Comparison of Virtual Network Embedding Algorithms for Data Center Networks

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Roadmap

- Introduction
- Virtual network embedding
- Data center network topologies
- Simulation scenarios and results
- Conclusion
- References

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Data centers

https://www.google.com/about/datacenters/gallery/#!/%23gallery

Data center networks virtualization

- Virtualization in data center networks:
  - reduces inefficient resource utilization and addresses high storage and processing demands
  - enables flexible network operability and maintenance by sharing the existing physical network resources
- Software defined network model:
  - decouples the network layer control and data planes
  - leads to logically centralized approach that facilitates network management

Virtualized network model

- Network virtualization:
  - Two types: infrastructure (InPs) and service (SPs) providers
- Virtual network embedding (VNE):
  - process of embedding virtual networks (VNs) onto substrate networks (SNs)
    - virtual node mapping (VNoM)
    - virtual link mapping (VLiM)
  - NP-hard problem with a large solution space
  - a crucial component in the VNE process is attending to virtual network requests (VNRs) with variable arrival rates

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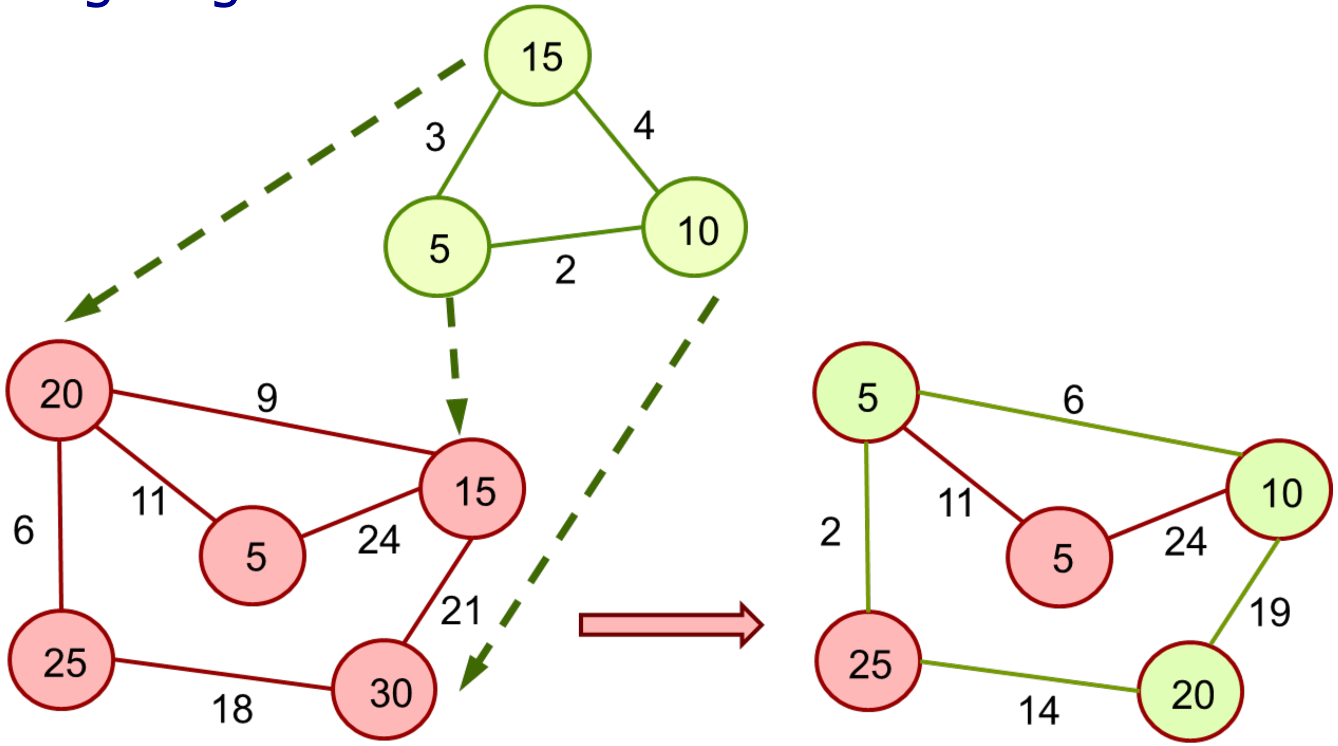
Virtual network embedding

- VNE problem may be solved by employing:
  - heuristic uncoordinated algorithms
  - coordination between embedding stages



VNE approaches: uncoordinated

- Uncoordinated two-stage algorithms solve:
  - VNoM:
    - heuristic
  - VLiM:
    - Shortest Path: without path splitting
    - Multi-Commodity Flow: with path splitting
  - Restricted solution space: algorithms ignore preselection of node mappings

VNoM: Virtual Node Mapping
VLiM: Virtual Link Mapping
SP: Shortest Path
MCF: Multi-Commodity Flow

VNE algorithms: coordinated

- The coordinated two-stage algorithms solve:
  - VNoM first while considering link constraints and availability
  - VLiM then employs SP or MCF techniques
- The coordinated one-stage algorithms:
  - simultaneously solved by creating a suitable optimal virtual link between the nodes

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Virtual networks embedding

Evaluated algorithms:

- Monte Carlo Tree Search (MCTS)-based:
  - Multi-Commodity Flow (MaVEn-M)
  - Shortest path (MaVEn-S)
- Deterministic (D-ViNE) and Randomized (R-ViNE)
- Global Resource Capacity (GRC)
- GRC with Multi-Commodity Flow (GRC-M)

Coordinated virtual networks embedding

- MCTS-based Multi-Commodity Flow (MaVEn-M):
  - coordinates stages and embeds virtual links using MCF
- MCTS-based shortest path (MaVEn-S):
  - employs breadth first search to coordinate stages and to embed virtual links
- Global Resource Capacity Multi-Commodity Flow (GRC-M):
  - improves substrate resources utilization by allowing path splitting

S. Haeri and Lj. Trajkovic, “Virtual network embedding via Monte-Carlo tree search,” *IEEE Transactions on Cybernetics*, vol. 47, no. 2, pp. 1–12, Feb. 2017.

S. Haeri, Q. Ding, Z. Li, and Lj. Trajković, “Global resource capacity algorithm with path splitting for virtual network embedding,” in *Proc. IEEE Int. Symp. Circuits and Systems*, Montreal, Canada, May 2016, pp. 666–669.

Coordinated virtual networks embedding

- ViNEYard:
  - deterministic: D-ViNE
  - randomized: R-ViNE
- Global Resource Capacity: GRC
  - nodes sorted based on GRC
  - embedded using greedy algorithms

M. Chowdhury, M. R. Rahman, and R. Boutaba, "ViNEYard: Virtual network embedding algorithms with coordinated node and link mapping," *IEEE/ACM Trans. Netw.*, vol. 20, no. 1, pp. 206–219, Feb. 2012.

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Performance metrics

- Virtual network request acceptance ratio
- Generated revenue
- Cost of mapping nodes and links
- Substrate resource utilization

Performance metrics: VNR acceptance ratio

- Accepted requests:

$$p_a^\tau = \frac{|\Psi^a(\tau)|}{|\Psi(\tau)|}$$

  - $|\Psi^a(\tau)|$: number of accepted VNRs in a given time interval τ
  - $|\Psi(\tau)|$: number of all arrived VNRs in time slot τ
- Goal: maximize acceptance ratio

VNR: Virtual network request

Performance metrics: generated revenue

- Revenue generated by embedding VNR Ψ_i :

$$\mathbf{R}(G^{\Psi_i}) = w_c \sum_{n^{\Psi_i} \in N^{\Psi_i}} \mathcal{C}(n^{\Psi_i}) + w_b \sum_{e^{\Psi_i} \in E^{\Psi_i}} \mathcal{B}(e^{\Psi_i})$$

  - $G^{\Psi_i}(N^{\Psi_i}, E^{\Psi_i})$: graph of the i^{th} virtual network request
  - w_c and w_b : weights for CPU and bandwidth requests
  - n^{Ψ_i} and e^{Ψ_i}: virtual nodes and links
  - $\mathcal{C}(n^{\Psi_i})$ and $\mathcal{B}(e^{\Psi_i})$: CPU and bandwidth requirements
  - Assumption: $w_c = w_b = 1$
- Goal: maximize revenue

