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Load-Optimization in Reconfigurable Networks: Algorithms and Complexity of Flow Routing

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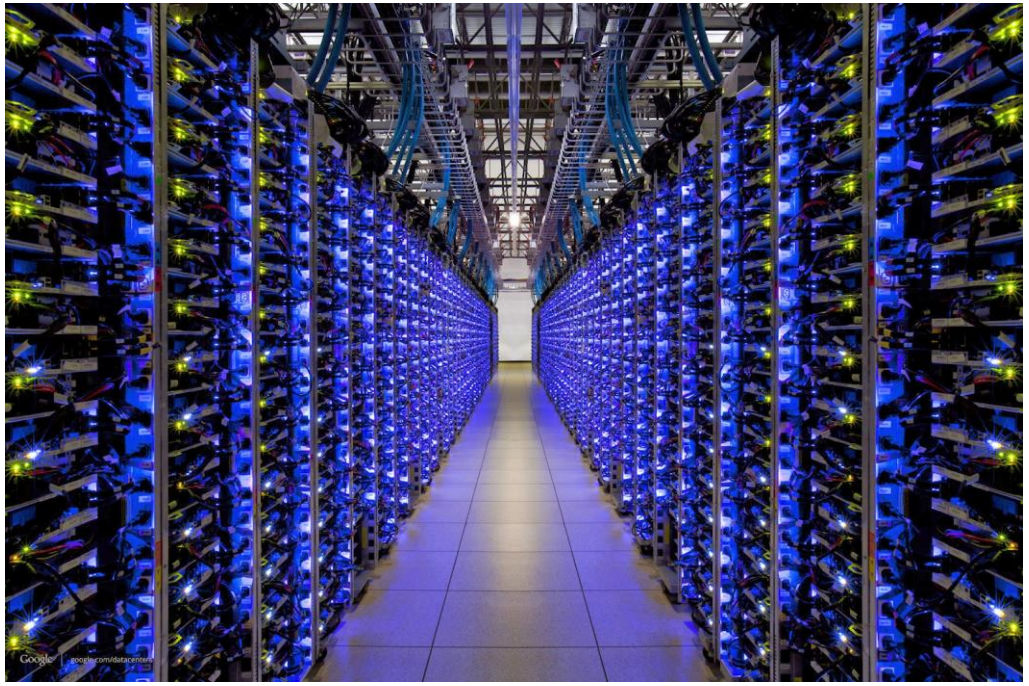
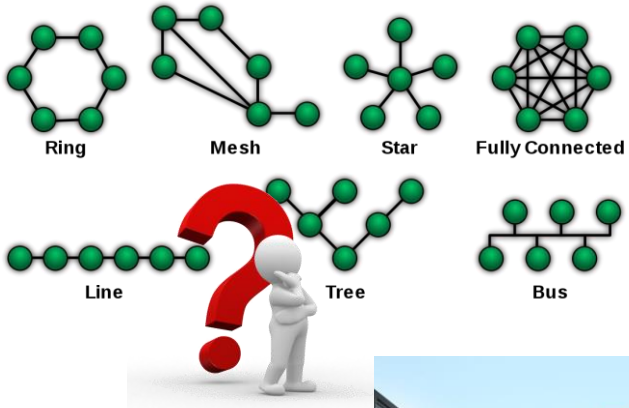
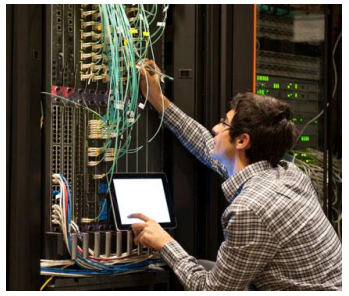
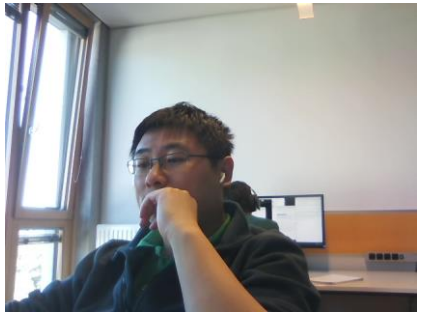
Motivation: Interconnecting Top of Rack in Datacenter



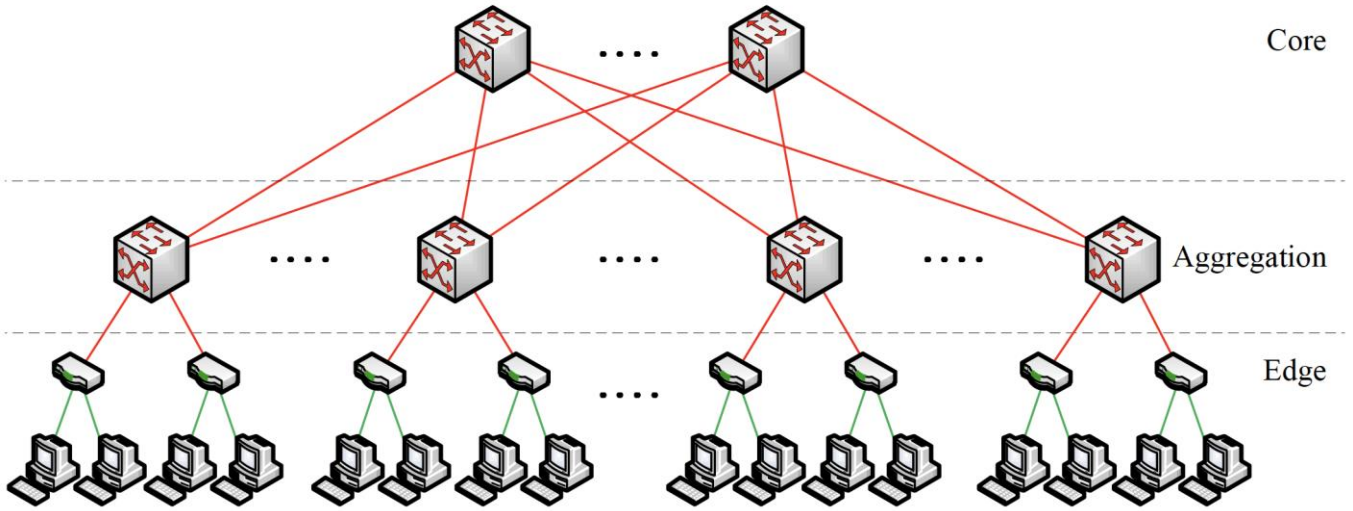






Fat-Tree (Clos) Topology for Data Centers

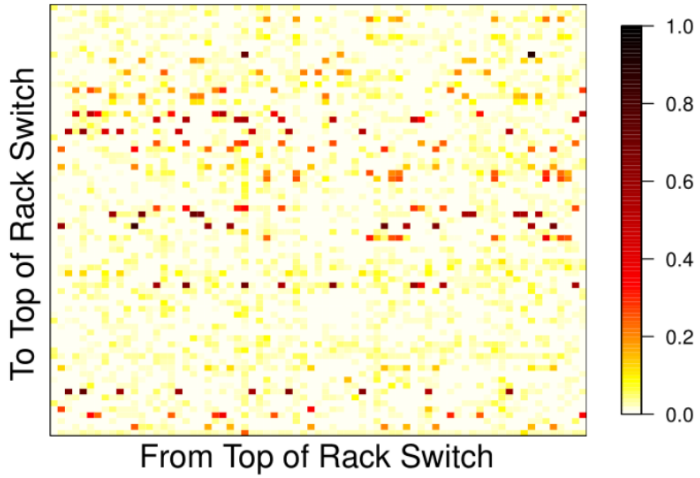
- Fat-Tree is good for all-to-all traffic



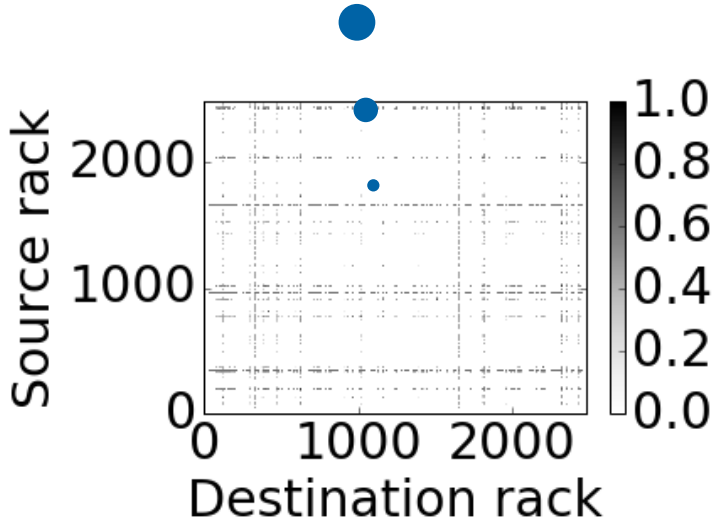
Data Center Traffic ≠ Uniform

- However, DCN traffic is often ***not*** all-to-all

"Data reveal that 46-99% of the rack pairs exchange no traffic at all"



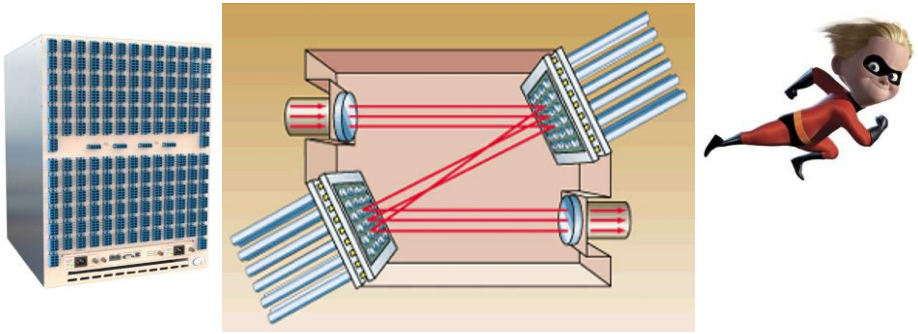
Traffic demands (normalized) between ToR switches. Halperin et al., SIGCOMM'11



Heatmap of rack to rack traffic. Color intensity is log-scale and normalized. Ghobadi et al., SIGCOMM'16

