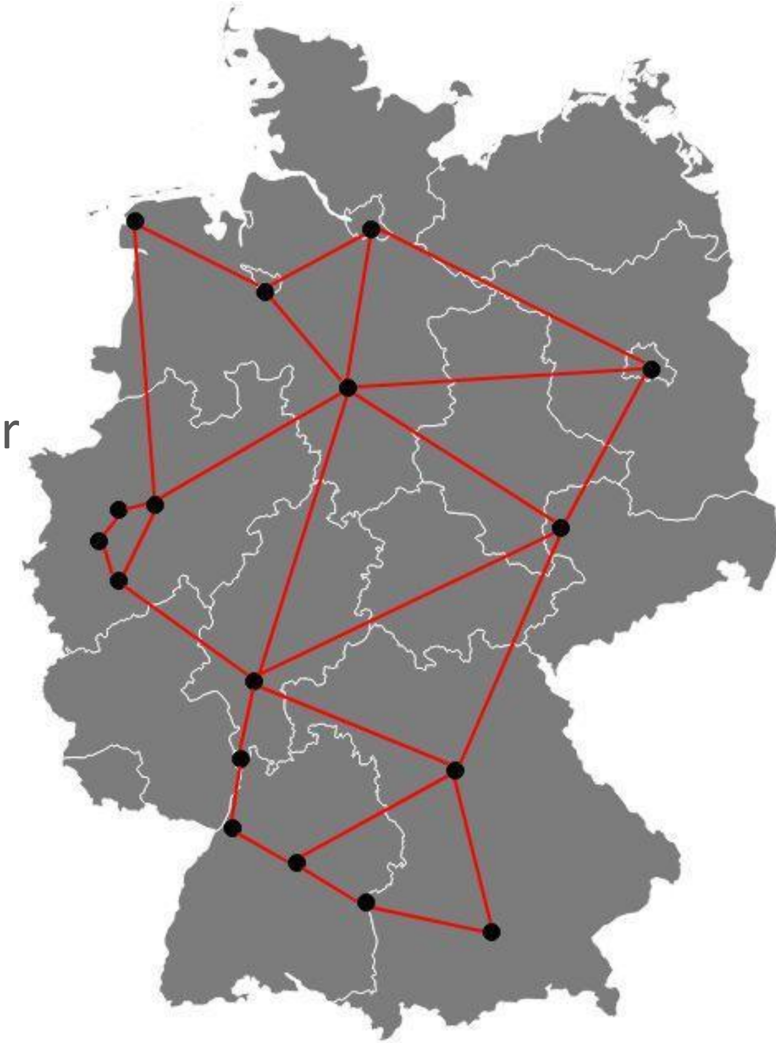
Optimization techniques:

- Pruning path multi-sets that violate differential delay constraint
- For a VLink with demand = D:
  - Solve the embedding for all d <= D and only one split
  - Find estimation for embedding using multiple splits (lower bound)
  - Only consider ones with better lower bound compared to best solution

Evaluation - Small Scale Benchmark

- Nobel Germany[1] EON
  - 17 Nodes and 26 Links
- Number of spectrum slices per link
  - Fixed grid: 12 slices of 50 GHz
  - Flex grid: 48 slices of 12.5 GHz
- Possible configurations provided by industry partner
- Max number of splits (q) is 4
- VNs are generated synthetically
  - Fixed node mapping
  - 8 VNodes
  - Variable LNR: from 1 to 2.5 (8 to 20 VLinks)
  - Latencies: Latency of the shortest path * α (α >= 1)