Performance metrics: incurred cost

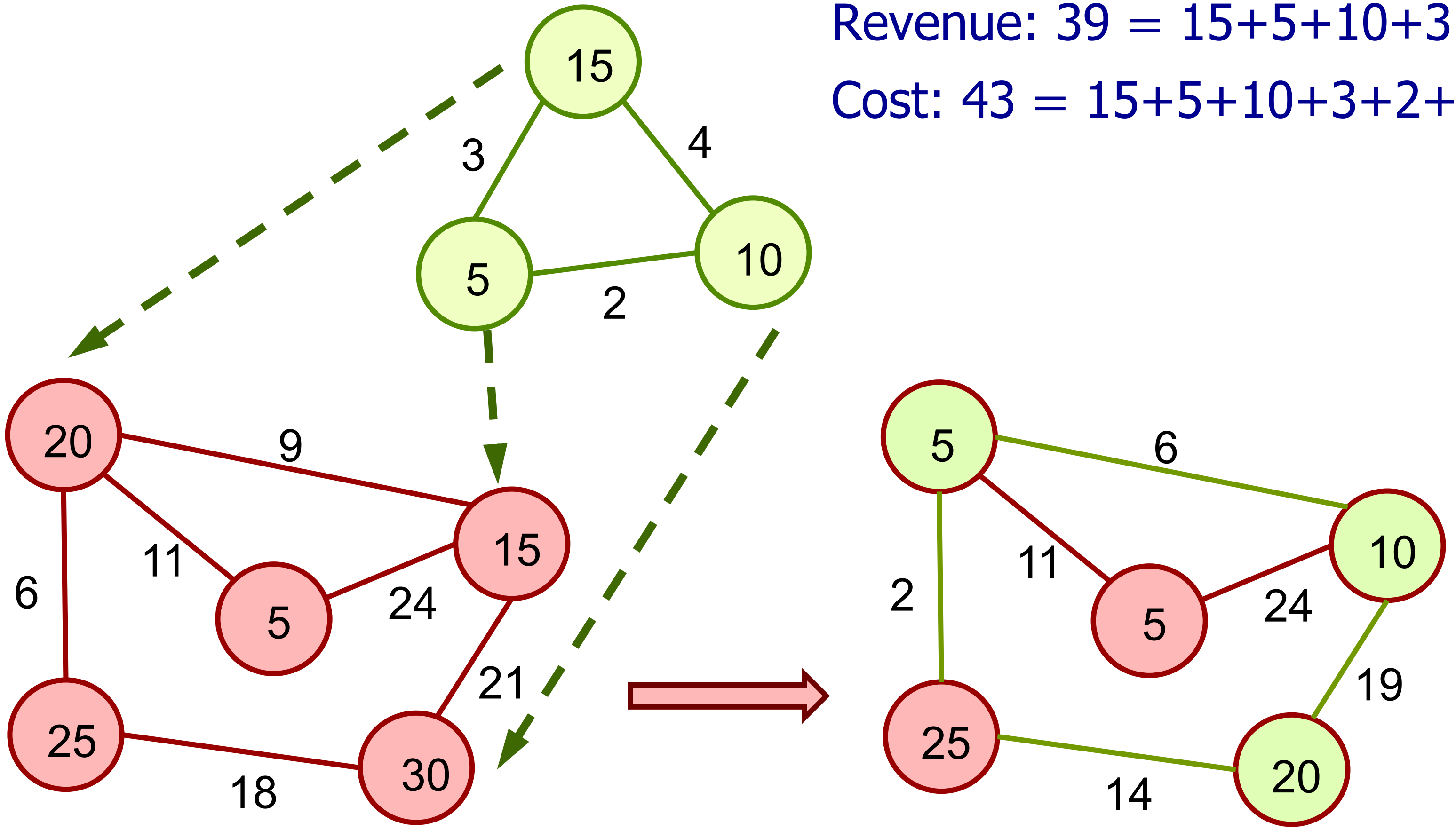
- Cost of embedding configuration and allocating substrate resources:

$$\mathbf{C}(G^{\Psi_i}) = \sum_{n^{\Psi_i} \in N^{\Psi_i}} \mathcal{C}(n^{\Psi_i}) + \sum_{e^{\Psi_i} \in E^{\Psi_i}} \sum_{e^s \in E^s} f_{e^s}^{e^{\Psi_i}}$$

  - $f_{e^s}^{e^{\Psi_i}}$: total bandwidth of substrate link e^S allocated to the virtual link e^{Ψ_i}
  - $\mathcal{C}(n^{\Psi_i})$: CPU requirements

- Goal: minimize the cost

VNE: example



Revenue: 39 = 15+5+10+3+2+4

Cost: 43 = 15+5+10+3+2+4+4

Performance metrics: node utilization

- Substrate node utilization:

$$\mathcal{U}(N^s) = 1 - \frac{\sum_{n^s \in N^s} \mathcal{C}(n^s)}{\sum_{n^s \in N^s} \mathcal{C}_{max}(n^s)}$$

  - $\mathcal{C}(n^s)$: available CPU resource of substrate node
  - $\mathcal{C}_{max}(n^s)$: maximum CPU resource of the node

- Goal: optimize the node utilization

Performance metrics: link utilization

- Substrate link utilization:

$$\mathcal{U}(E^s) = 1 - \frac{\sum_{e^s \in E^s} \mathcal{B}(e^s)}{\sum_{e^s \in E^s} \mathcal{B}_{max}(e^s)}$$

  - $\mathcal{B}(e^s)$: available bandwidth of substrate link
  - $\mathcal{B}_{max}(e^s)$: maximum bandwidth of the link

- Goal: optimize the link utilization

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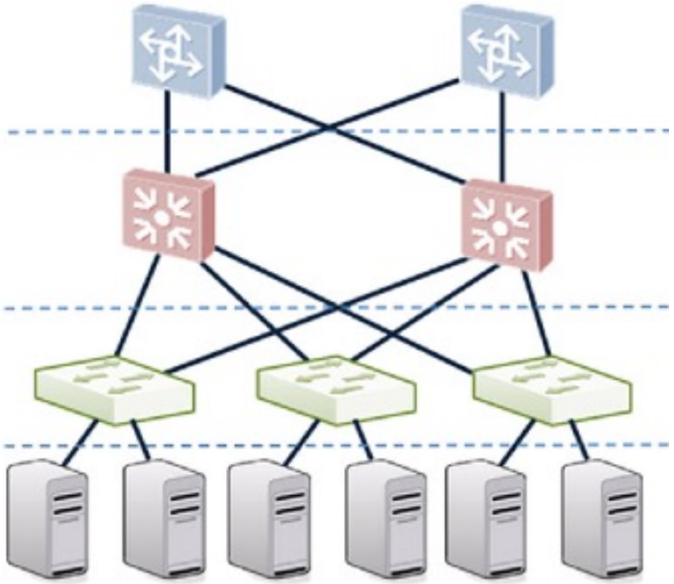
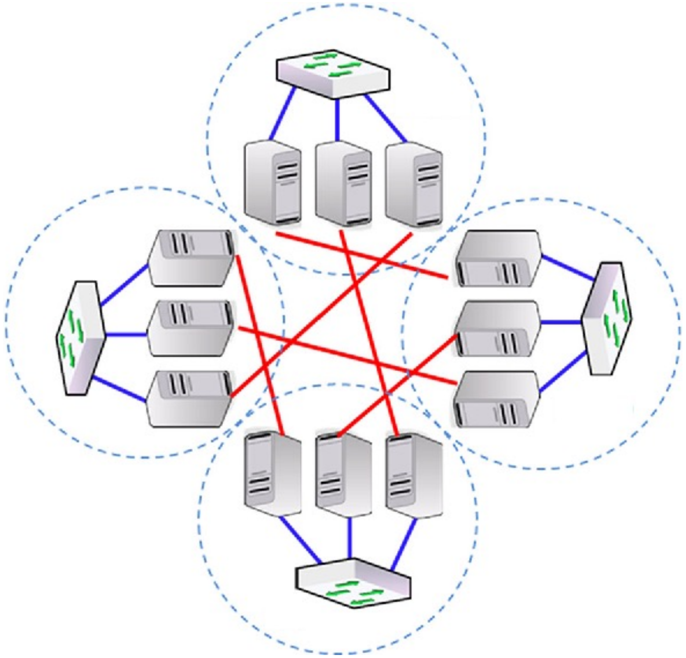
Data center topologies

- Classified based on the implementation of packet forwarding:

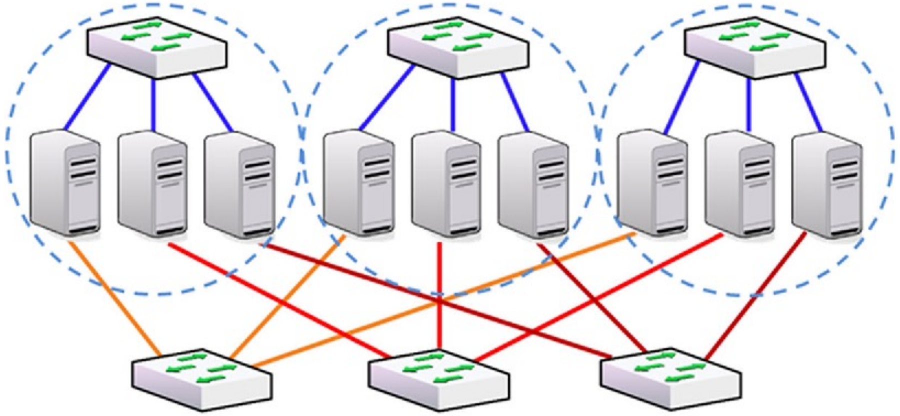
switch-centric



server-centric



hybrid



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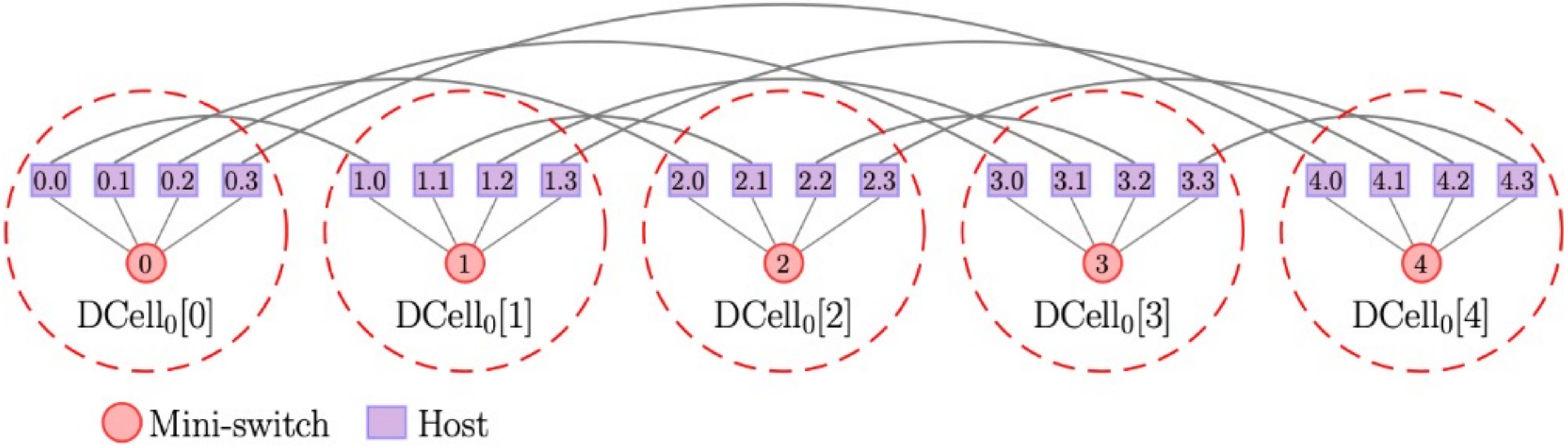
Data center network topologies

- Switch-Centric:
  - Fat-Tree
  - F^2Tree
  - Diamond
  - Spine-Leaf
  - Three-Tier
  - Collapsed Core

- Server-Centric:
  - BCube
  - DCell
  - FiConn
  - Crystal
- Hybrid:
  - Star-wired ring

Server-centric topologies: DCell



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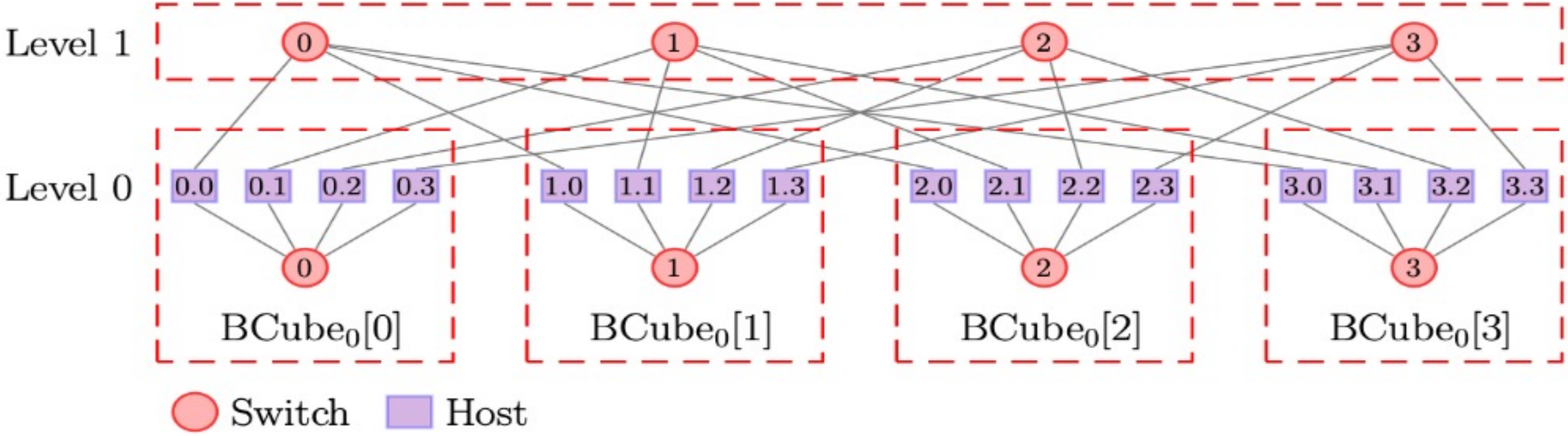
Server-centric topologies: BCube



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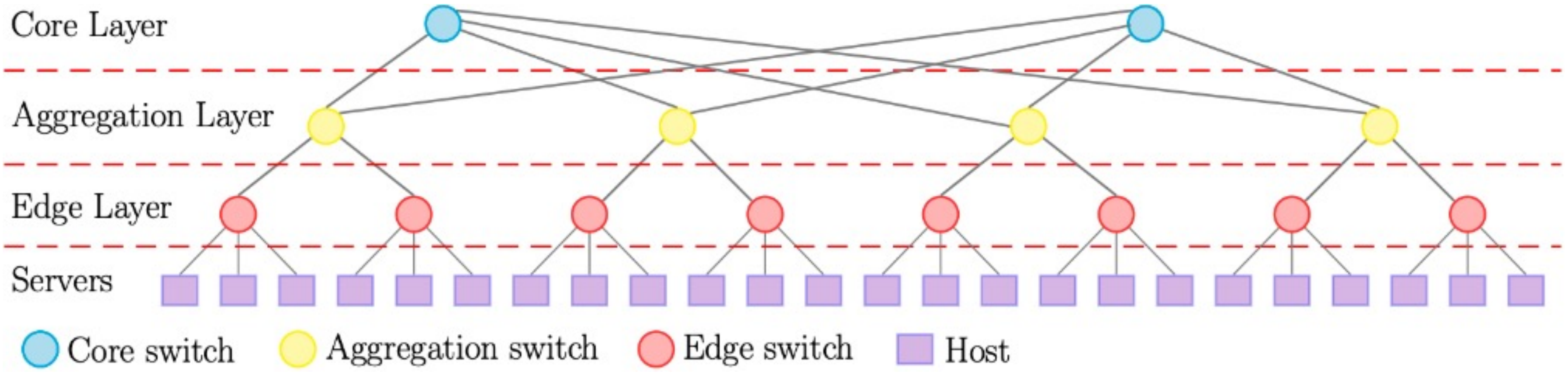
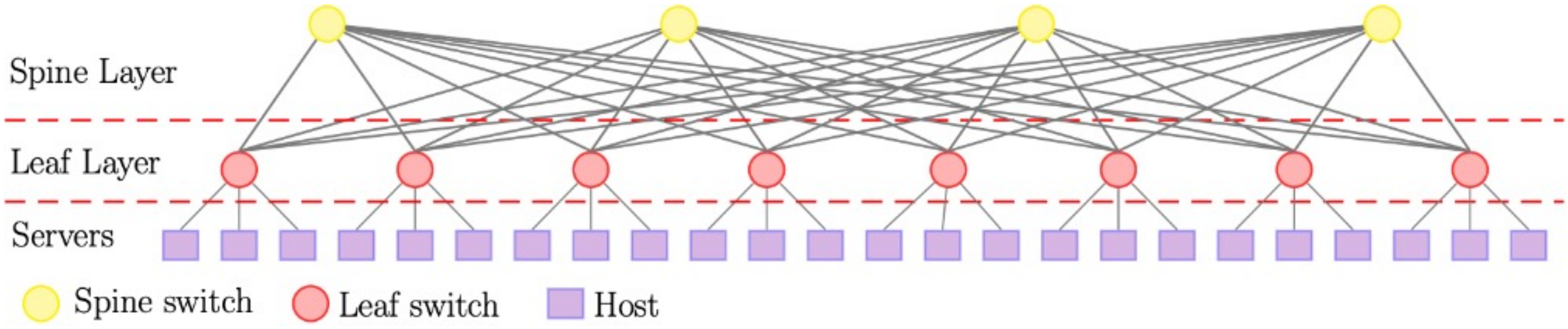
Switch-centric topologies: Three-Tier



N. Grozev and R. Buyya, “Multi-cloud provisioning and load distribution for three-tier applications,” *ACM Trans. Auton. Adapt. Syst.*, vol. 9, pp. 1–21, July 2014.