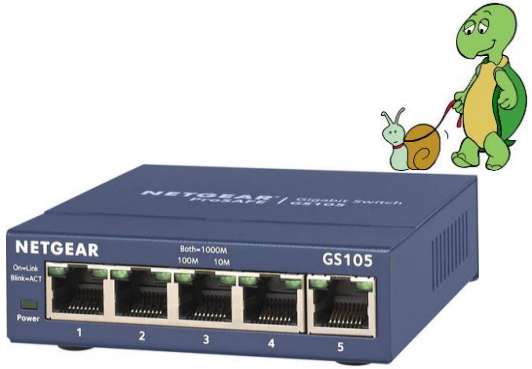
Circuit Switches vs Packet Switches

1. Circuit Switches: usually *optical*
   - Fast (high bandwidth)
   - Connection between ports can be adjusted dynamically



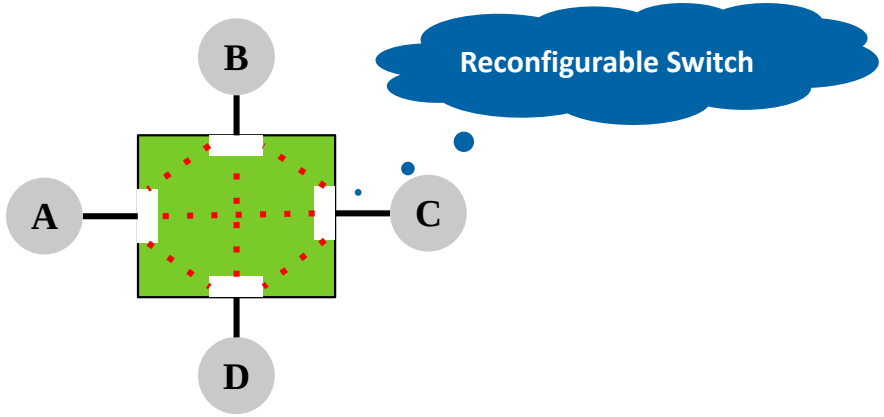
https://www.laserfocusworld.com/optics/article/16556781/many-approaches-taken-for-alloptical-switching (Hecht, 2001)

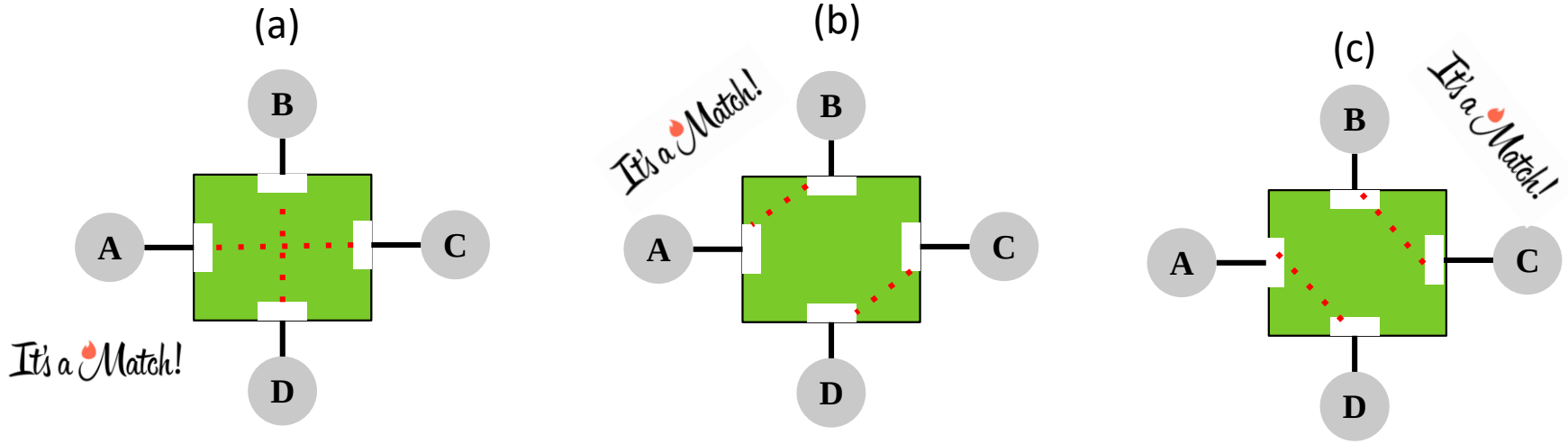
2. Packet Switches: usually electronic
   - Low bandwidth
   - The connections of links are fixed after deployment



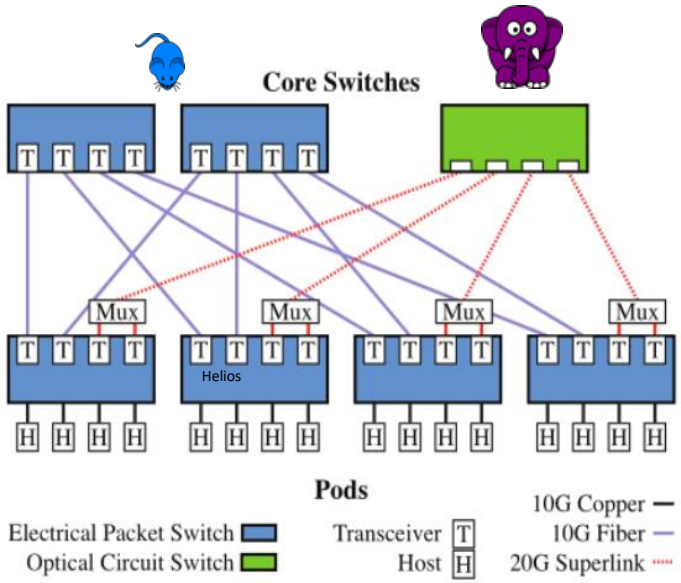
Understand Circuit Switches Physical layer: It‘s a Match(ing)!

- Idea: implement “physical” connections
  - Difference: Not all-to-all switch
    - E.g. just 1 connection per node
- A matching is selected to connect nodes

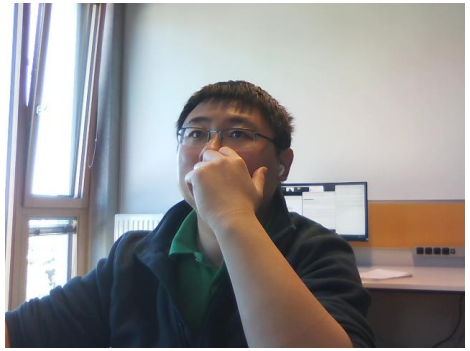




Hybrid Architecture for Datacenter (Helios, Farrington et al., SIGCOMM '10)



- Adjust the topology **dynamically** for variant demands:
  - Elephant (big) flows → Circuit Switches
  - Mice (small) flows → Packet Switches



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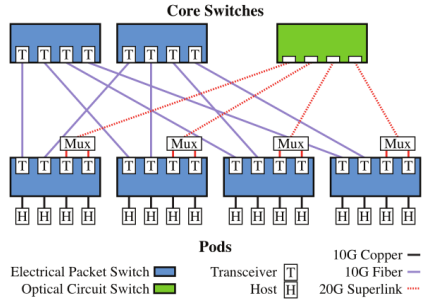
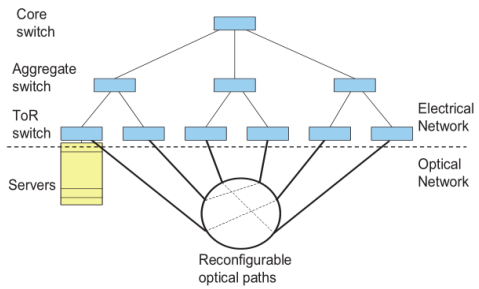
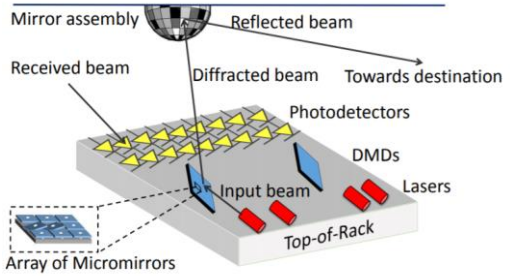
Reconfigurable Data Center Networks (DCNs)



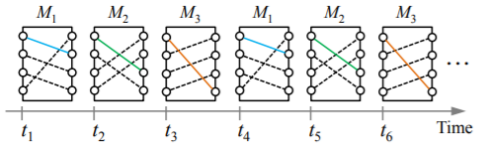
Helios (core)
Farrington *et al.,* SIGCOMM '10



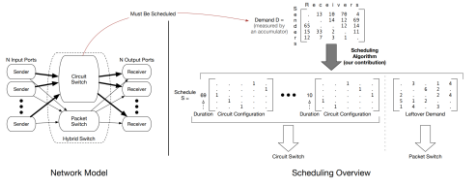
c-Through (*HyPaC* architecture)
Wang *et al.,* SIGCOMM '10



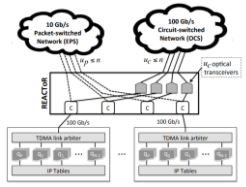
ProjecToR interconnect
Ghobadi *et al.,* SIGCOMM '16



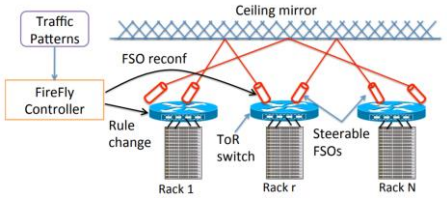
Rotornet (rotor switches)
Mellette *et al.,* SIGCOMM '17



Solstice (architecture & scheduling)
Liu *et al.,* CoNEXT '15



REACToR
Liu *et al.,* NSDI '15



FireFly
Hamedazimi *et al., SIGCOMM* '14

… and many more …

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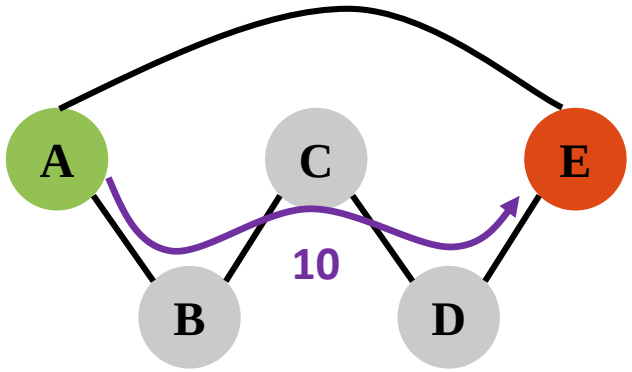
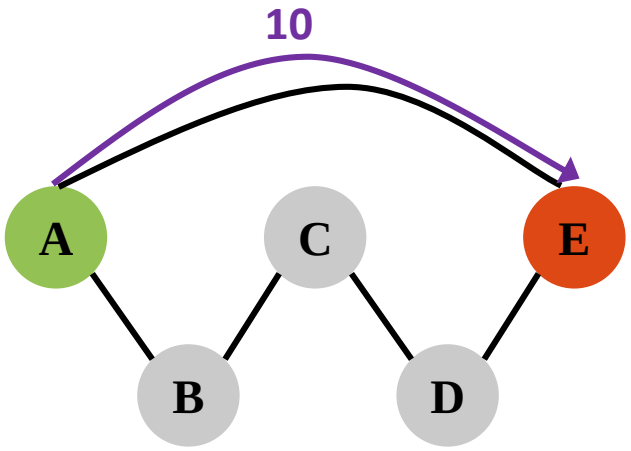
Routing Models: Unsplittable vs Splittable

