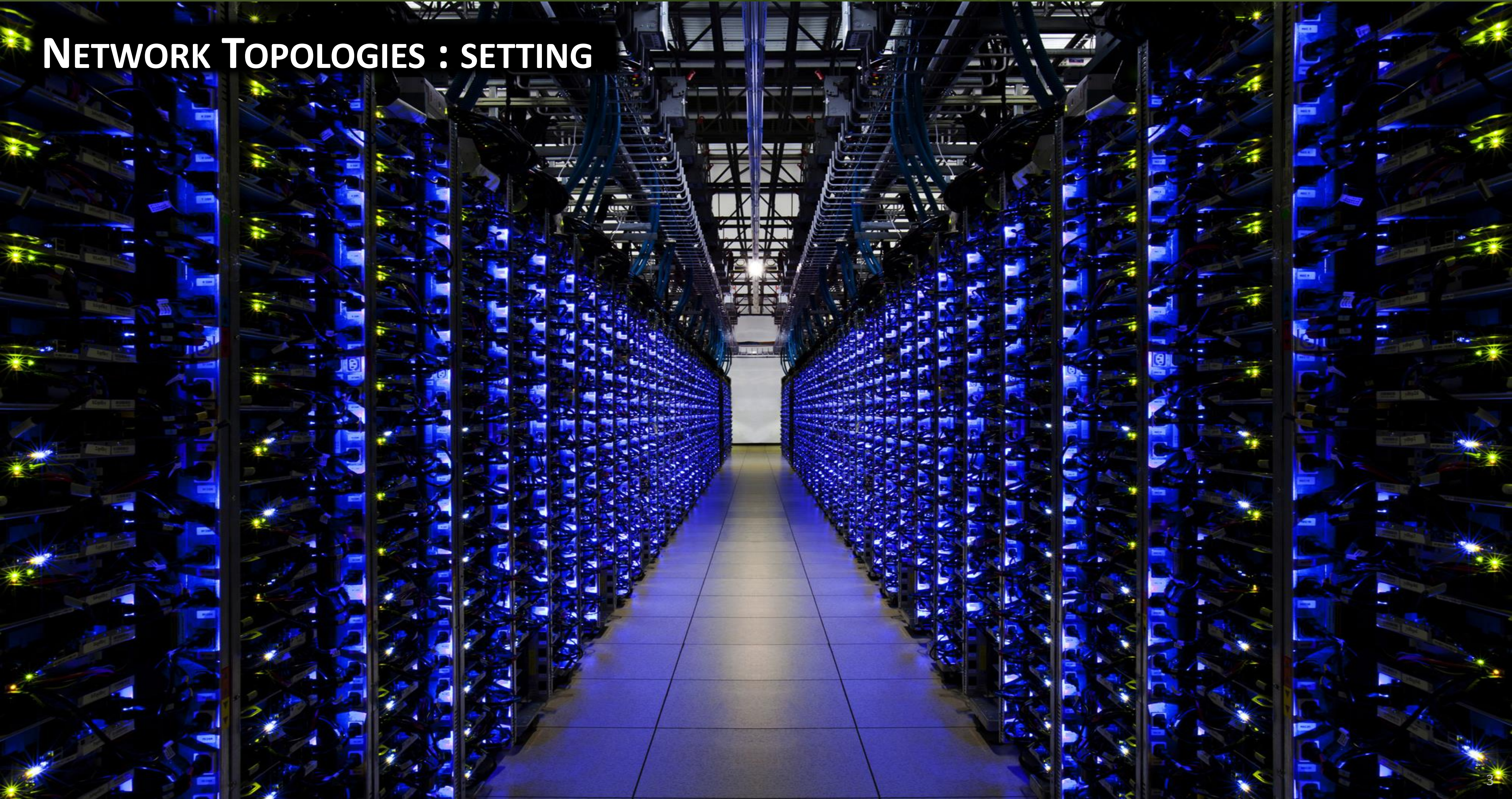
FatPaths: Routing in Supercomputers and Data Centers when Shortest Paths Fall Short

Maciej Besta, Marcel Schneider, Marek Konieczny, Karolina Cynk
Erik Henriksson, Salvatore Di Girolamo, Ankit Singla, Torsten Hoefler


summit
IBM
NASA

The interconnect: a key part of supercomputers and data centers, relevant both for high performance and low cost