Switch-centric topologies: Spine-Leaf (Leaf-Spine)



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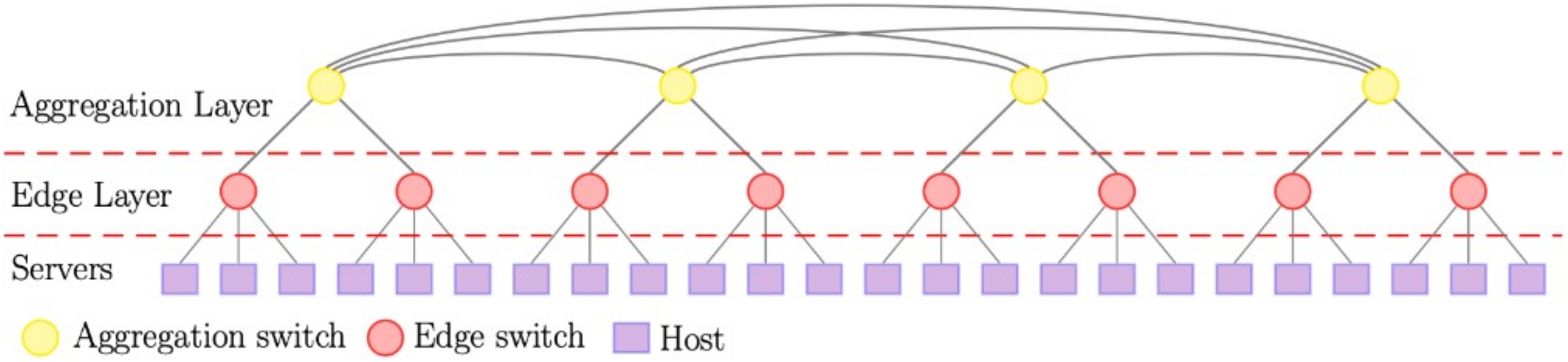
Switch-centric topologies: Collapsed Core



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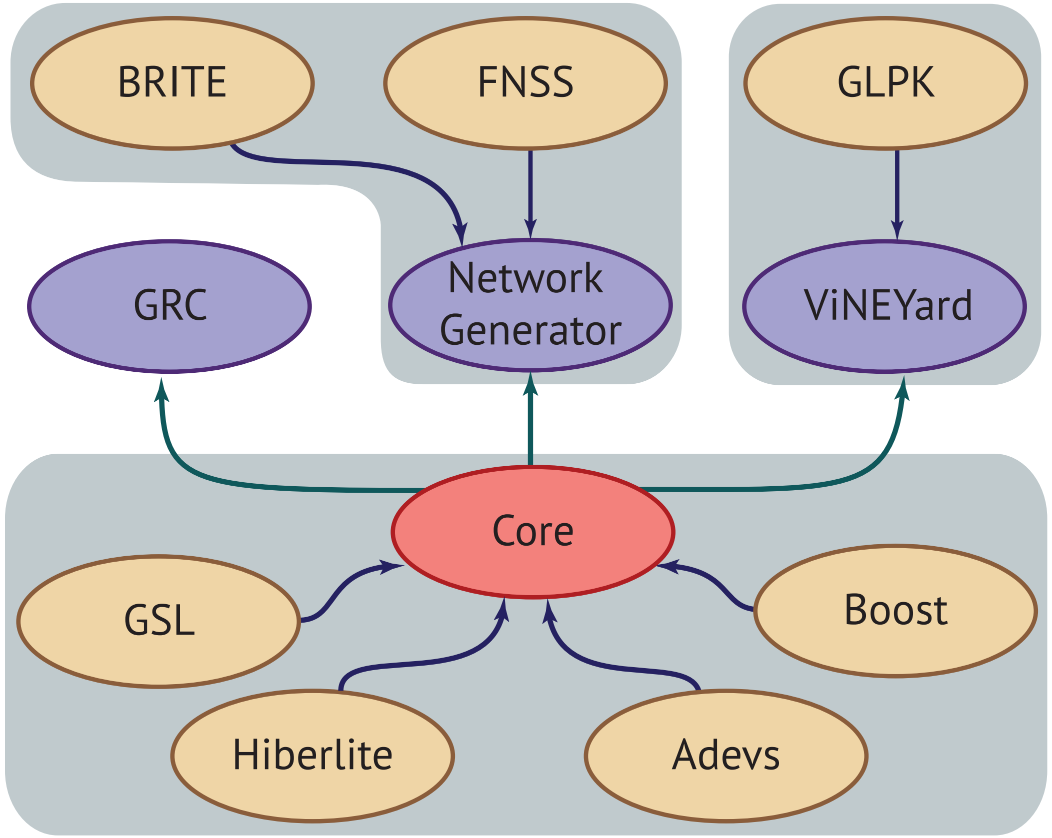
VNE-Sim: simulation platform



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https://bitbucket.org/shaeri/vne-sim

Elements of DCN topologies

DCN Topology	Servers (hosts)	Switches (layer/level k)	Links
DCell(1,4)	20	5 (DCell$_0$)	30
Bcube(2,4)	16	4 (BCube$_1$) 4 (BCube$_0$)	32
Three-Tier	90	3 (core) 6 (aggregation) 18 (edge)	126
Spine-Leaf	90	6 (spine) 18 (leaf)	198
Collapsed Core	90	6 (spine) 18 (leaf)	123

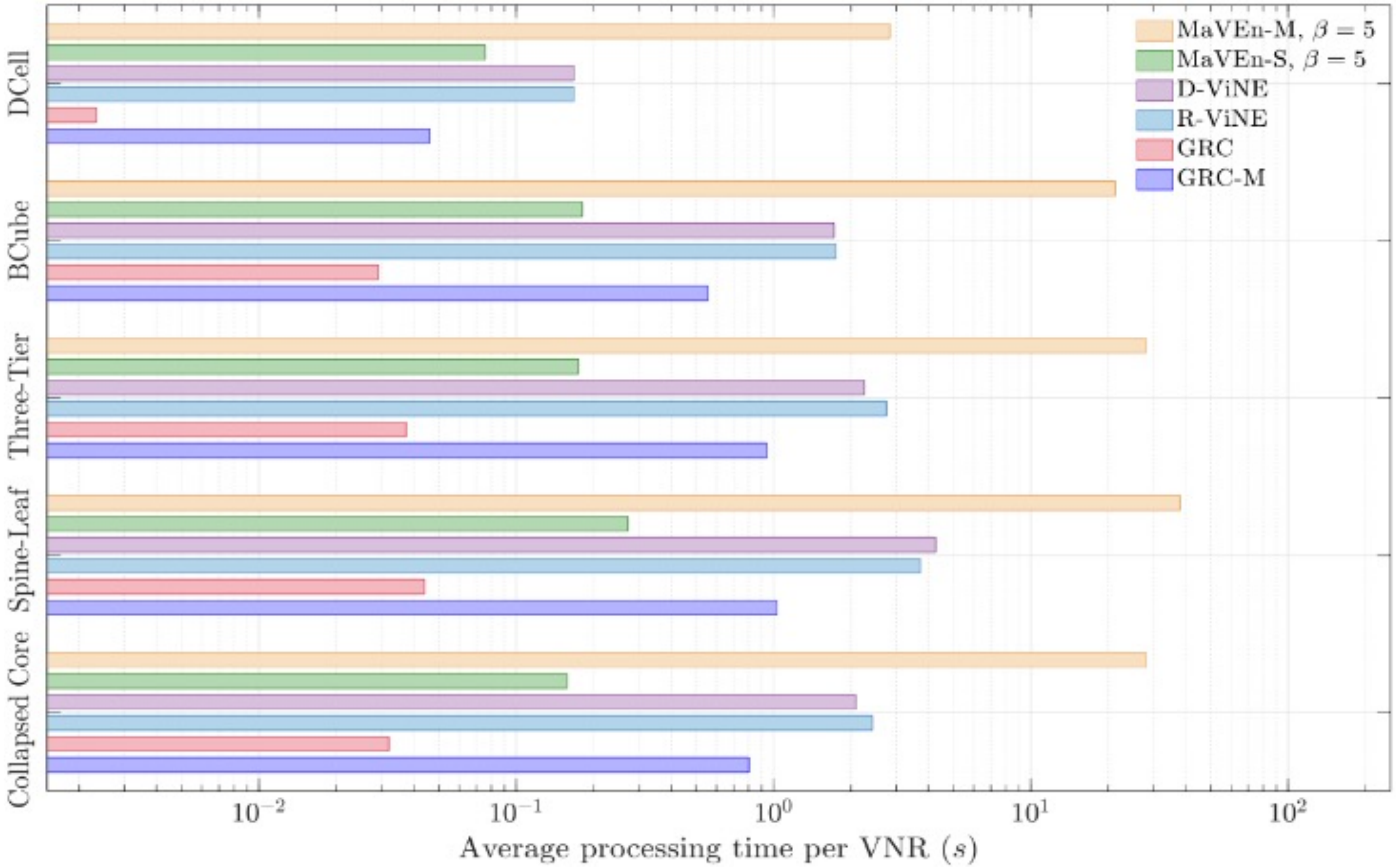
Parameters: substrate and virtual networks