$$L(\alpha) = L(\text{path with lowest latency}) \times \alpha$$



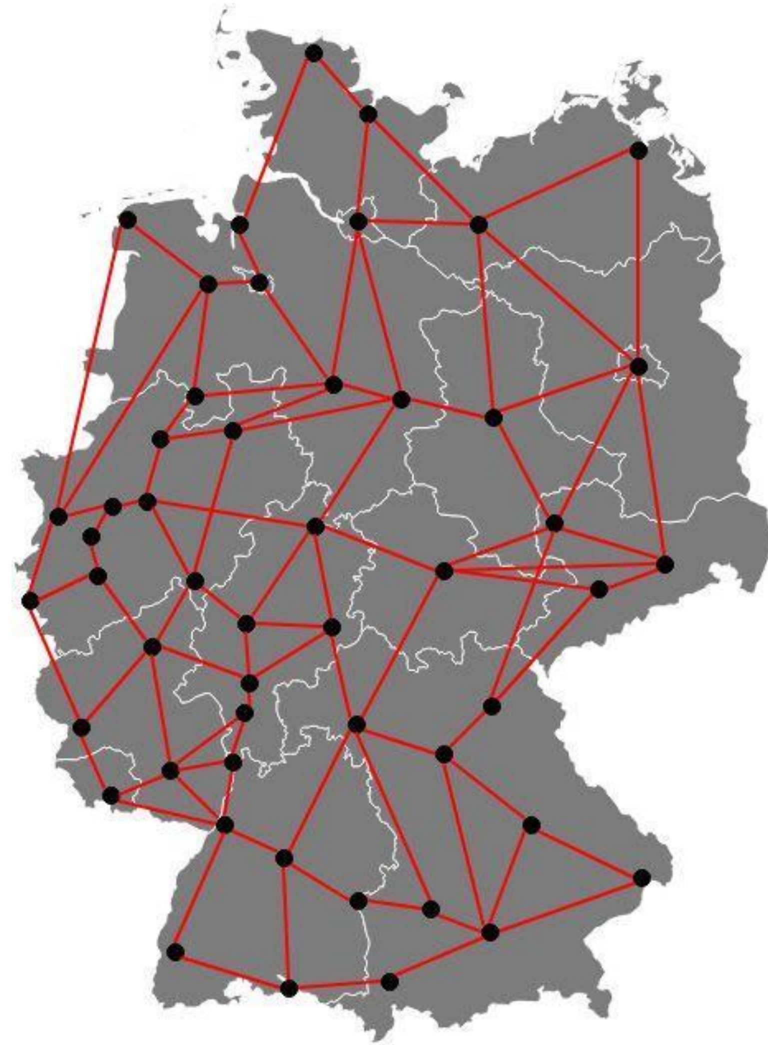
1. http://sndlib.zib.de/

Evaluation - simulation settings

Large Scale:

- EON: Germany50[1]: 50 Nodes, 88 Links
- Number of spectrum slices per link:
  - Fixed grid: 80 slices of 50 GHz