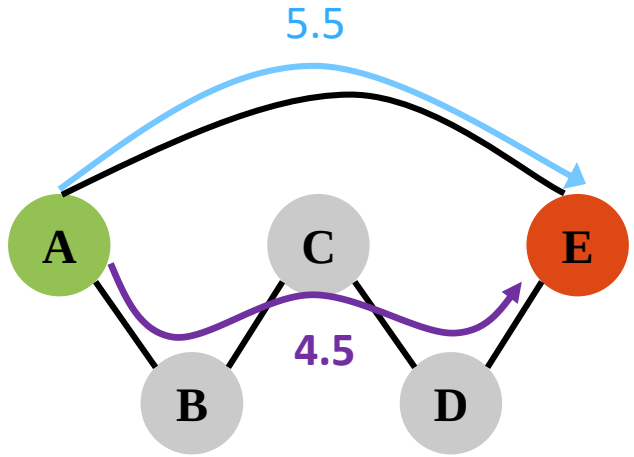
- For each demand, e.g., **A→E: 10**



Unsplittable



Unsplittable



Splittable

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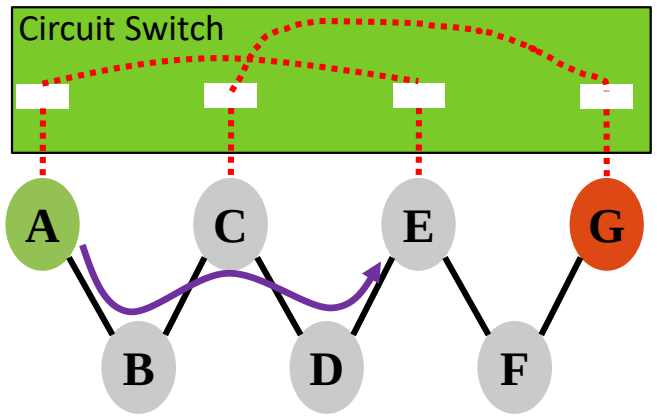
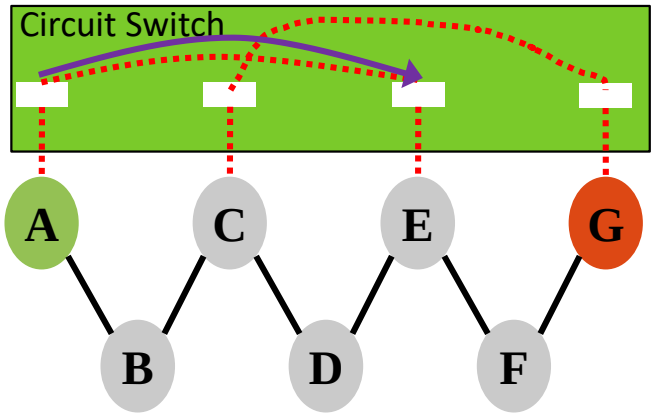
Routing Models: Segregated vs Nonsegregated

- In a reconfigurable datacenter, for each demand:

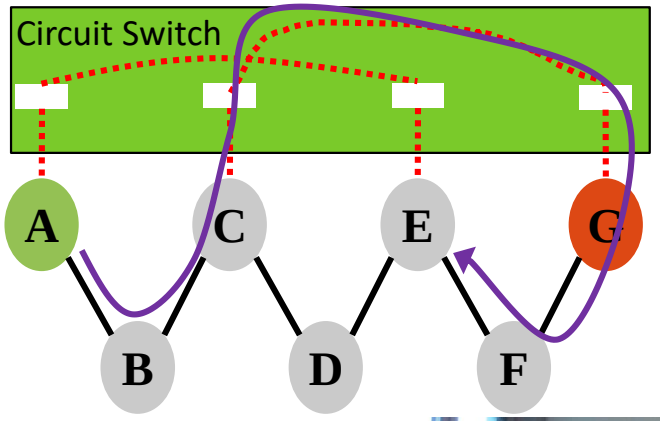
  E.g., demand: **A→E**



Segregated



Segregated



Nonsegre

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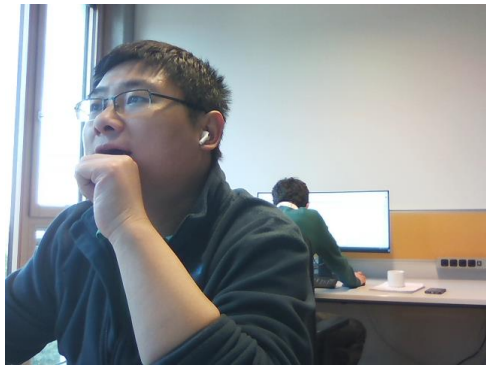


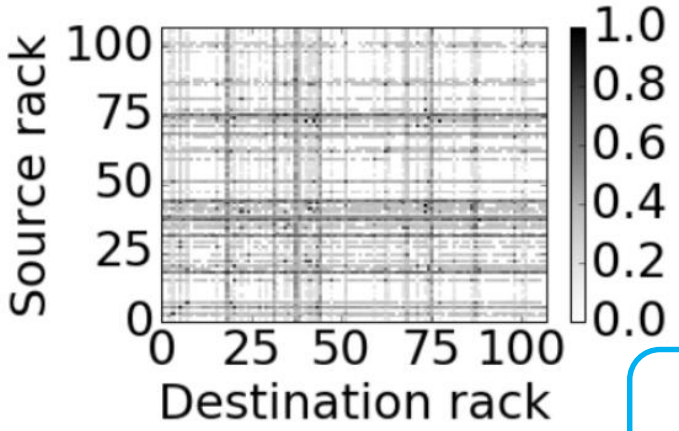
Four Routing Models in Reconfigurable Networks

Routing Models	Segregation Model	Nonsegregation Model
Splittable Model	SS	SN
Unsplittable Model	US	UN

Load-Optimization Reconfiguration Problem (Our Problem)

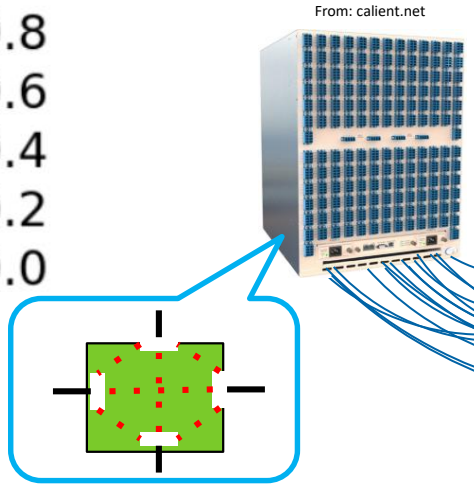
- Given: A routing model $\tau \in \{SS, SN, US, UN\}$

Routing Models	Segregation Model	Nonsegregation Model
Splittable Flow	SS	SN
Unsplittable Flow	US	UN

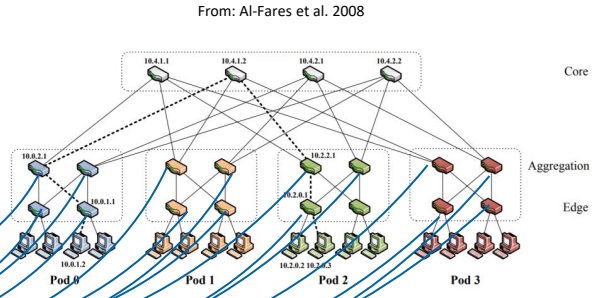


Demands Matrix D

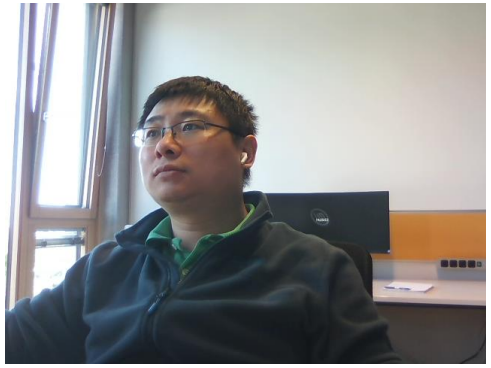
Circuit Switches



Static Network $\mathrm{N} = (V, E, C)$



Set of reconfigurable links $\mathcal{E}$

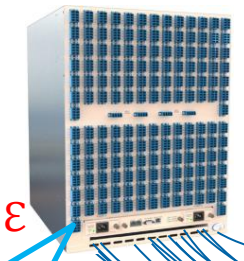


Load-Optimization Reconfiguration Problem (Our Problem)

- Compute: a matching from reconfigurable links; and optimal routing schemes for demands

Circuit Switches

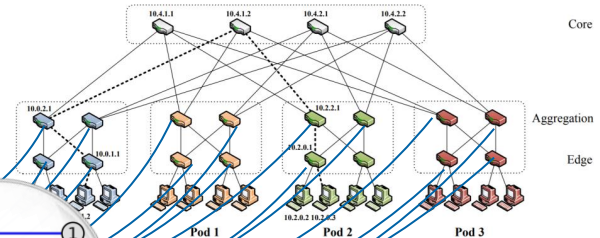
From: calient.net



Matching $M \subset \mathcal{E}$

Static Network $\mathrm{N} = (V, E, C)$

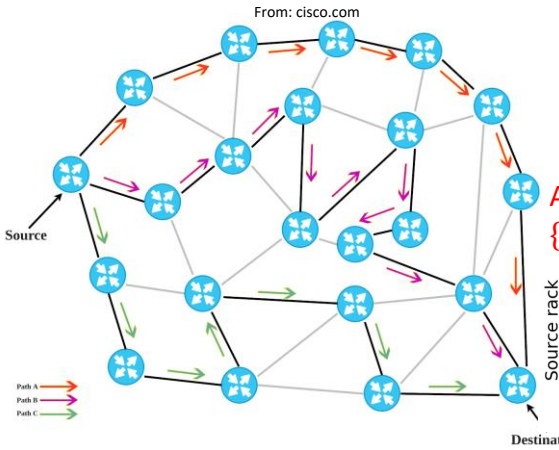
From: Al-Fares et al. 2008



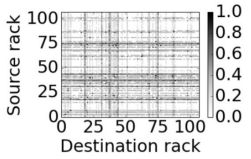
Set of reconfigurable links $\mathcal{E}$