Parameter	Value and Distribution
SN CPU capacity	100 units
SN link bandwidth	100 units
Virtual CPU requirement	Uniformly distributed between 2 and 20 units
Virtual link bandwidth requirement	Uniformly distributed between 1 and 10 units
Link splitting rate	0.1
VNRs arrival	Poisson distribution with mean arrival rate λ of requests per unit time
VNRs life-time	Exponentially distributed with a mean $(\mu = 1{,}000)$
VNRs traffic	$\lambda \times {}^{1}/_{\mu}$ Earlangs

Simulation parameters

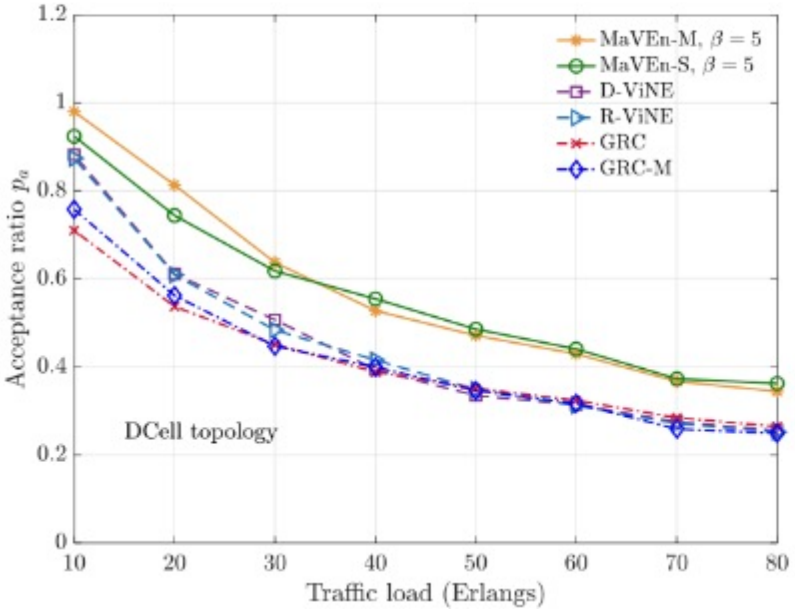
- Constant VNR arrival rate of 1 request per 100 time units:
    - traffic load of 10 Erlangs
- Duration of each scenario:
    - 50,000 time units
- Computational budget (number of simulations) $\beta = 5$:
    - number of evaluated action samples per selection cycle