  - Flex grid: 320 slices of 12.5 GHz
- VNs are generated synthetically
  - Fixed node mapping
  - 50 VNodes
  - Variable LNR: from 1 to 3.5 (50 to 175 VLinks)
  - Latencies: Latency of the shortest path * α (α >= 1)

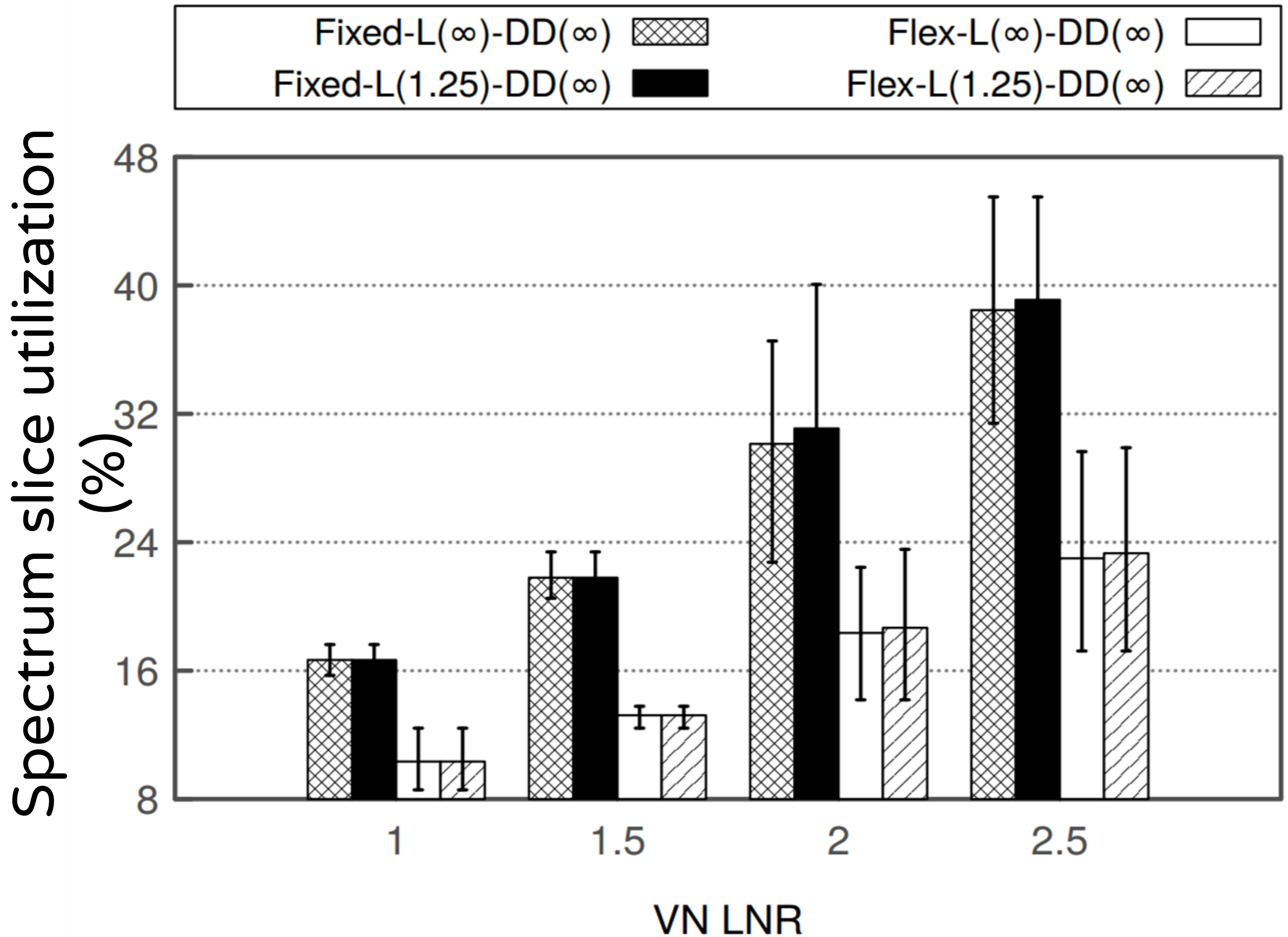
$$L(\alpha) = L(\text{path with lowest latency}) \times \alpha$$