+

From: cisco.com

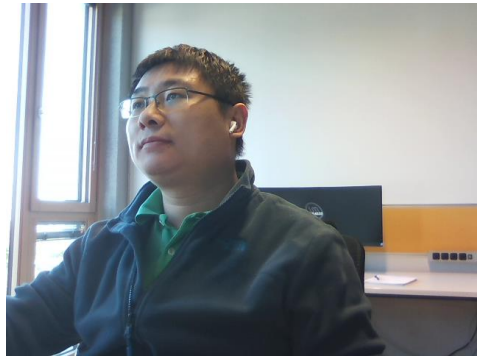


A routing model $\tau \in \{SS, SN, US, UN\}$

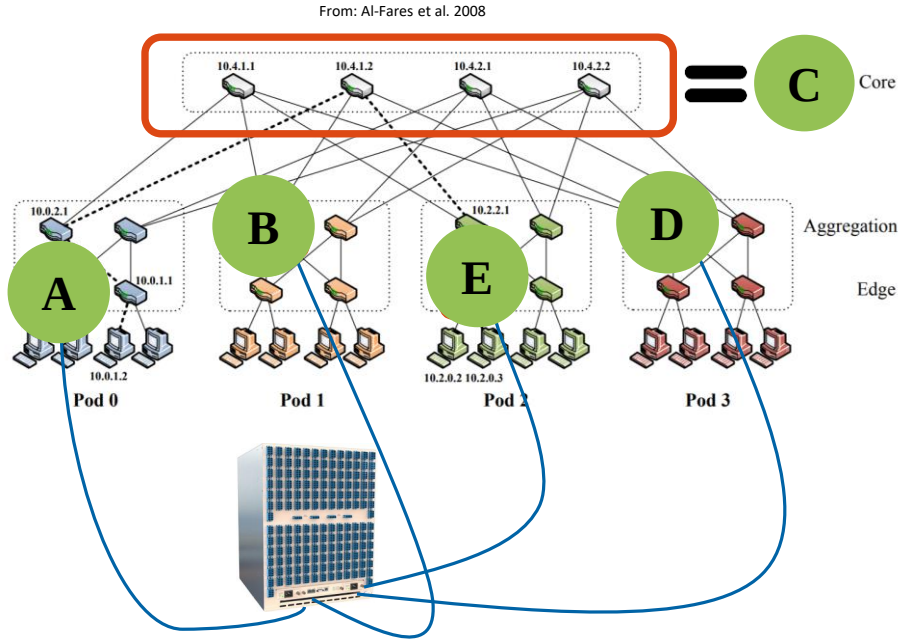


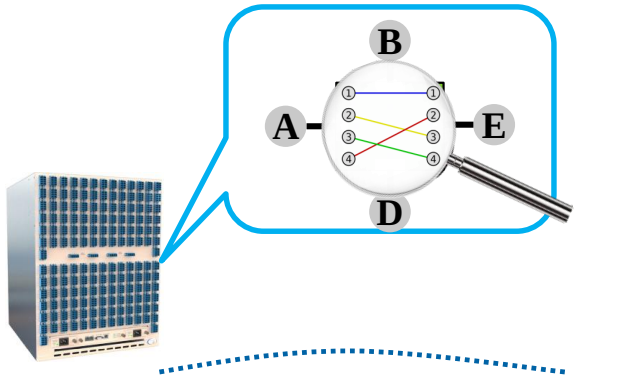
Optimal routing schemes for demands in the hybrid network $(V, E \cup M, C)$

- Objective: minimize the maximum link load in the hybrid network $(V, E \cup M, C)$

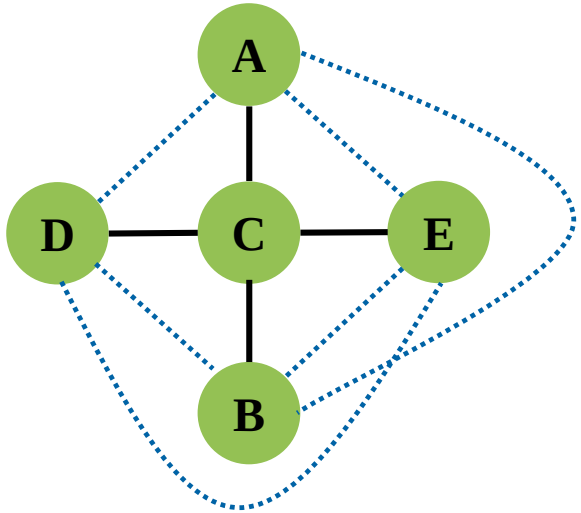


An Example For Load-Optimization Reconfiguration Problem





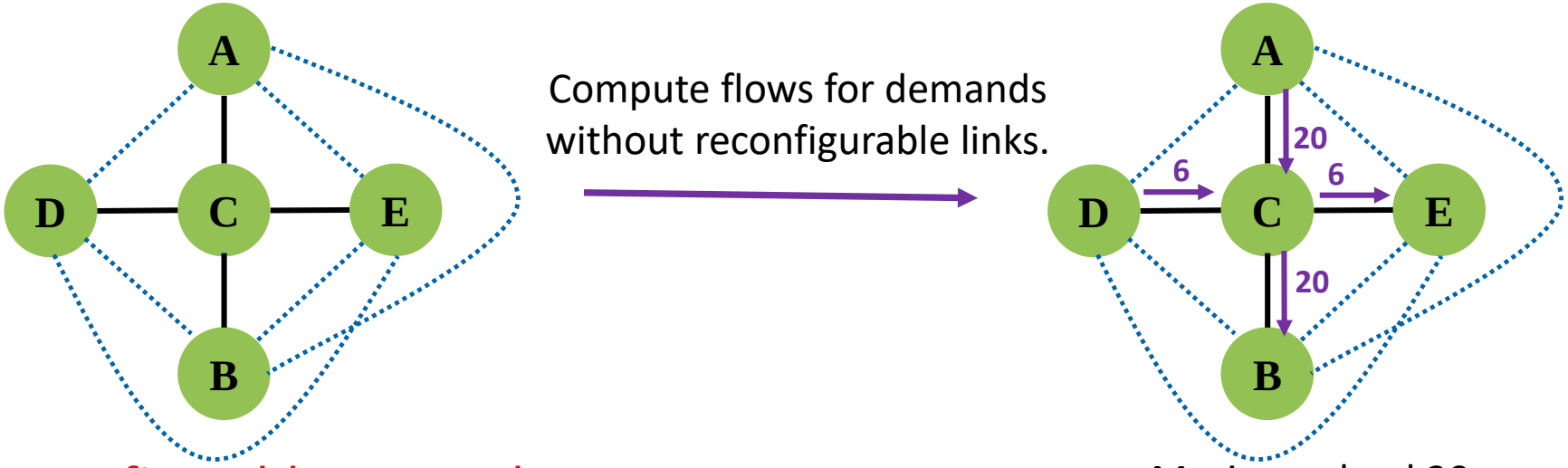
Reconfigurable links



Reconfigurable network

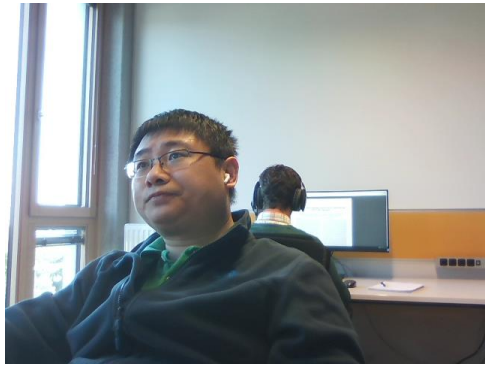
Example: Loads Depend on Reconfigurations

- Consider demands D: **A→B: 8, A→C: 6, C→B: 6, D→B: 6, A→E: 6**
- Goal: determine a matching in reconfigurable links to minimize the maximum load