Average processing time

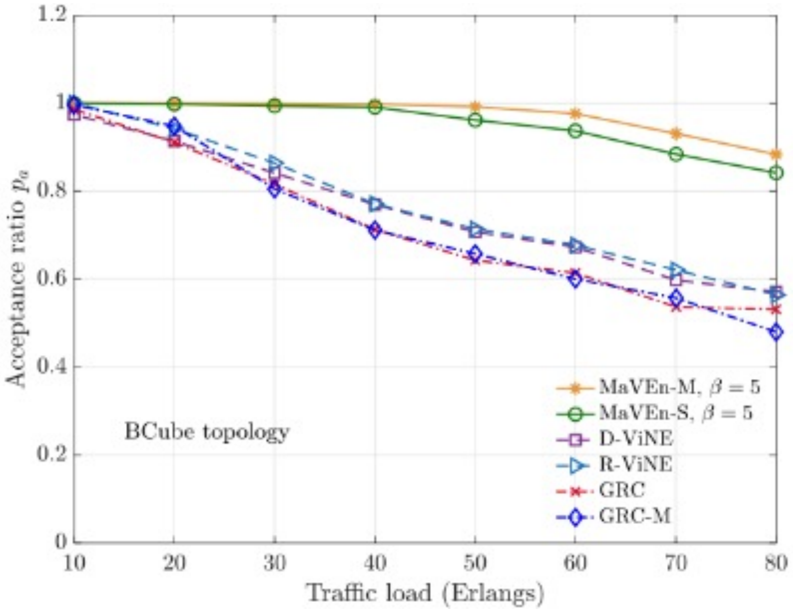


Acceptance ratio: server-centric topologies

DCell

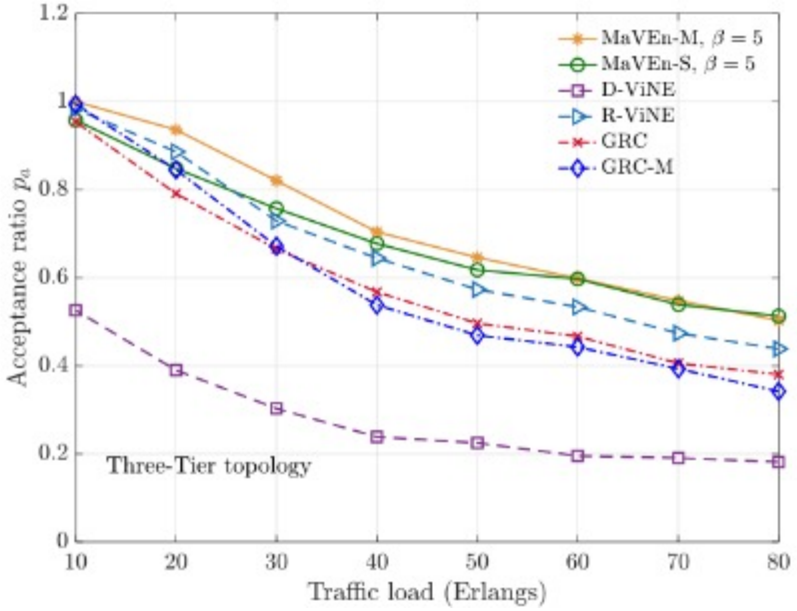


BCube

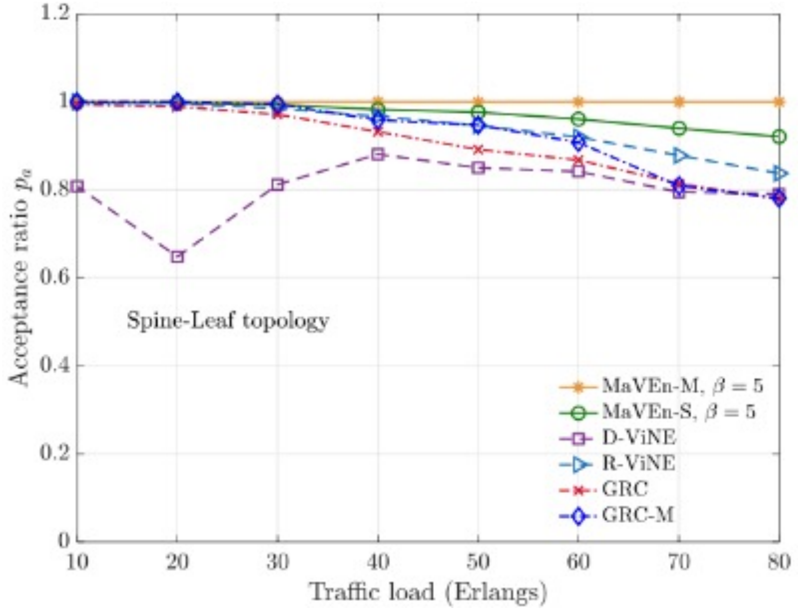


Acceptance ratio: switch-centric topologies

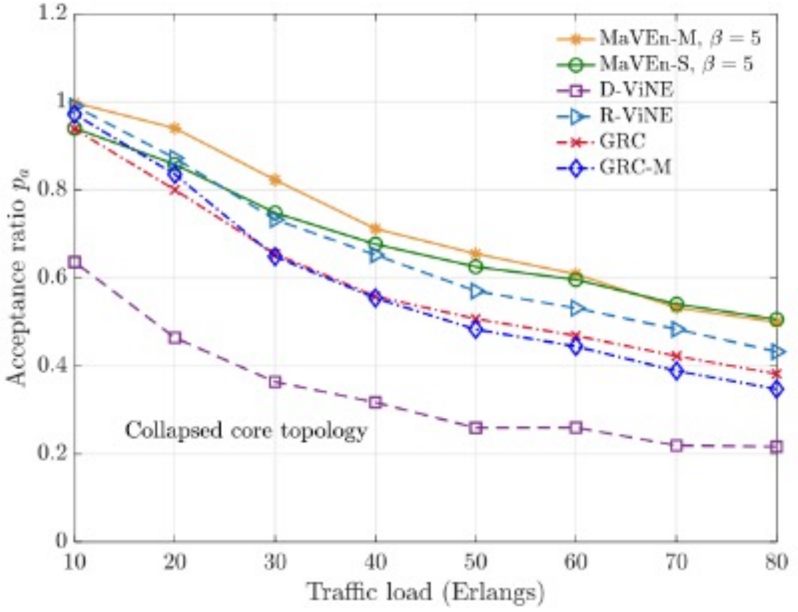
Three-Tier



Spine-Leaf

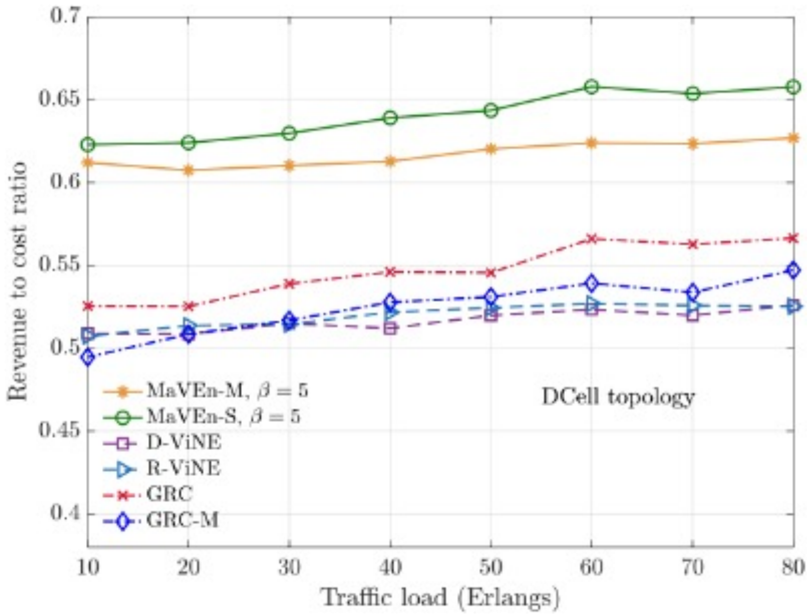


Collapsed Core

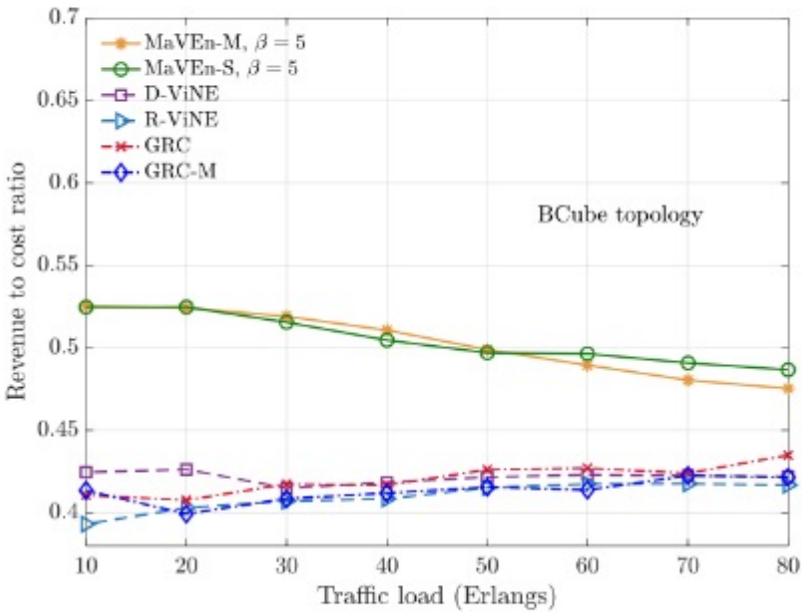


Revenue to cost ratio: server-centric topologies

DCell

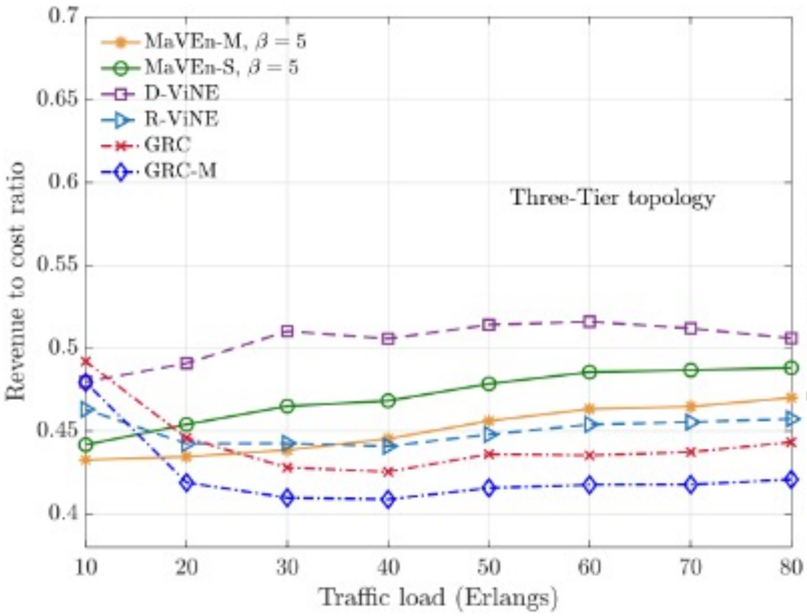


BCube

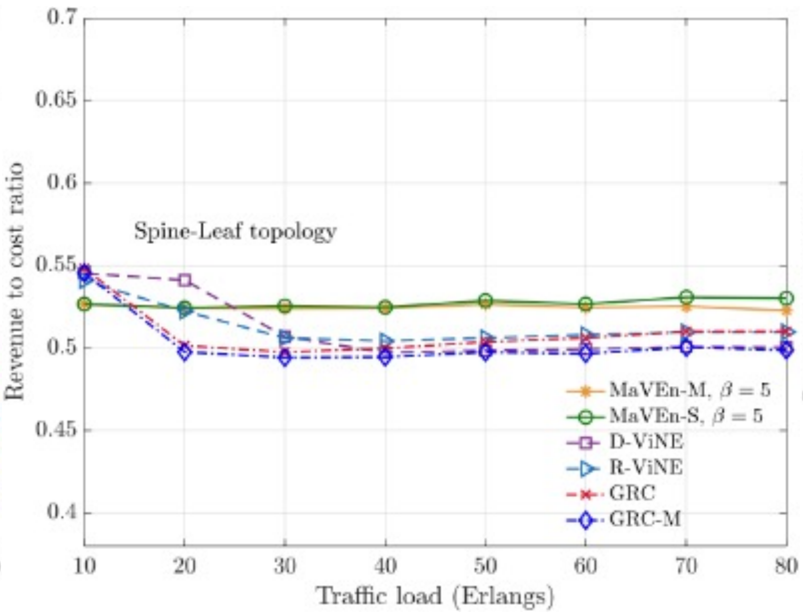


Revenue to cost ratio: switch-centric topologies

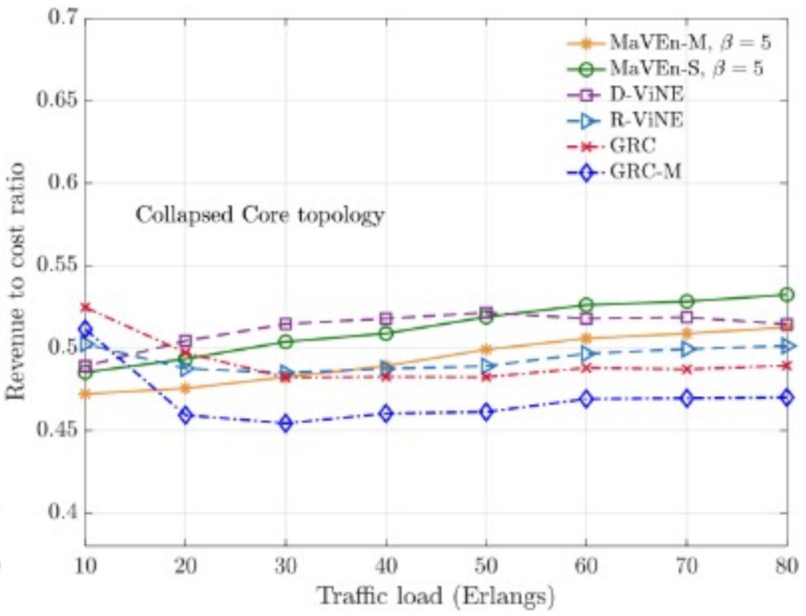
Three-Tier



Spine-Leaf

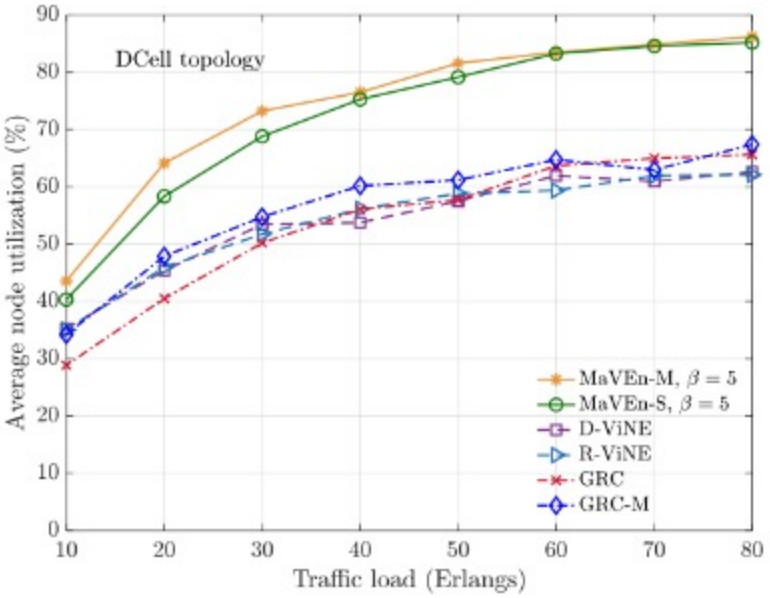


Collapsed Core