1. http://sndlib.zib.de/

Evaluation - Small Scale Benchmark

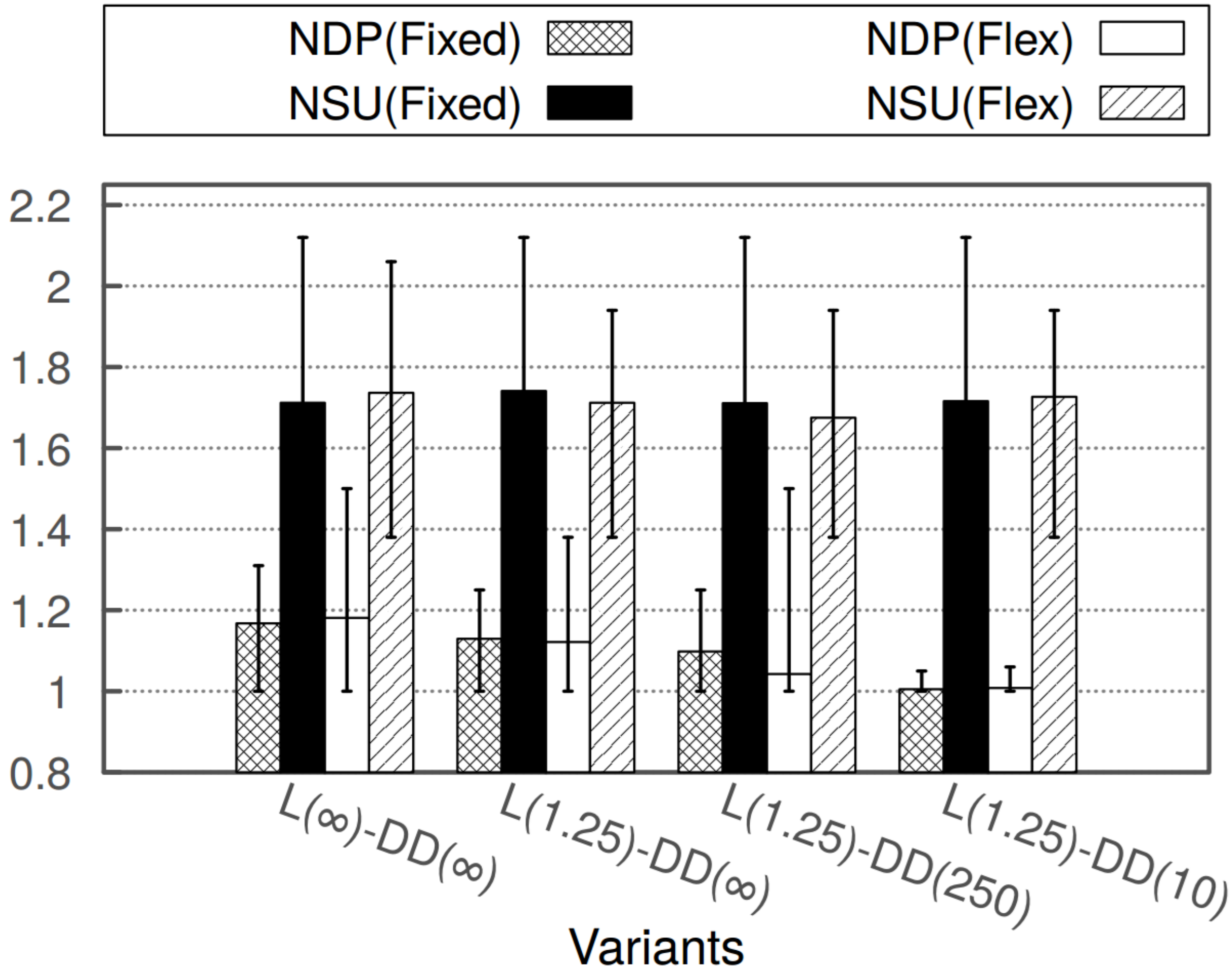
- Impact of the latency constraints on resource utilization
- Compared variants
  - Fixed-L(α)-DD(β):
    - Fixed grid
    - α: latency factor
    - β: max differential delay
  - Flex-(α)-DD(β):
    - Flex grid
    - α: latency factor
    - β: max differential delay