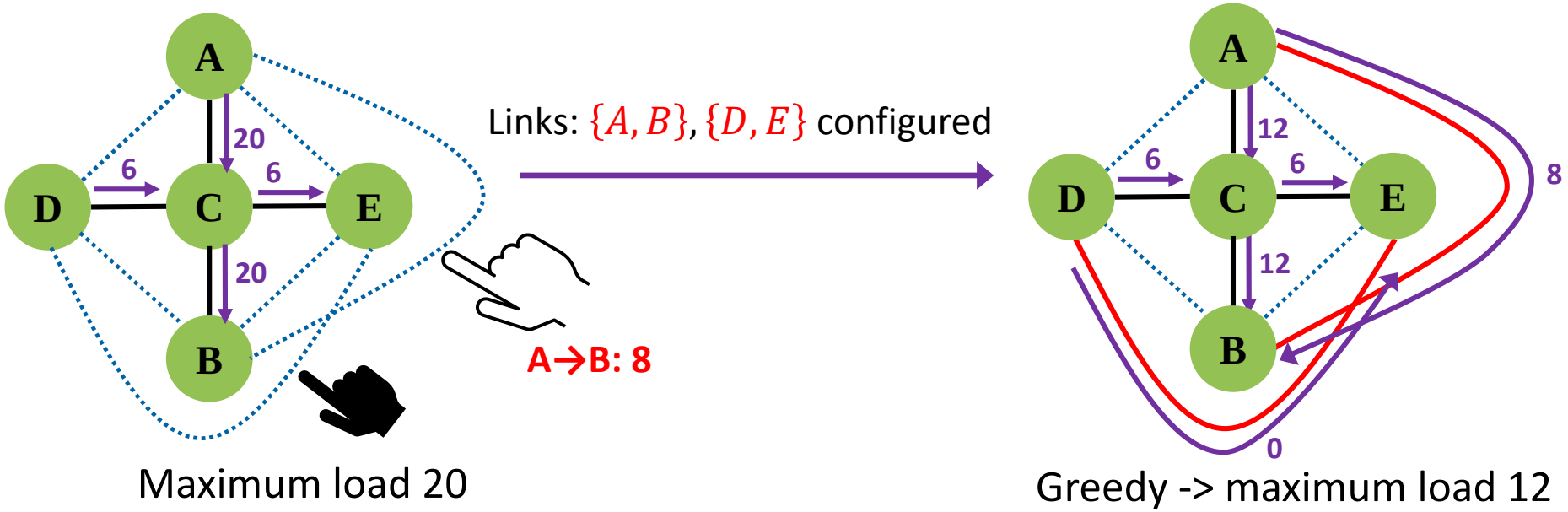
Reconfigurable network

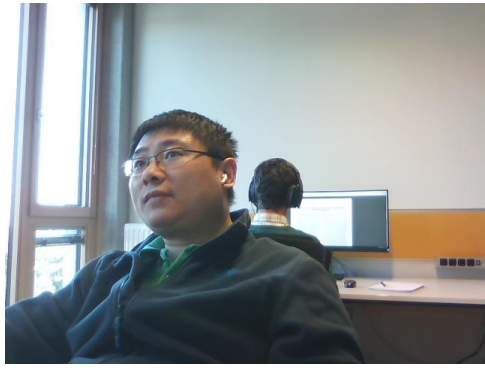
Maximum load 20



Example: Determine Matching by Greedy

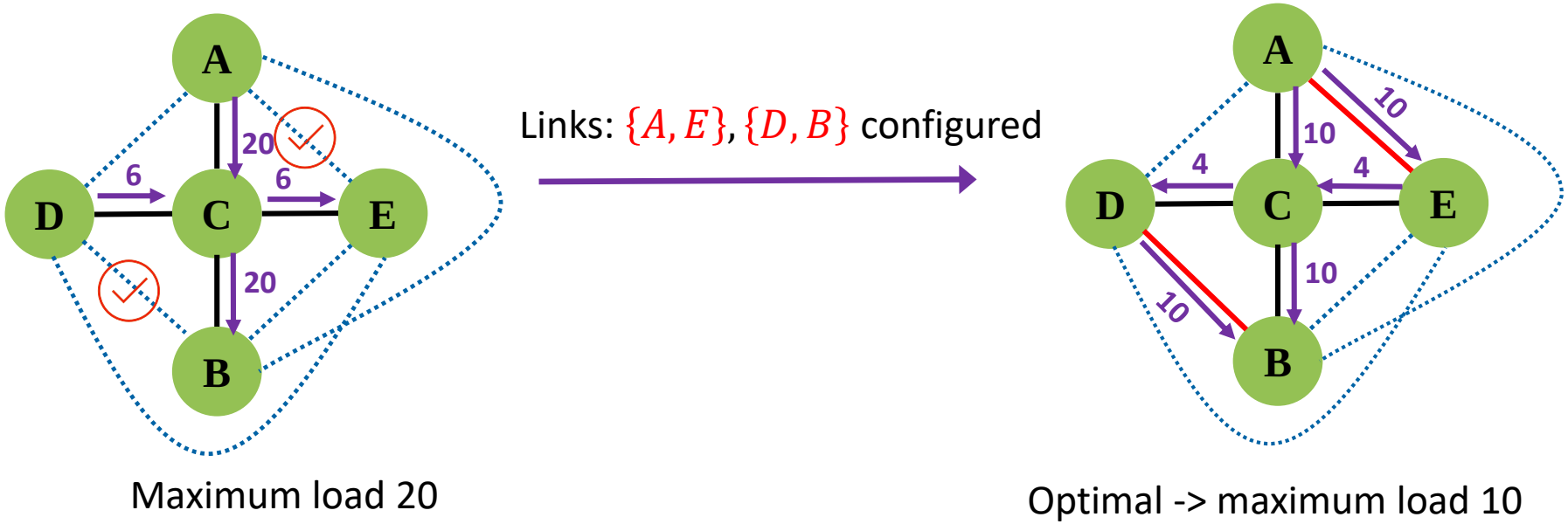
- *Demands D*: **A→B: 8, A→C: 6, C→B: 6, D→B: 6, A→E: 6**
  - Greedy chooses $\{A, B\}$ to serve **A→B**, then the matching is $\{A, B\}$ and $\{D, E\}$





Example: Optimal Matching

- *Demands D*: **A→B: 8, A→C: 6, C→B: 6, D→B: 6, A→E: 6**
  - The optimal matching is $\{D, B\}$ and $\{A, E\}$



Maximum load 20

Optimal -> maximum load 10

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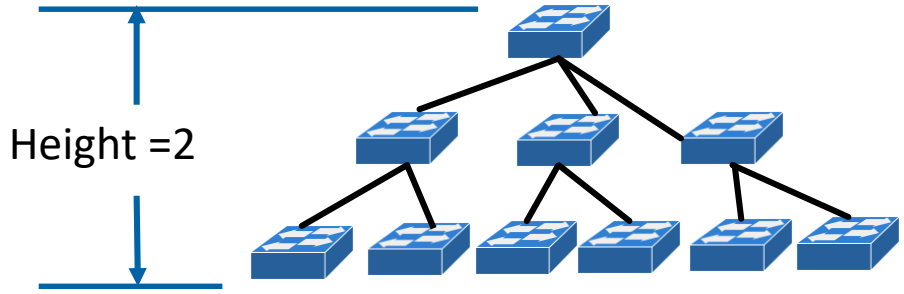
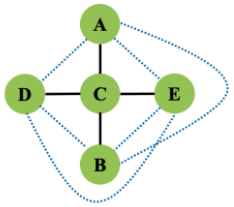
Complexity for Simple Trees



- If the given static network is a tree with a height >=2, then

Time Complexity	Segregation Model	Nonsegregation Model
Splittable Model	SS is strongly NP-hard	SN is strongly NP-hard
Unsplittable Model	US is strongly NP-hard	UN is strongly NP-hard

  - Reduction from 3-Partition problem
- Especially, UN model is weakly NP-hard for star networks
  - Reduction from 2-Partition problem
  - Not hard anymore for small demands



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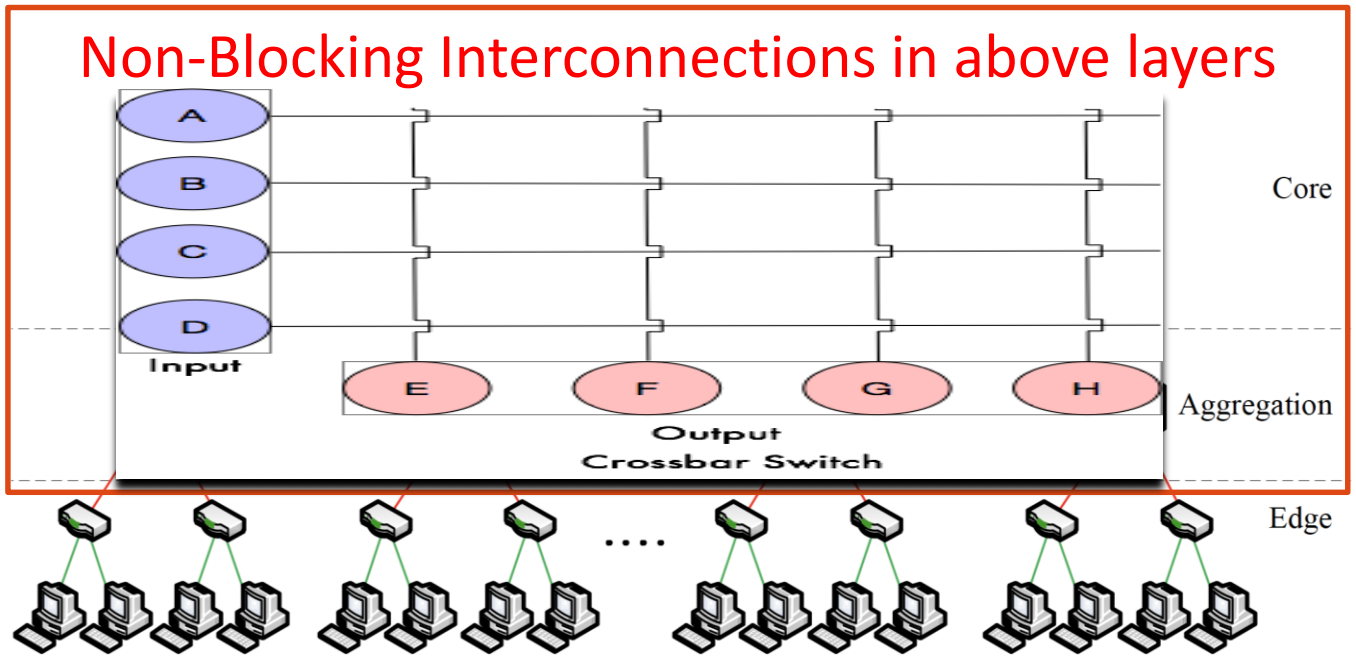
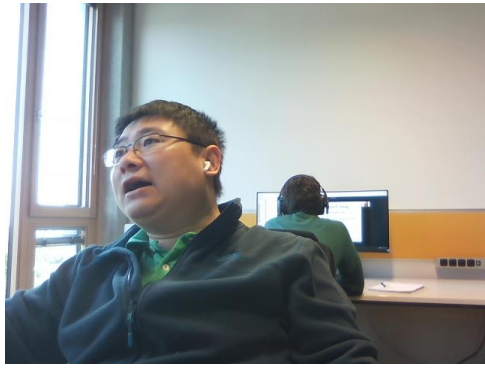
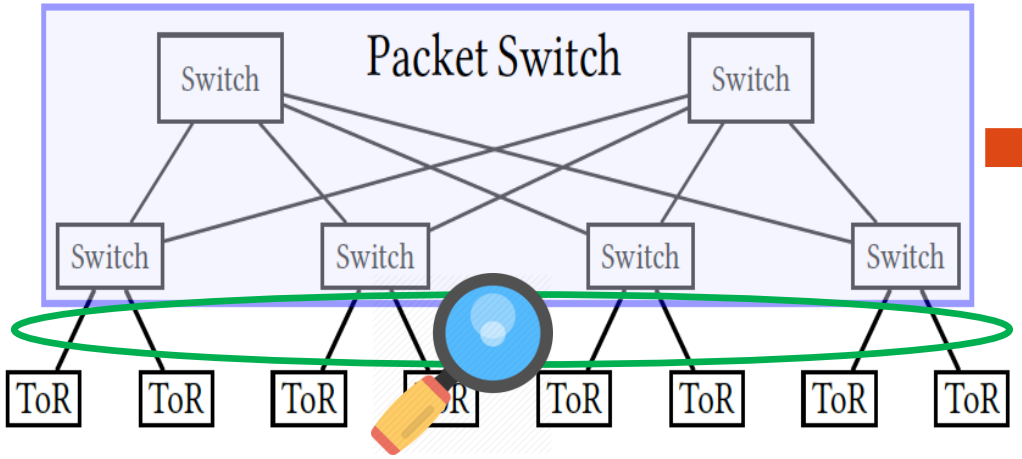
Non-Blocking Interconnects, e.g., Clos, Fat-Tree etc.