Network Topologies : setting



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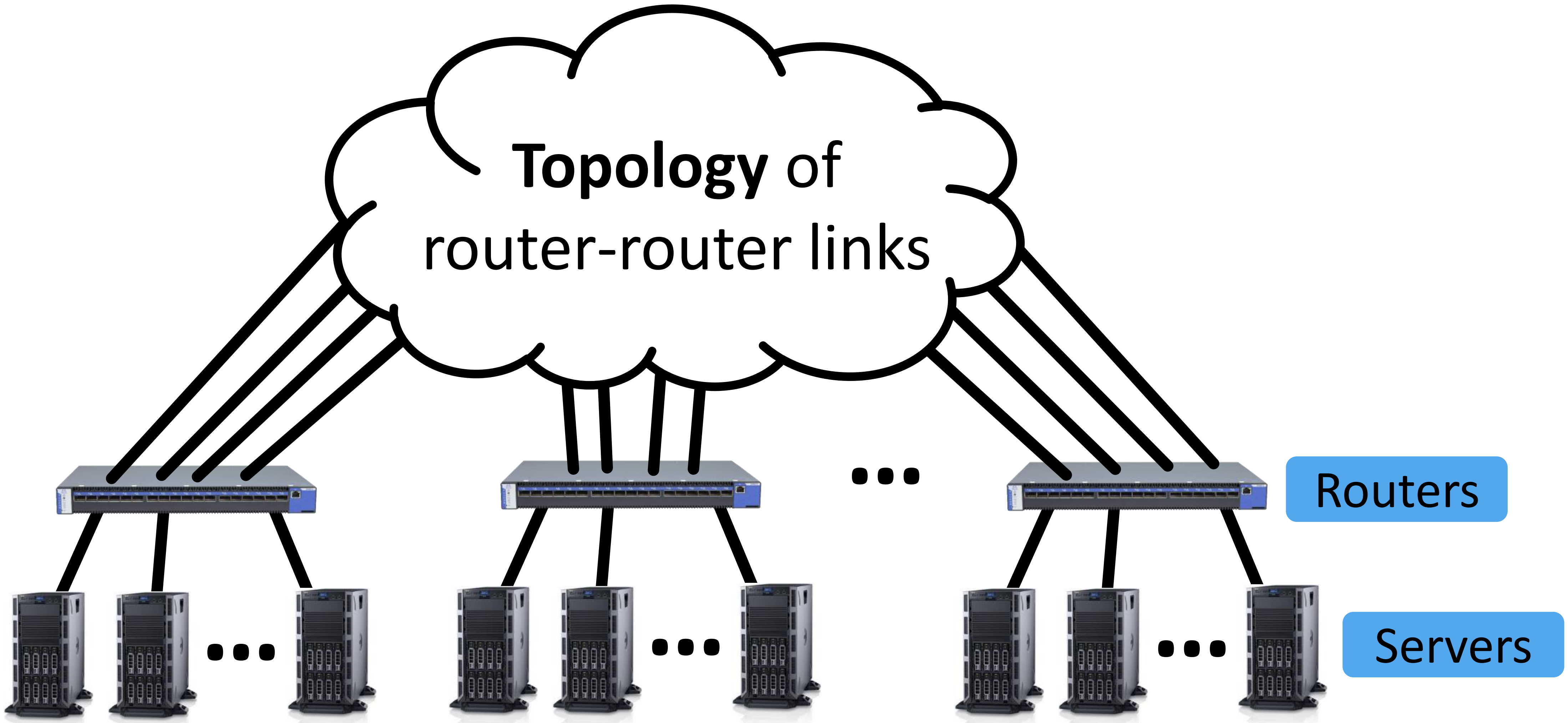