Evaluation - Small Scale Benchmark

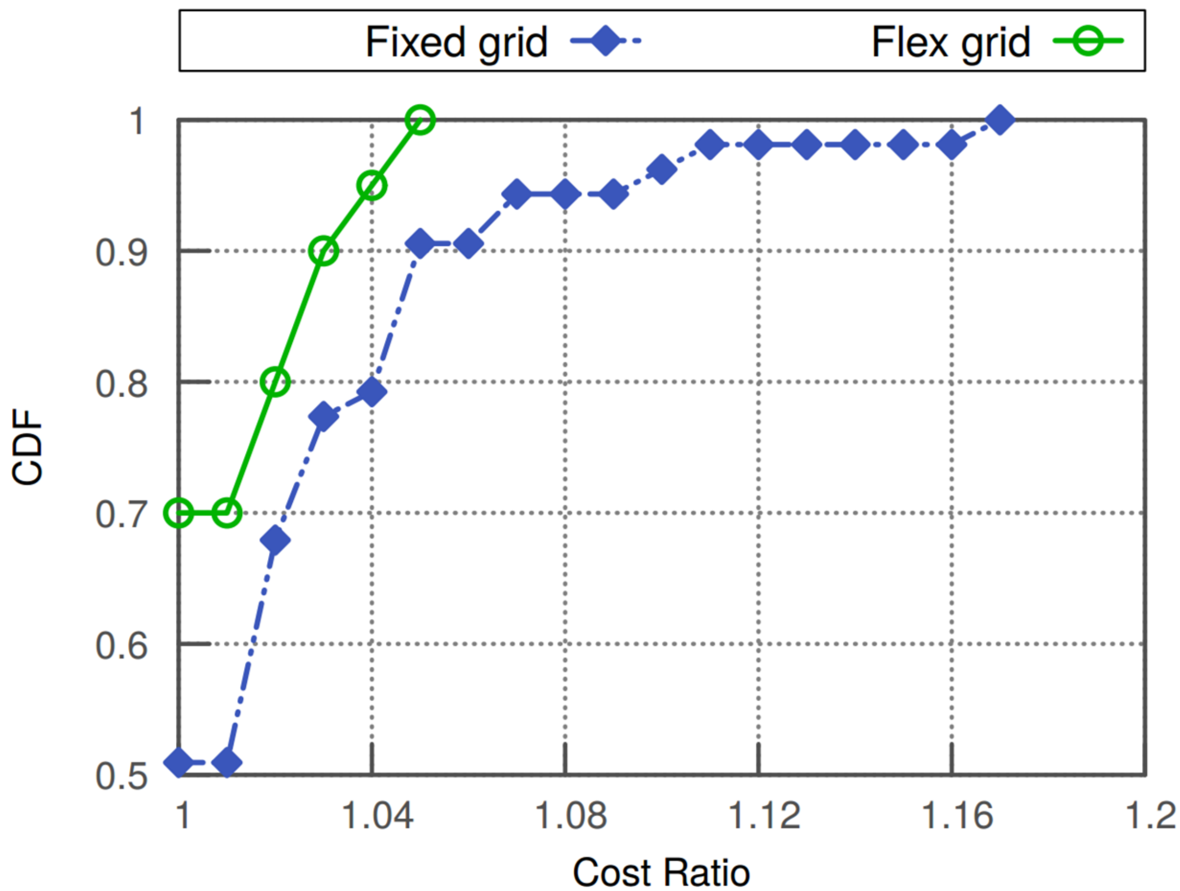
- Impact of differential delay on substrate path selection