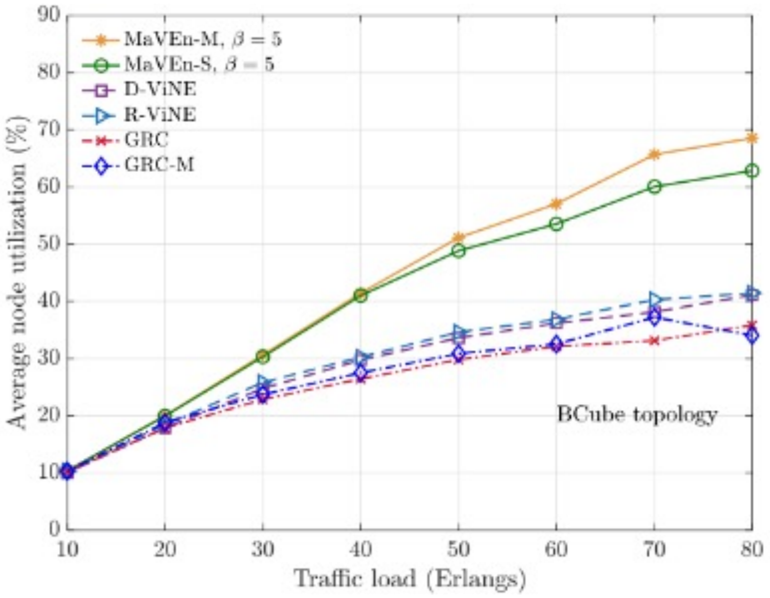


Average node utilization: server-centric topologies

DCell

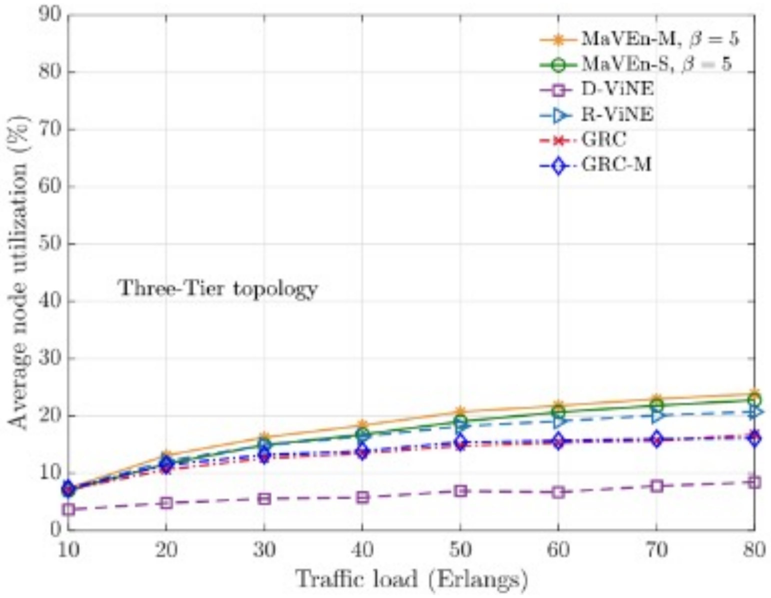


BCube

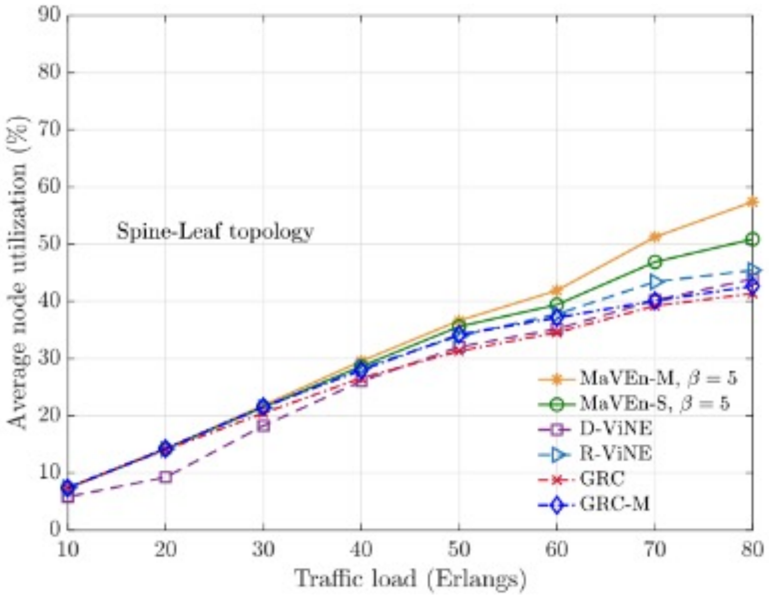


Average node utilization: switch-centric topologies

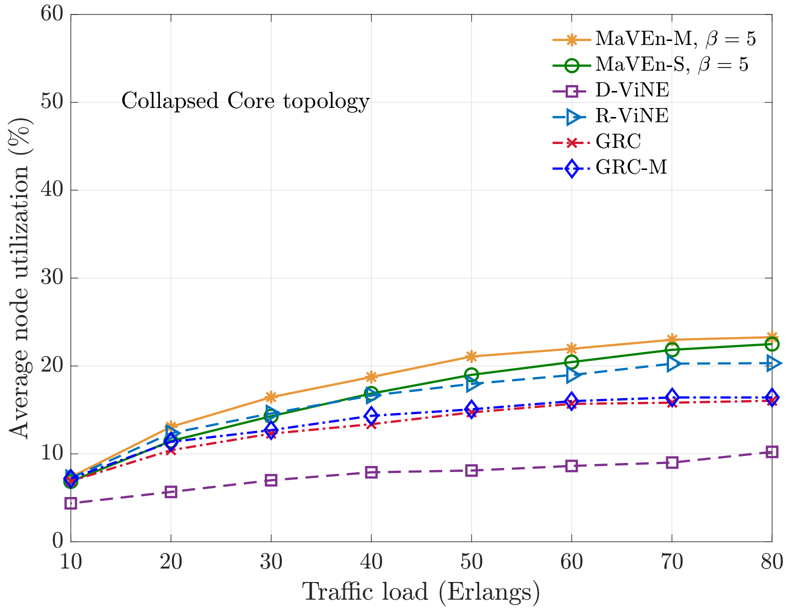
Three-Tier



Spine-Leaf

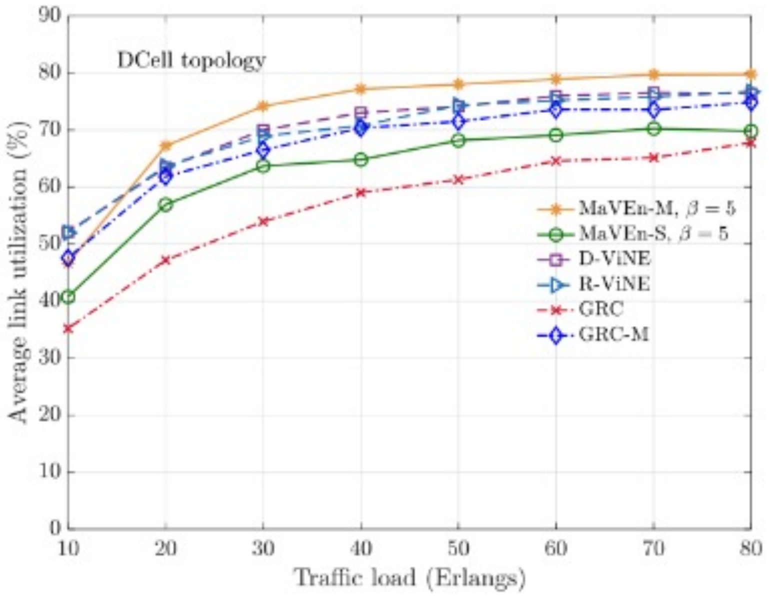


Collapsed Core

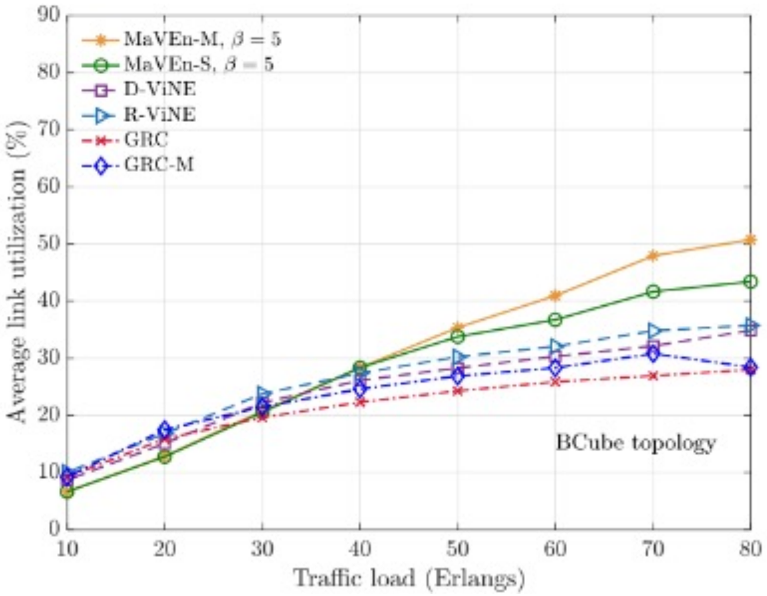


Average link utilization: server-centric topologies

DCell



BCube



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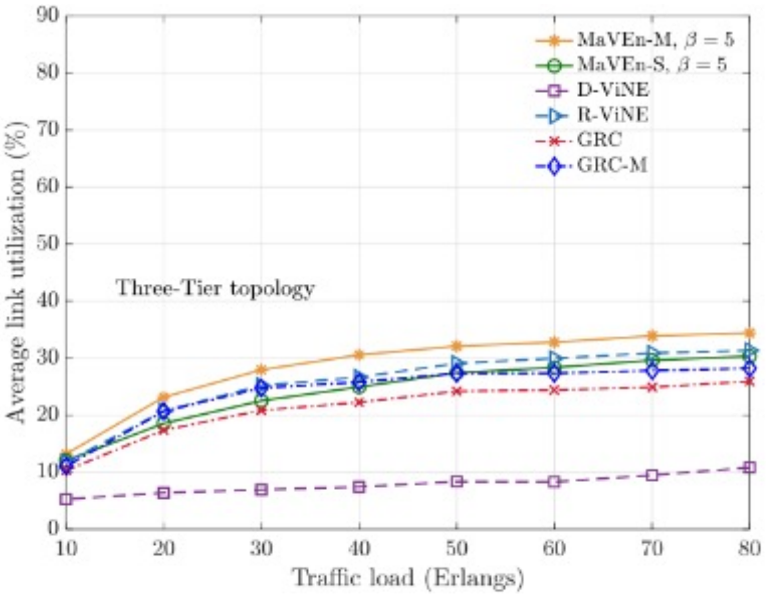
Three-Tier



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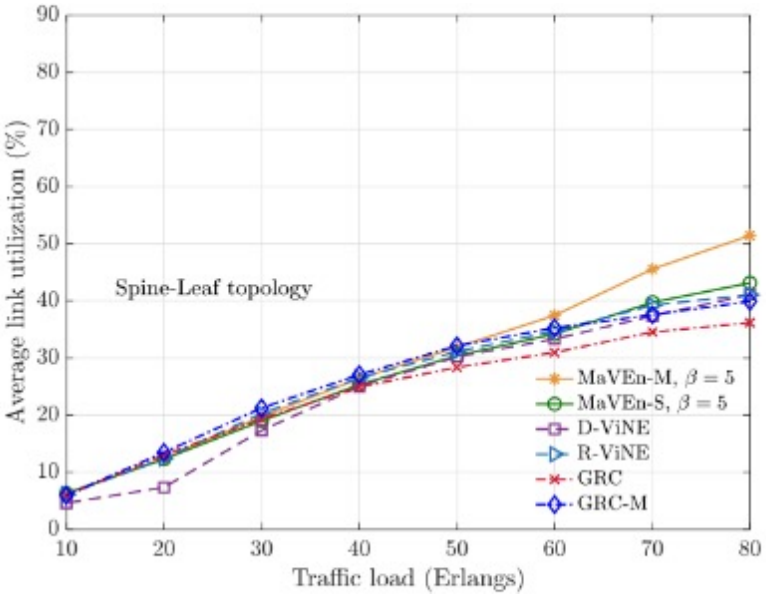
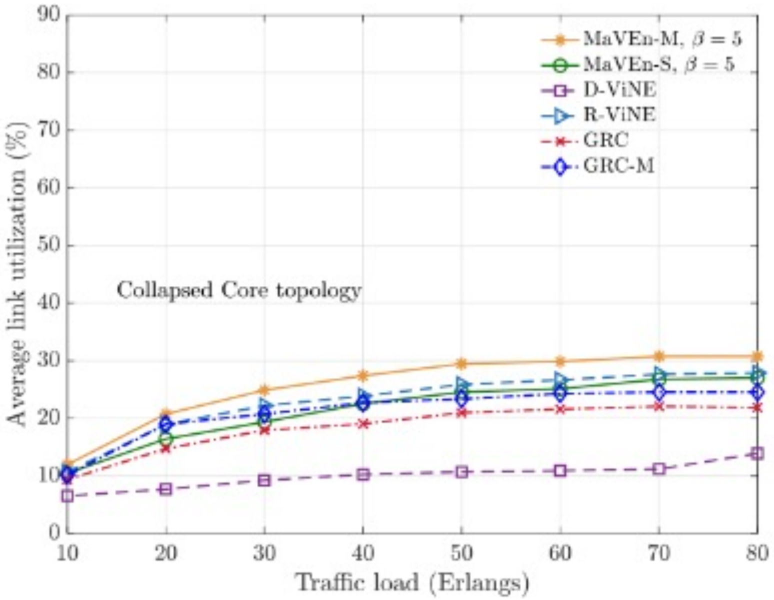


Collapsed Core



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Conclusion

- We evaluated performance of:
  - MaVEn-M, MaVEn-S, D-ViNE, R-ViNE, GRC, and GRC-M VNE algorithms
  - DCell, BCube Spine-Leaf, Three-Tier, and Collapsed Core, data center network topologies
- GRC algorithm required the shortest processing time
- In most cases, MaVEn-M and MaVEn-S outperformed other algorithms due to their optimized embeddings
- Comparable performance was achieved using DCell:
  - fewer network elements than other DCN topologies
  - recursive connections between hosts

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Data Center Networks:

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Virtual Network Embedding Algorithms:

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