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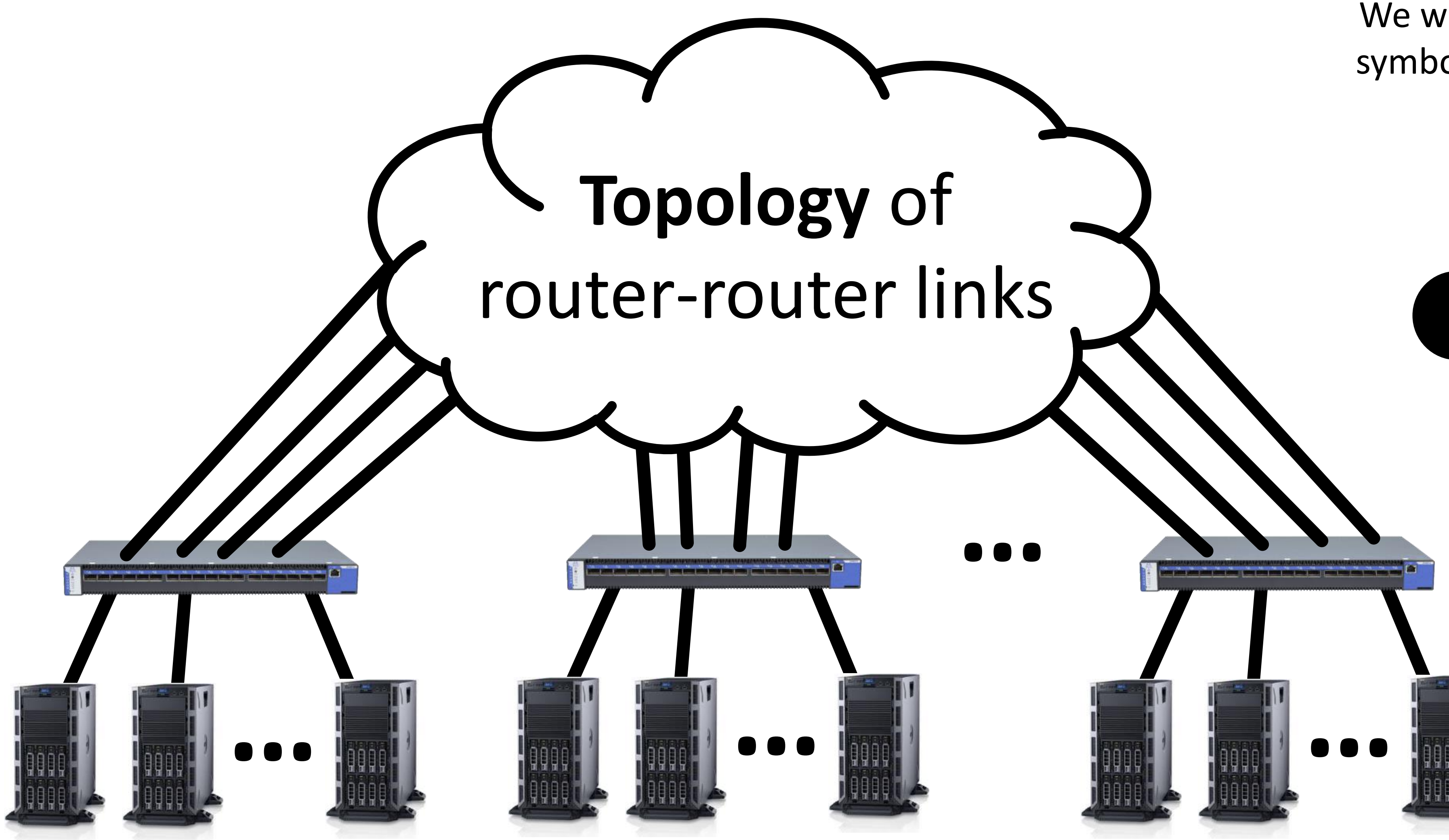
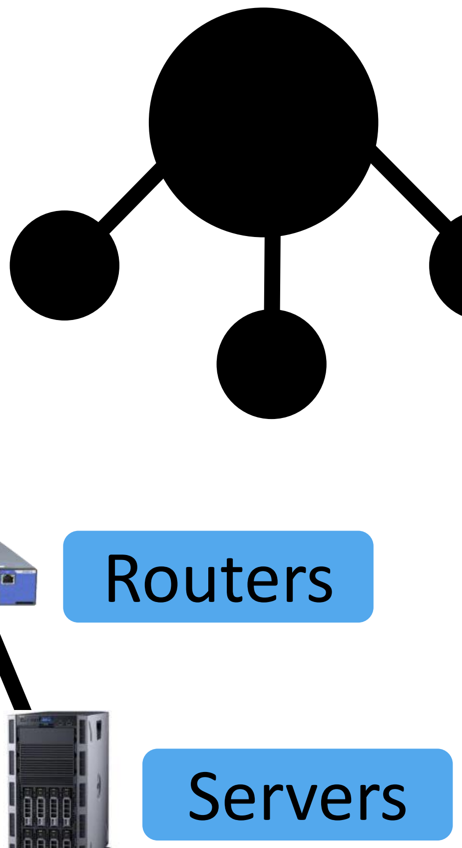
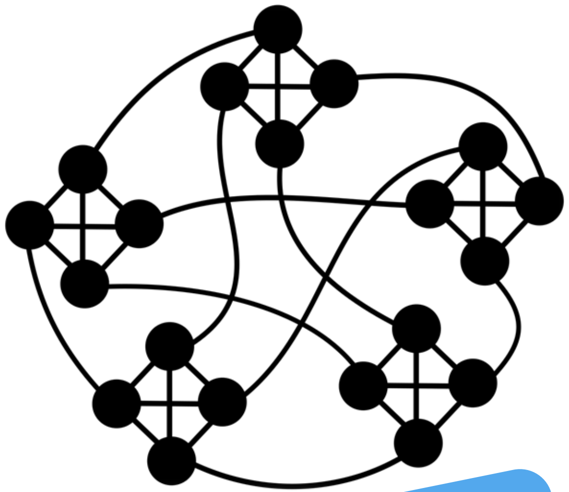