- Metrics
  - NDP (Fixed/Flex)
    - Avg. number of **distinct path** used to embed a VLink
  - NSU (Fixed/Flex)
    - Avg. number of **splits** used to embed a VLink

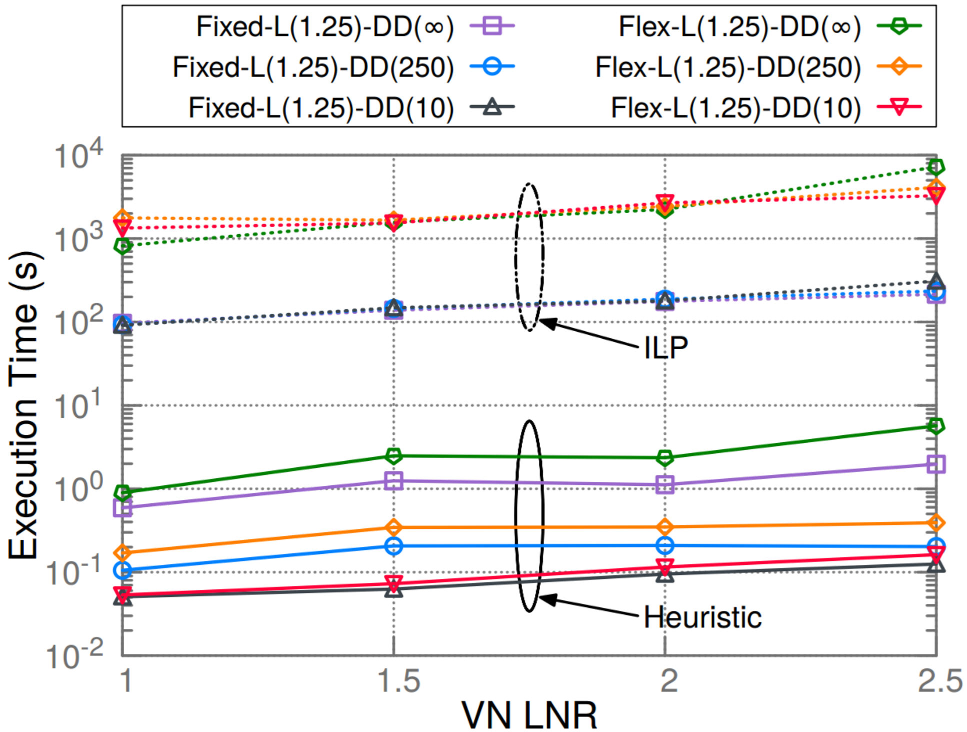


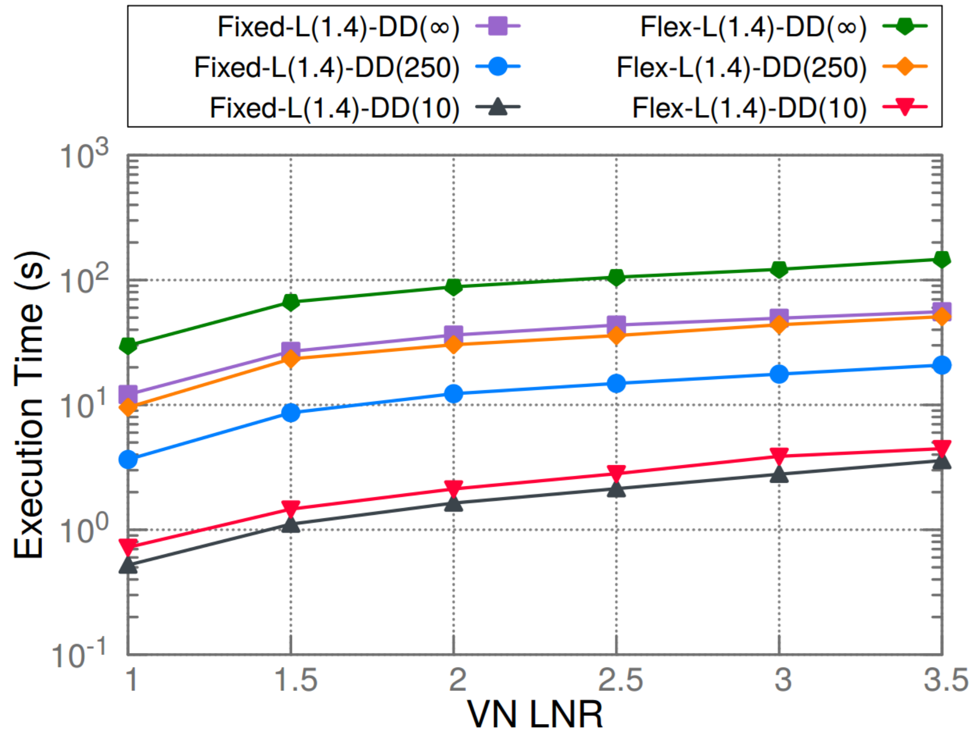
Evaluation - Small Scale Benchmark

- Optimality of heuristic
- Compared variants
  - Fixed grid EON
  - Flex grid EON
  - Varying latency and differential delay for both cases