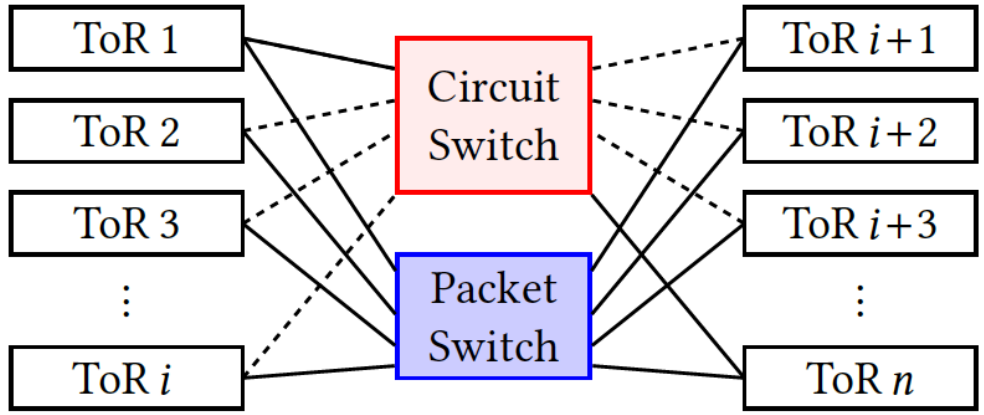




Simplified Problem defined by Non-Blocking Interconnections

Above layers abstracted as a packet switch.





(Mohammad Alizadeh et al. 2016).

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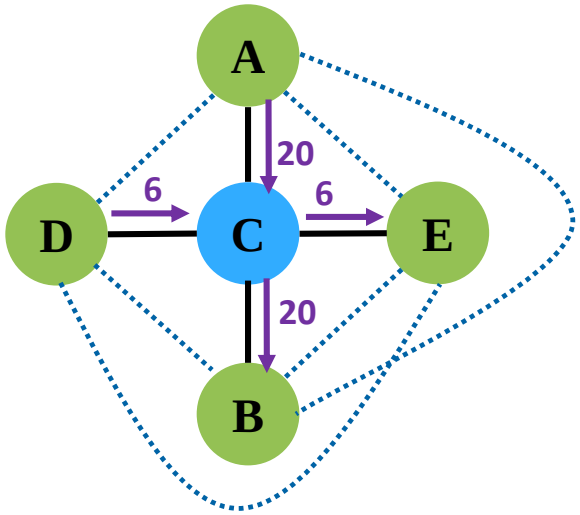
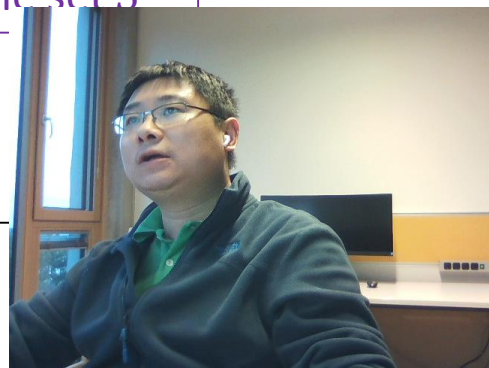
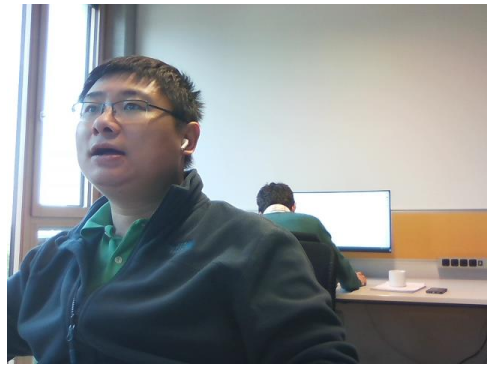
Optimal Algorithms for Simplified Problem (Notations)

- Consider a decision problem
- Assume the optimized maximum load: θ
- Let S be the set of possible values for θ
- S contains the load for each static link before reconfiguration
- Next, we show how to compute the set S



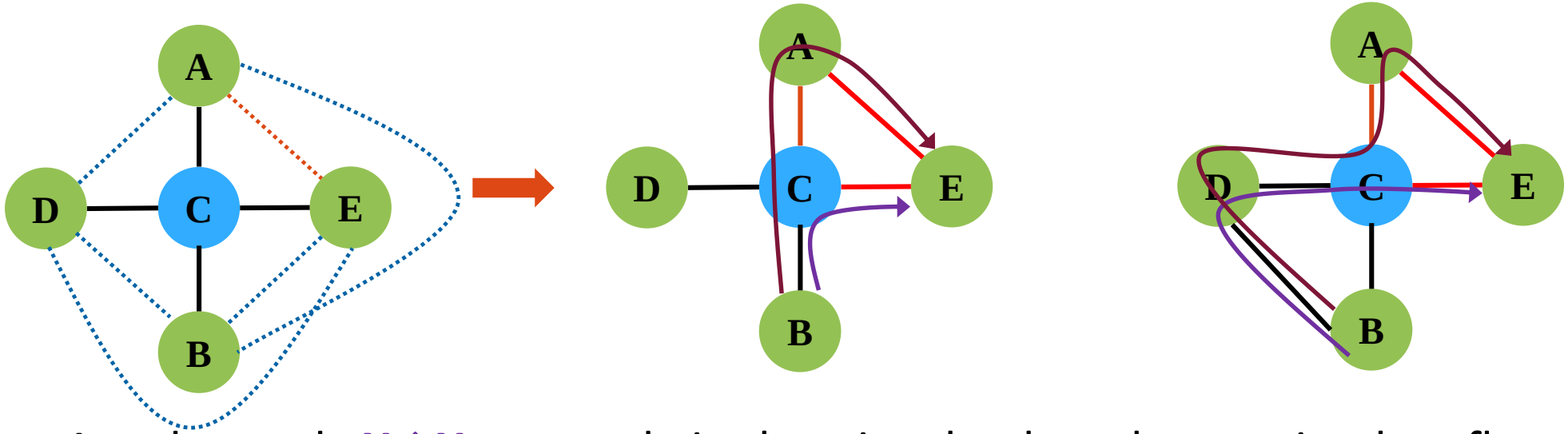
The set S



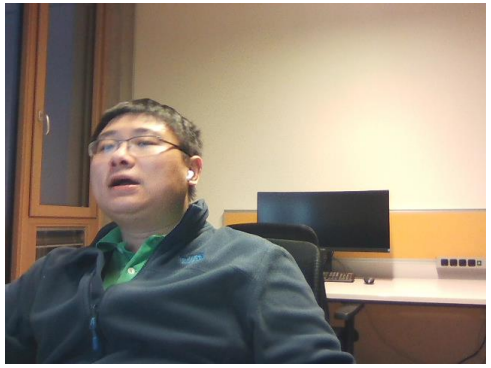


Useful Observations

- For each reconfigurable link $\{X, Y\}$, focus on its triangle.
- E.g., the triangle $\{A, E, C\}$ E.g., demand : **B→E**

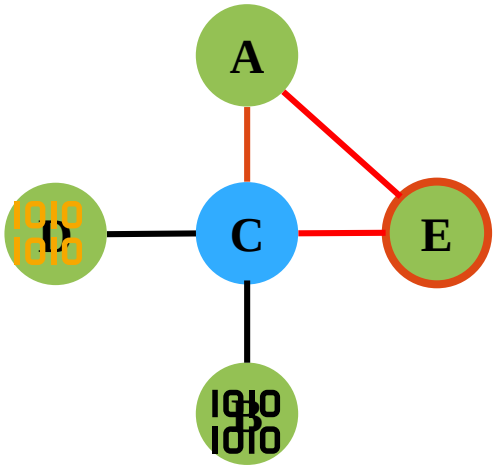


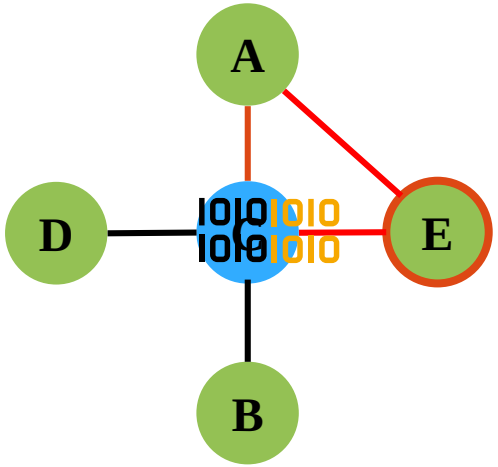
Any demand : **X→Y,** one node in the triangle, the other not in, then flows always go through the center



Local Optimization For Each Triangle

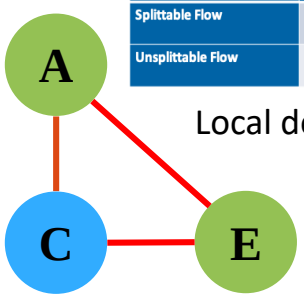
- For each reconfigurable link $\{X, Y\}$, in the triangle $\{X, Y, C\}$:
  - Compute local demands, and find optimal load for the local demands





Routing Models	Segregation Model	Nonsegregation Model
Splittable Flow	SS	SN
Unsplittable Flow	US	UN

Local demands D’