We will often use the following symbols for routers and servers



LOW-DIAMETER NETWORK TOPOLOGIES

Low-Diameter Network Topologies



Dragonfly [2008]
diameter = 3

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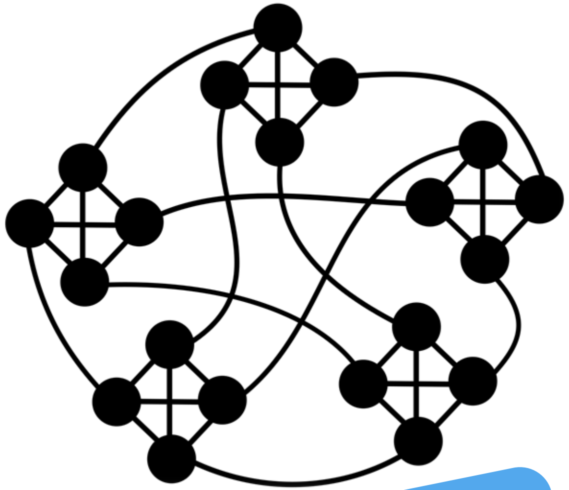

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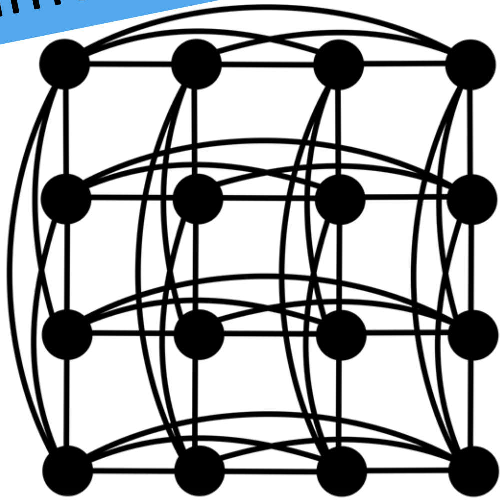
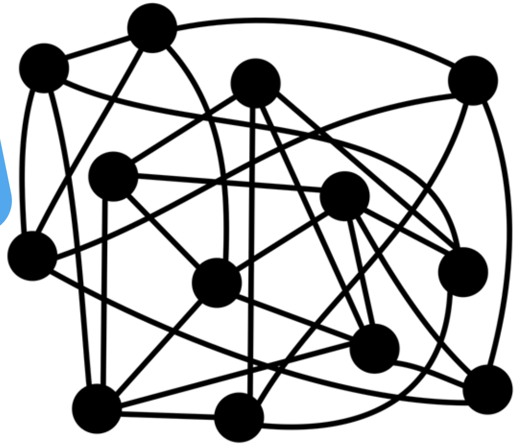
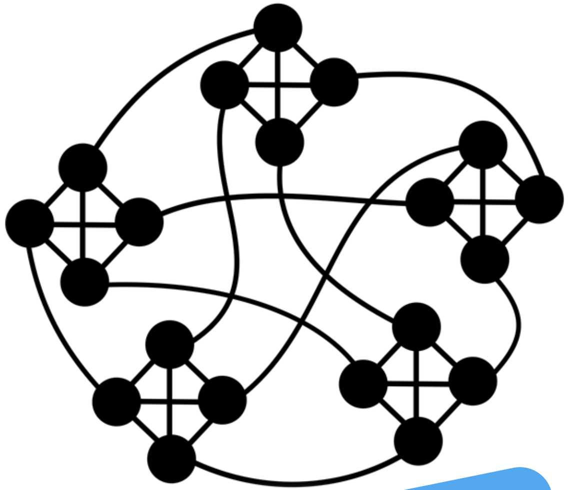


LOW-DIAMETER NETWORK TOPOLOGIES

Jellyfish [2012]
diameter ≤ 3





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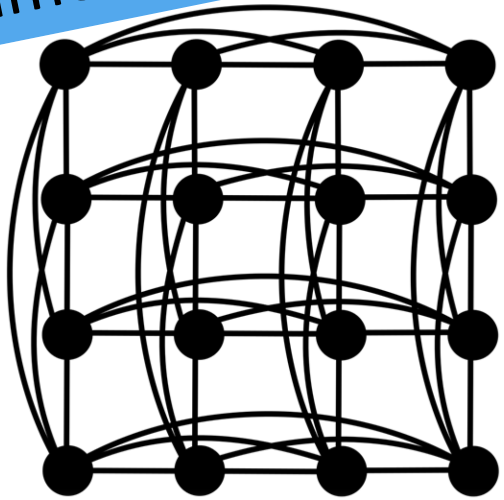