Evaluation - scalability

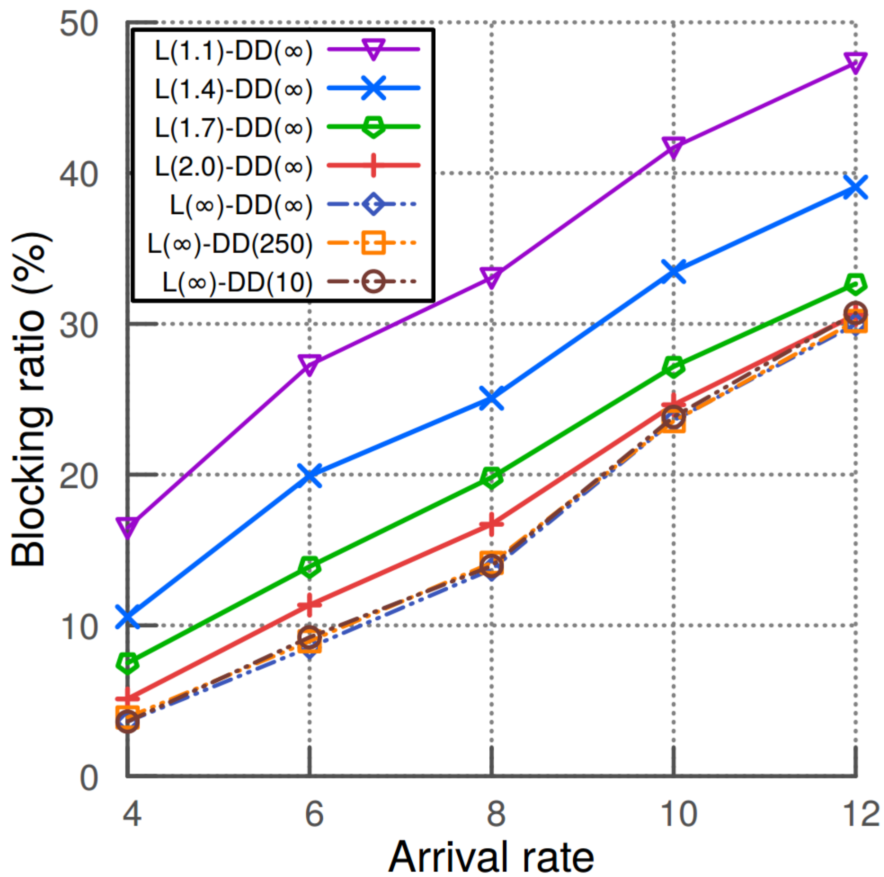




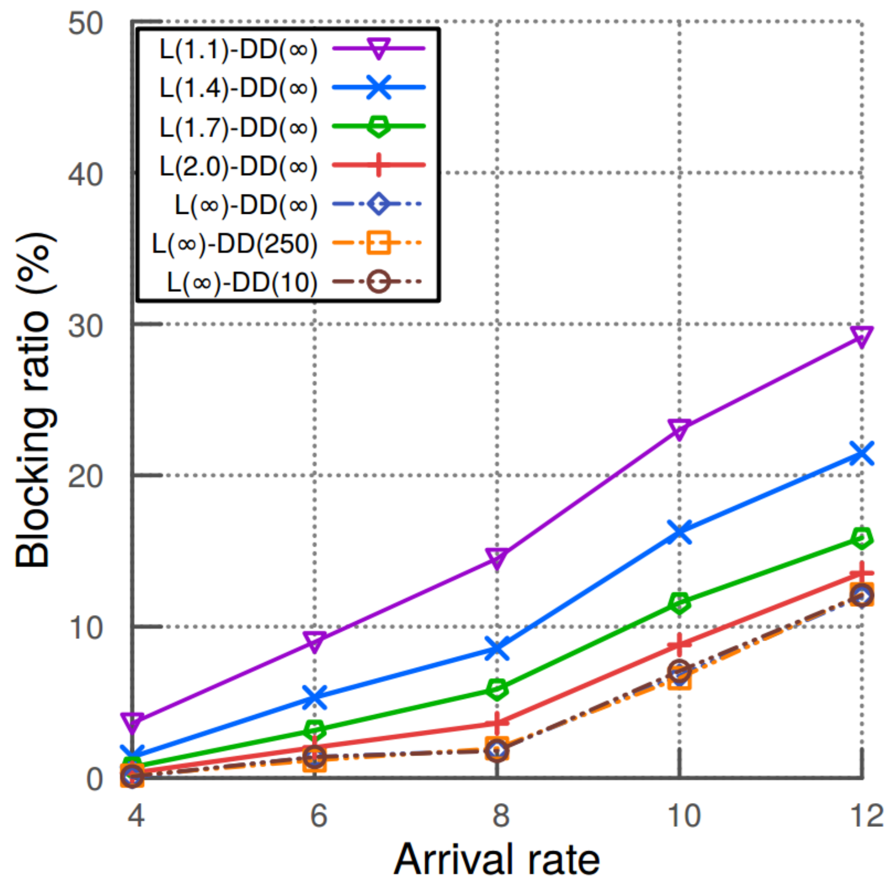
Evaluation - Steady State Analysis

- Arrival and departure time for VNs
  - Arrival rate: Poisson distribution
    - 4 to 12 VNs per 100 time units
  - VN life time: Exponential distribution
    - Mean of 100 time units
- VN and SN properties
  - 8 VNodes
  - Random number of VLinks: 8 to 28
  - Nobel Germany flex grid EON: **320 slices of 12.5 GHz**
- Simulation time: **10000** time units
  - Excluding the first 1000 time units
- 5 different simulation scenarios
- Report VN **blocking ratio**
  - Percentage of VNs that could not be embedded