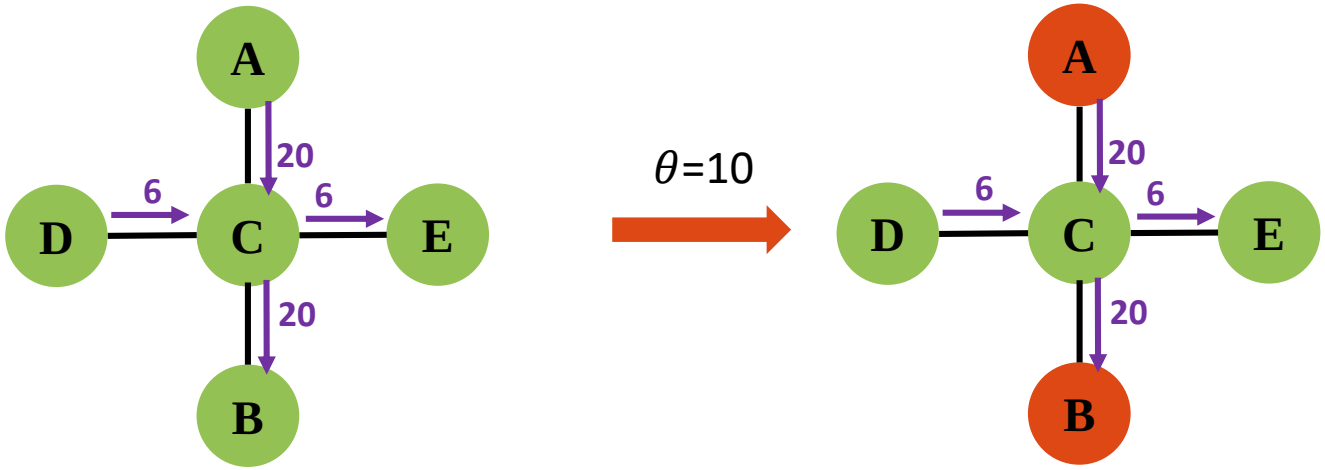


Local demands :D’(**C→E**)=D(**B→E)+**D(**D→E)**
D’(**E→C**)=D(E**→B)+**D(**E→D)**

- Find optimal routing in $O(1)$
- Let the maximum load be Δ_i
- Put Δ_i into the set S

Optimal Algorithm: Mark Target Nodes

- Binary search in the set S to find the actual θ (optimized maximum load) within $O(\log |V|)$
- For a specific θ:
  - Mark each node "target" ($V^r \subseteq V$) if its link load is larger than θ before reconfiguration



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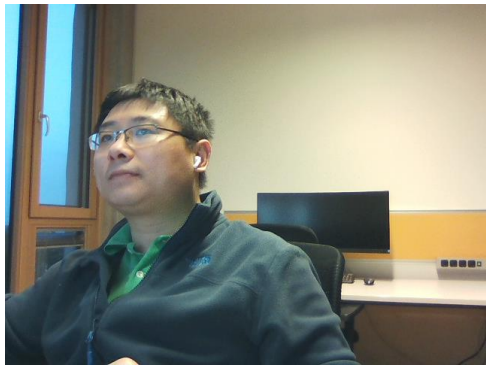
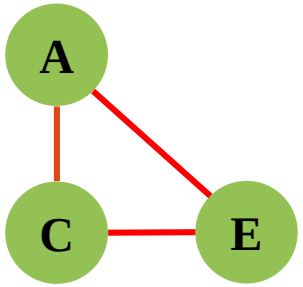


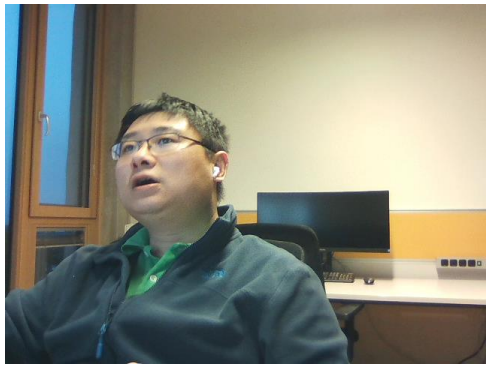
Optimal Algorithm: Compute Useful Reconfigurable Links

- For a specific θ:
  - Define a set $\mathcal{E}'$: useful reconfigurable links, where $\mathcal{E}' \subseteq \mathcal{E}$
  - For each triangle, if its maximum load $\Delta_i \leq \theta$, put its reconfigurable link $\mathcal{E}'$

Routing Models	Segregation Model	Nonsegregation Model
Splittable Flow	SS	SN
Unsplittable Flow	US	UN

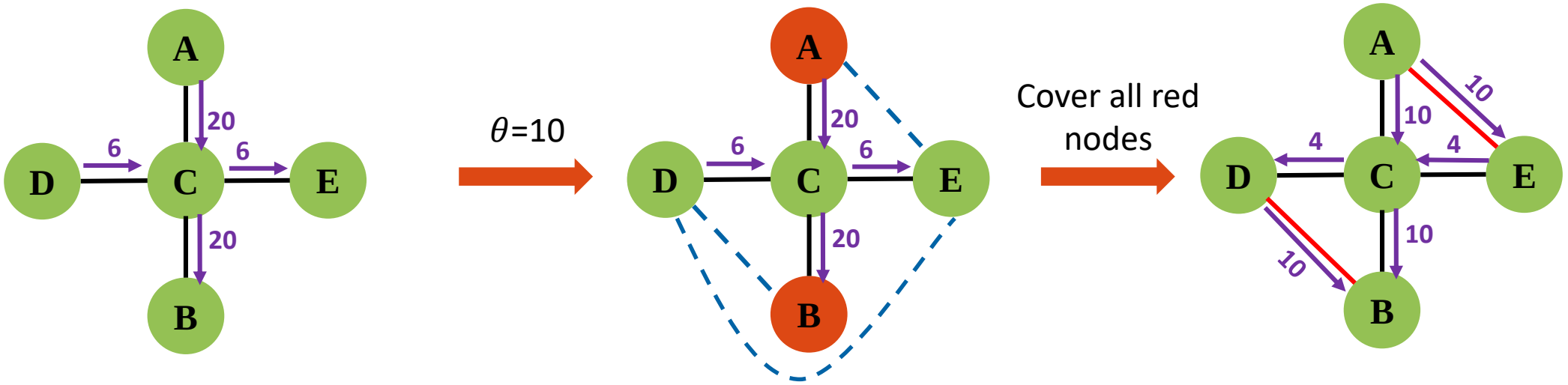


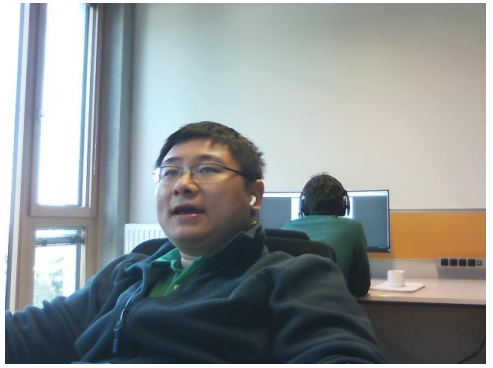
- Find optimal routing in $O(1)$
- Let the maximum load be Δ_i
- If $\Delta_i \leq \theta$, put $\{A, E\}$ in the set $\mathcal{E}'$



Optimal Algorithm: Red-Target Matching and Binary Search

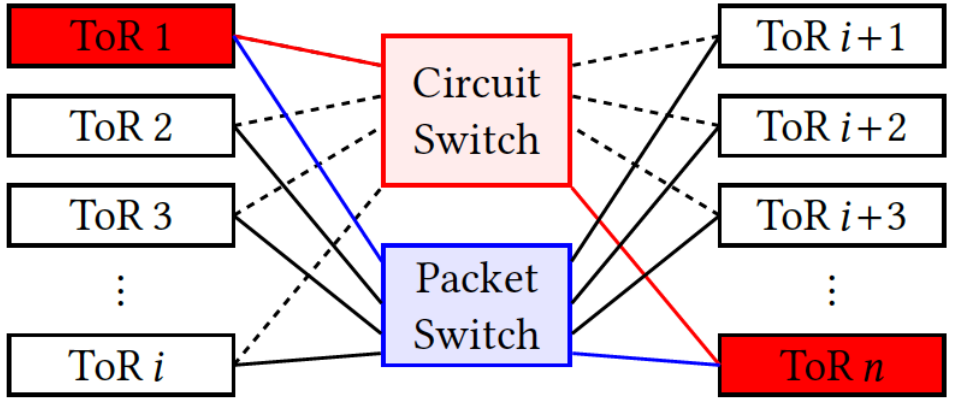
- For each specific θ: (V^r and $\mathcal{E}'$ computed)
  - Obtain a new graph $\mathrm{G}' = (V, \mathcal{E}')$
  - Find a matching M in G' to cover all target nodes V^r (by maximum weight matching)
- Total run-time cost: $O(\log |V| * T)$, and T is the run-time of maximum weight matching





Theoretical Analysis of Performance

- Lower bound: the maximum load decreased by 50% by adding reconfigurable links
- Why: at most two paths between any two nodes
- Our optimal algorithm achieves the lower bound
- Maximum matching works badly:
  - For some cases, maximum matching can only decrease the maximum load by an arbitrarily small value ε



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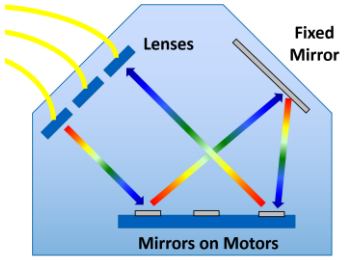
performance 2x, similar run time