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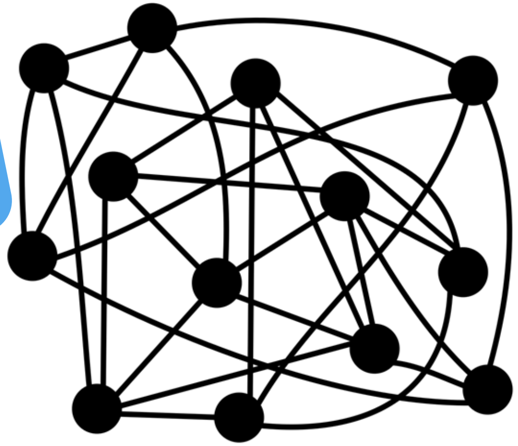
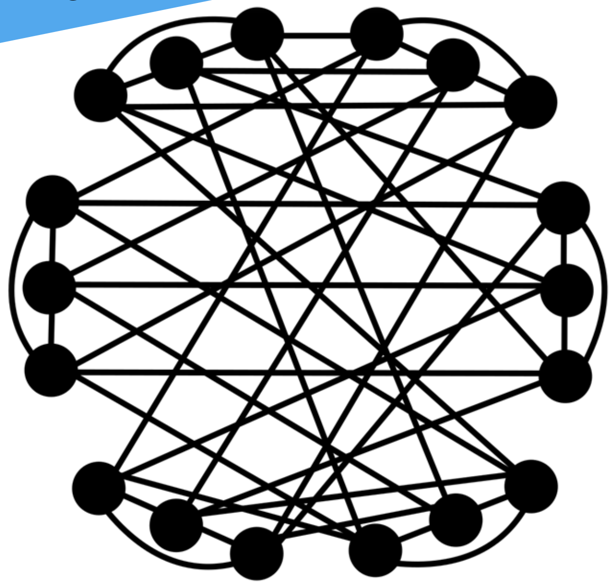
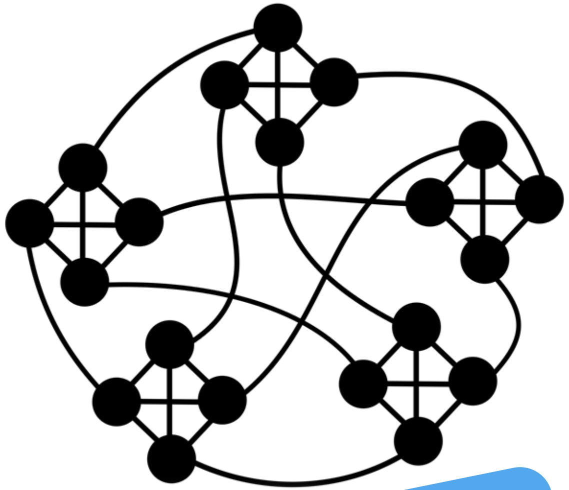


Slim Fly [2014]
diameter = 2





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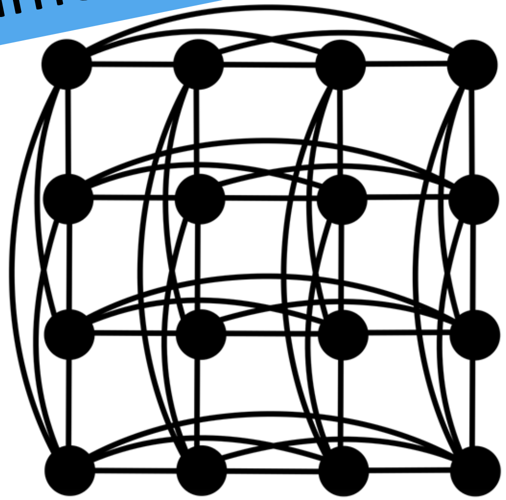

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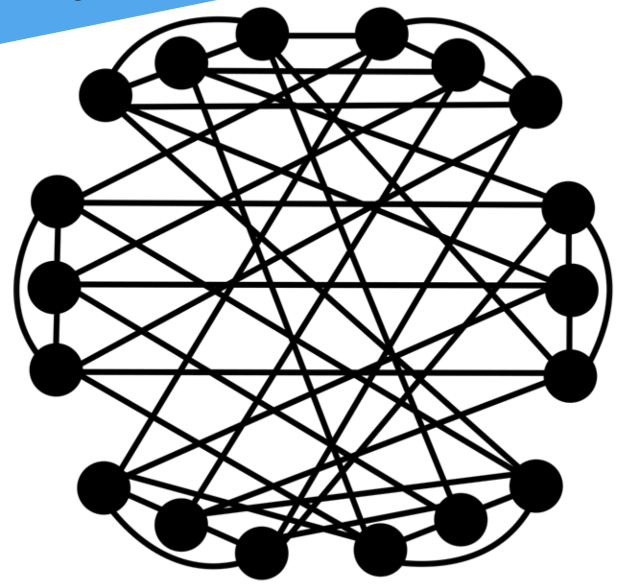