Evaluation - Steady State Analysis

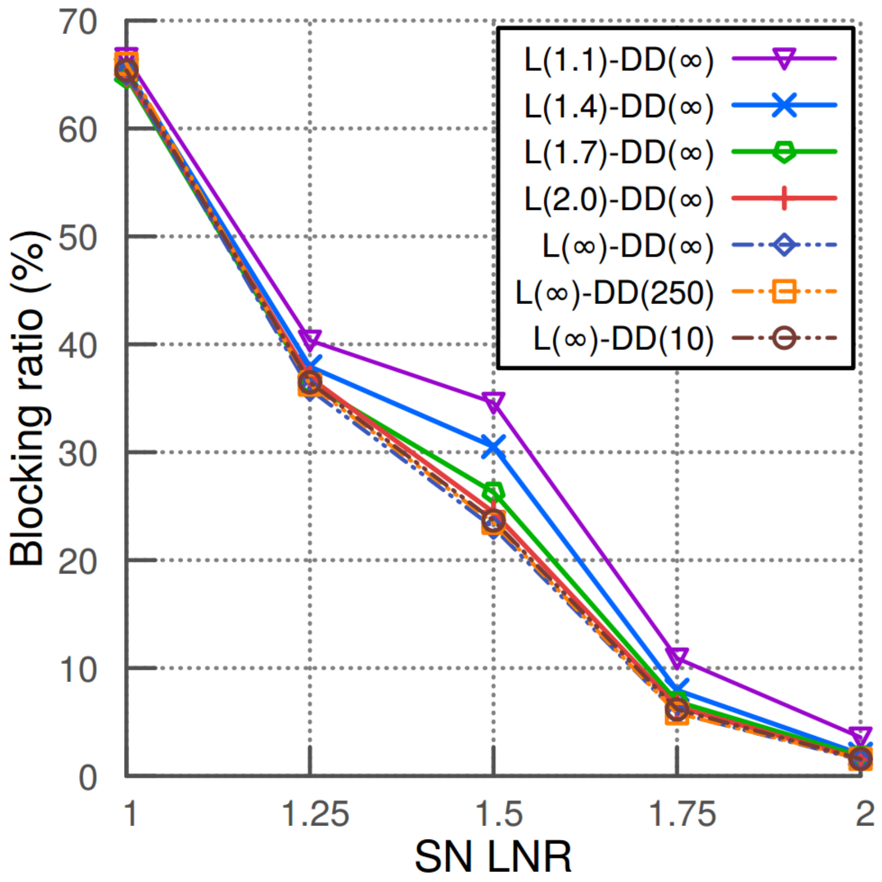


Fixed Grid

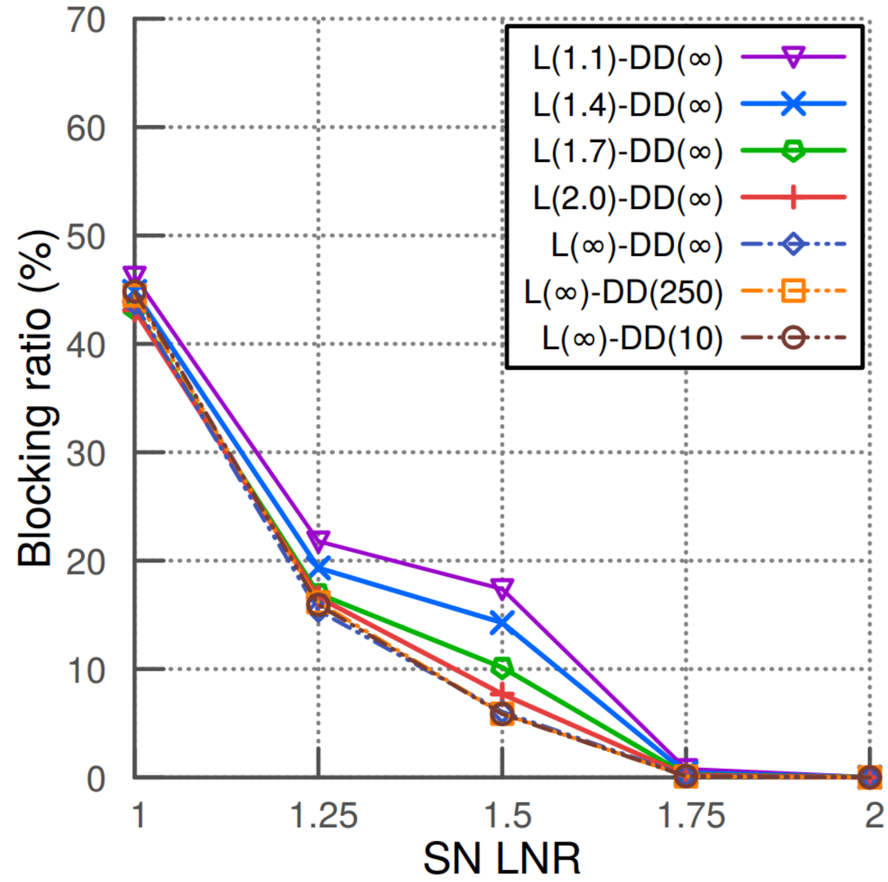


Flex Grid

Evaluation - Steady State Analysis



Fixed Grid



Flex Grid

Conclusion & Future Work

- Virtual network embedding over EON
  - Path-based latency guarantees
  - Considering full flexibility in all transmission parameters of an EON
- An ILP based optimization model
- A faster heuristic algorithm that obtains near optimal solutions
- Key takeaways
  - Latency constraints has less impact on spectrum usage but profound impact on blocking
  - Flexibilities of an EON help reduce these impact
- Future work
  - Different cost function to decrease blocking probability
  - Design an admission control to maximize the revenue

Thank You!