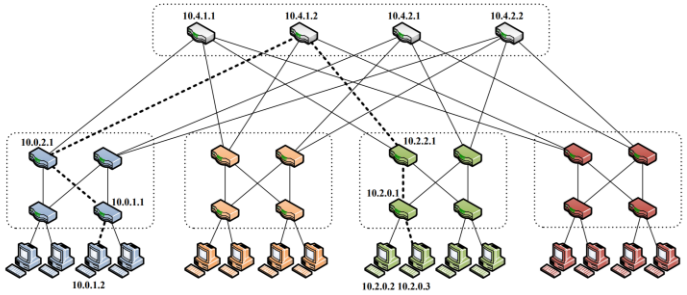
Evaluation: Minimize Maximum Link Load

- Traces from facebook

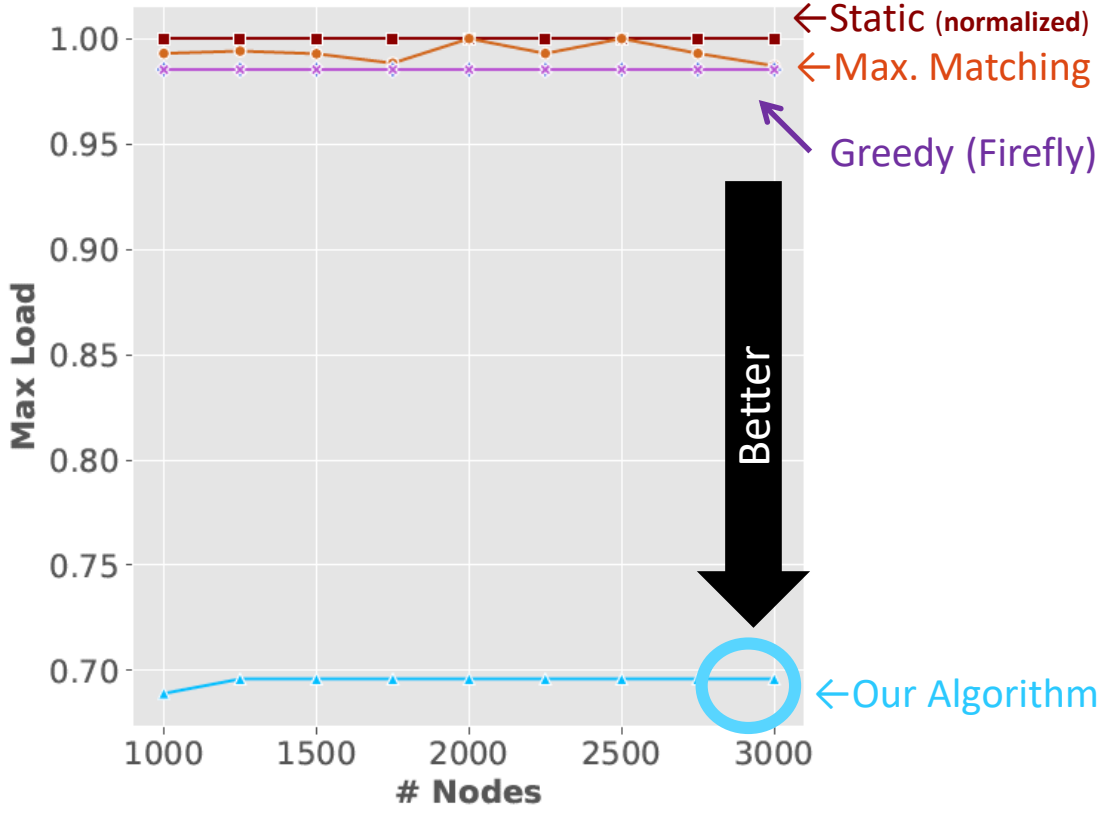


Optical Circuit Switch

+



Topology



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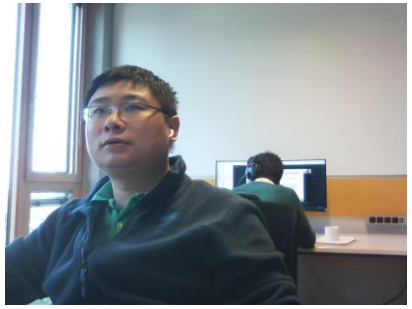
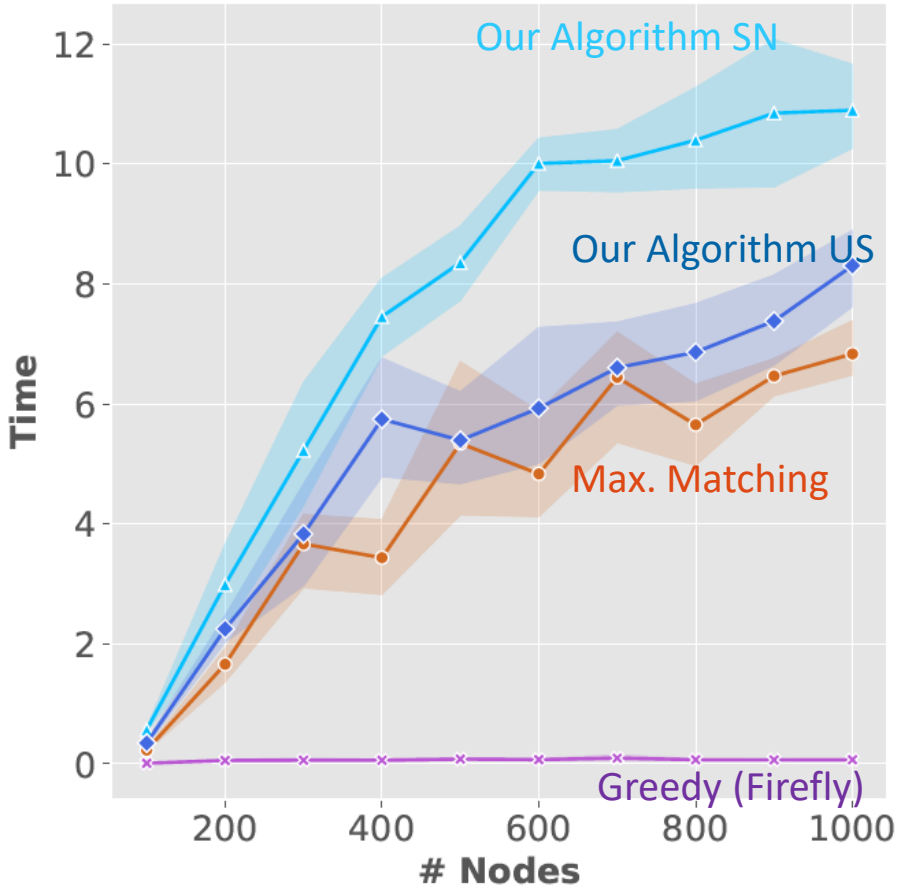


Evaluation: Comparing Time Costs

- Theoretical Running Time:
  - Greedy: $O(|V|)$
  - Maximum Matching (Blossom Alg.): $O(|E||V|^2)$
  - Our Algorithm: $O(\log|V| * |E||V|^2)$

- The experiments match our theoretical analysis



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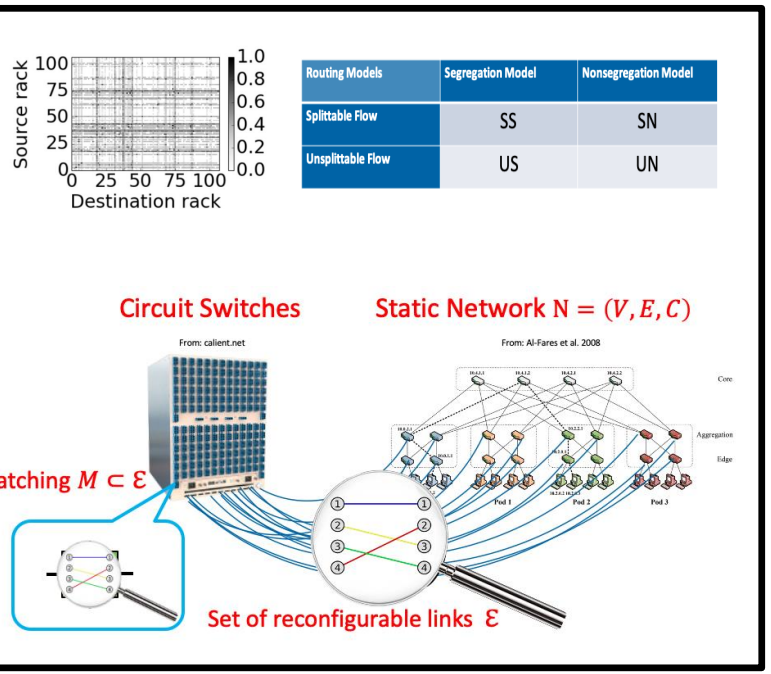
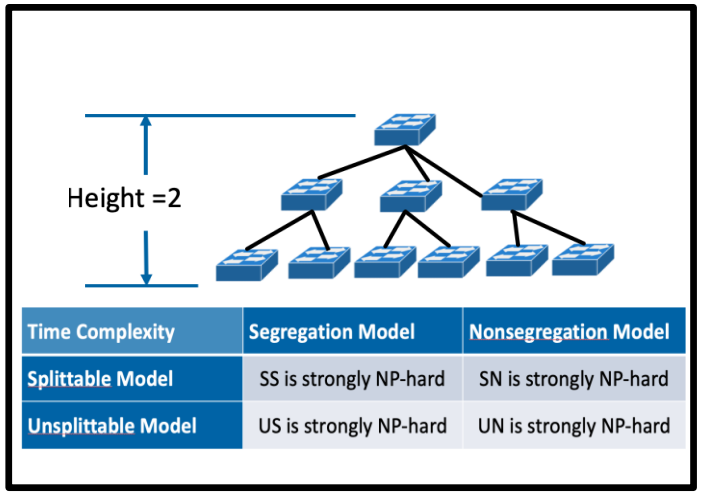
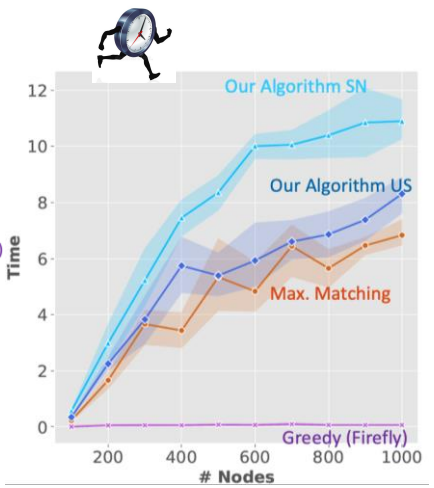
Thank you! ☺

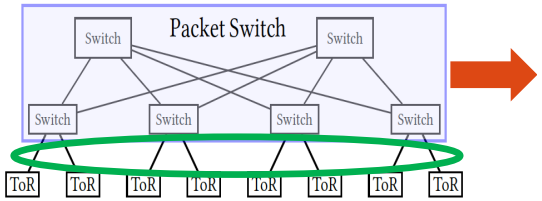
Load-Optimization in Reconfigurable Networks: Algorithms and Complexity of Flow Routing

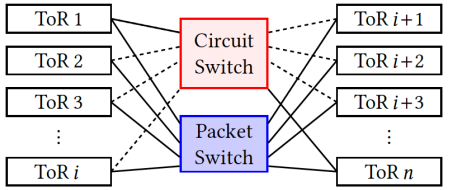
Wenkai Dai, Klaus-T. Foerster, David Fuchssteiner, Stefan Schmid (CT Group, University of Vienna)











- Theoretical Running Time:
  - Greedy: $O(|V|)$;
  - Maximum Matching (Blossom Alg.): $O(|E||V|^2)$;
  - Our Algorithm: $O(\log|V| * |E||V|^2)$.