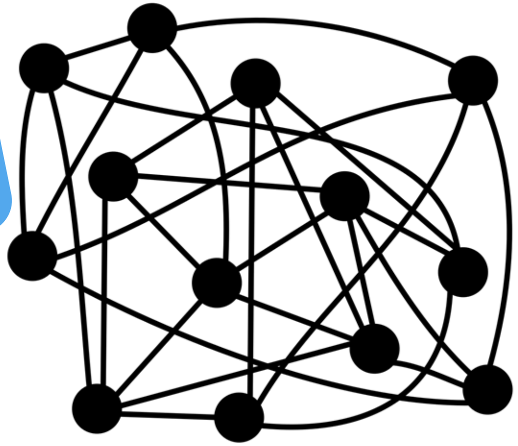

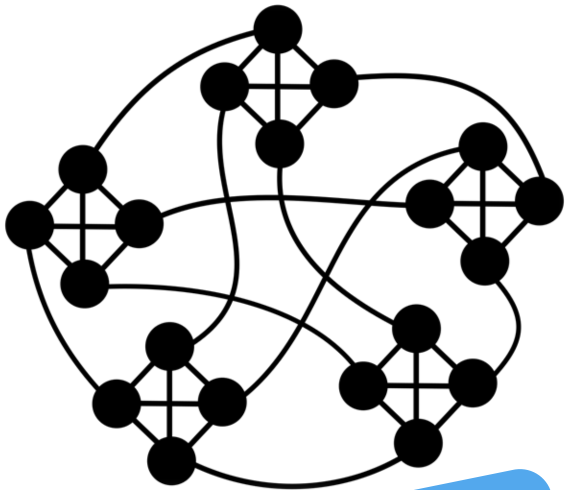

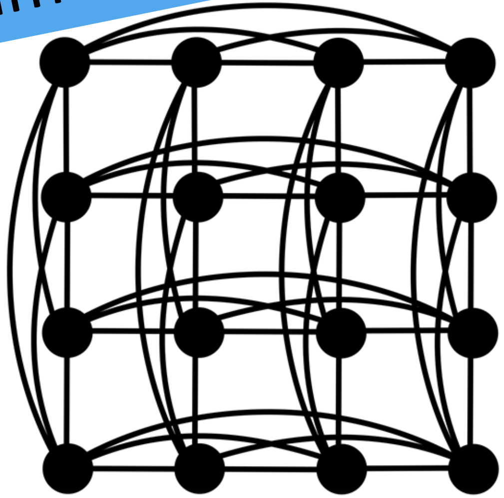

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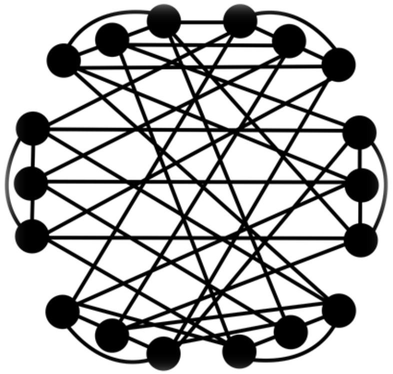
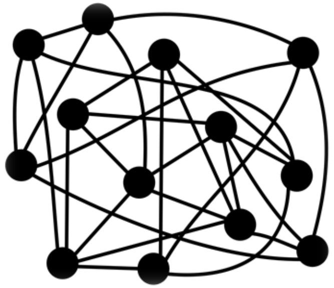
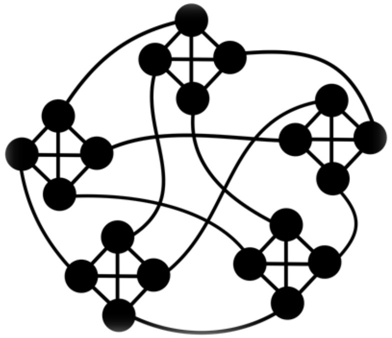
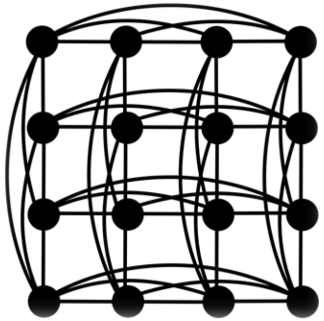
Why care? (there is already Clos, Fat tree, etc.).









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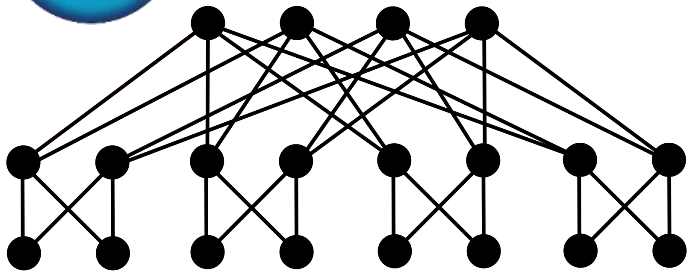

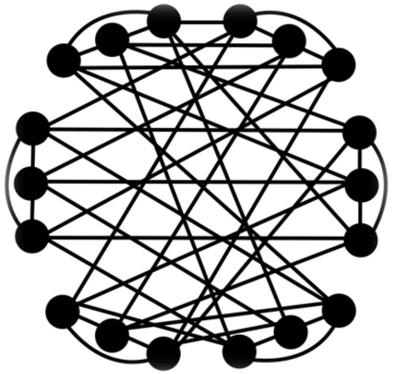

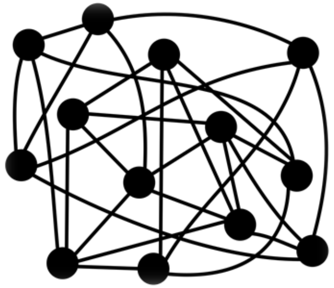

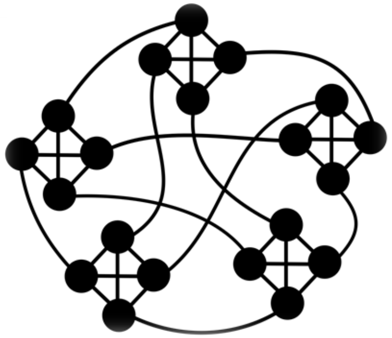

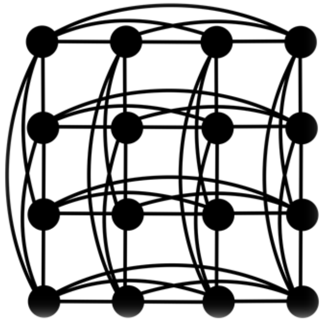

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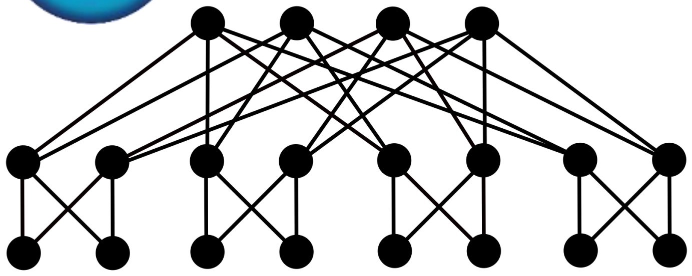

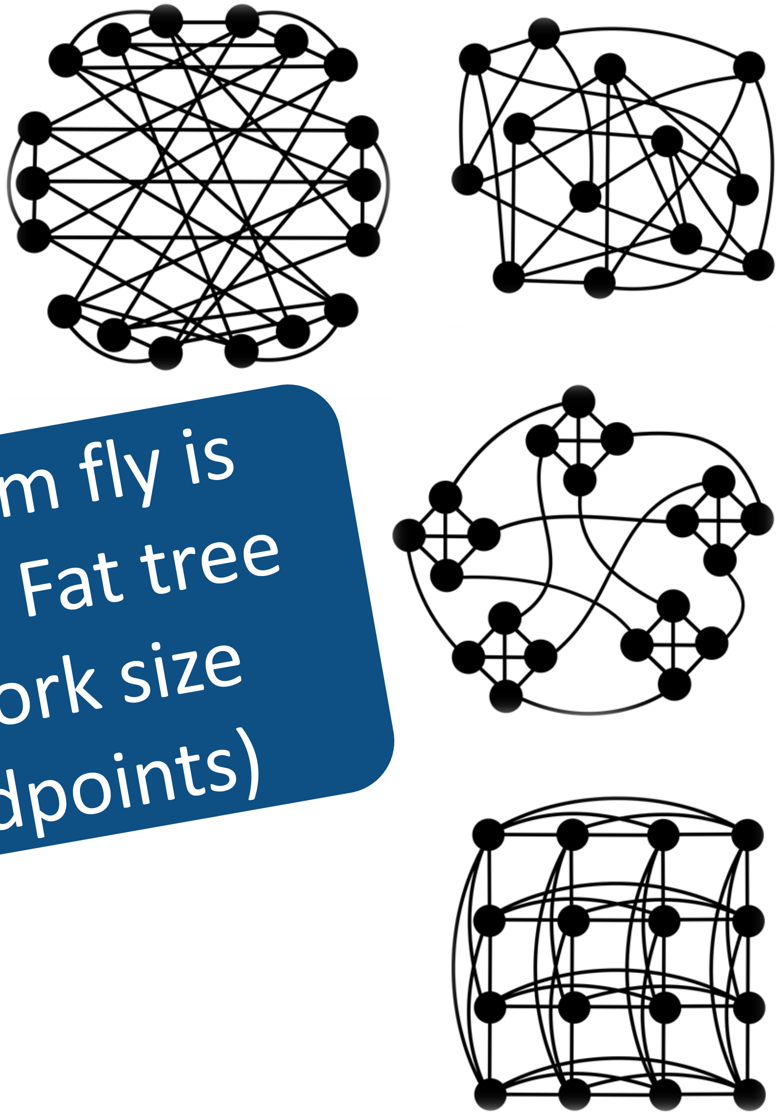

Cost-effective (Slim fly is 50% cheaper than Fat tree for a fixed network size counted in #endpoints)

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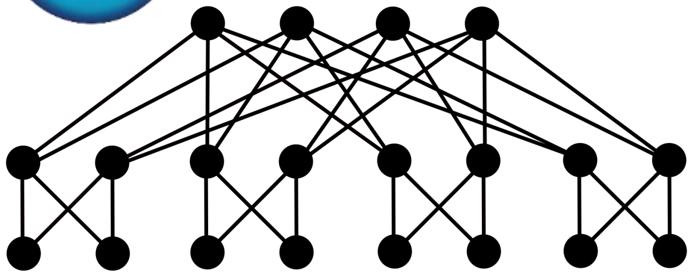

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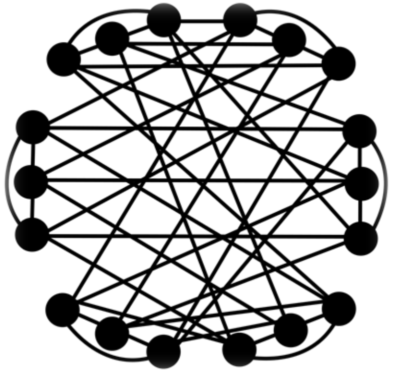

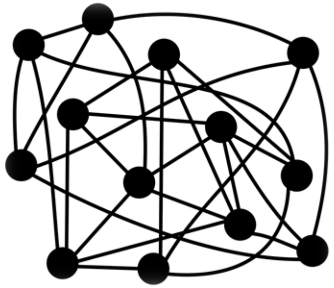

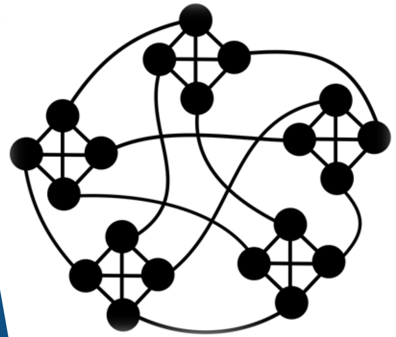

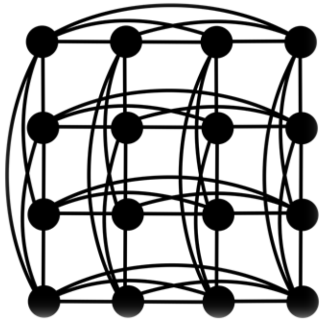

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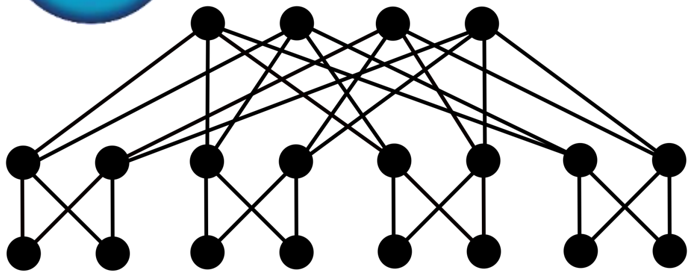

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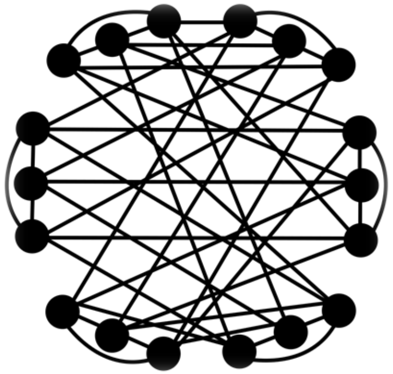
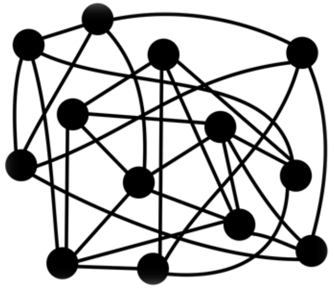
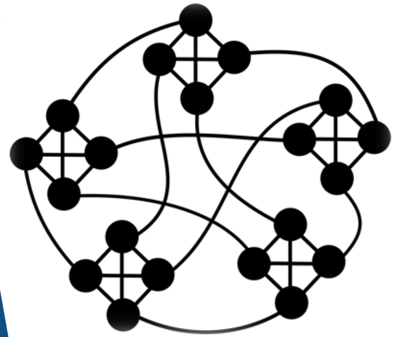
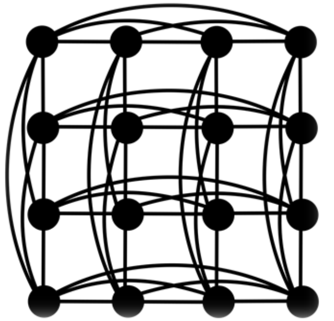
Low latency (from low diameters)

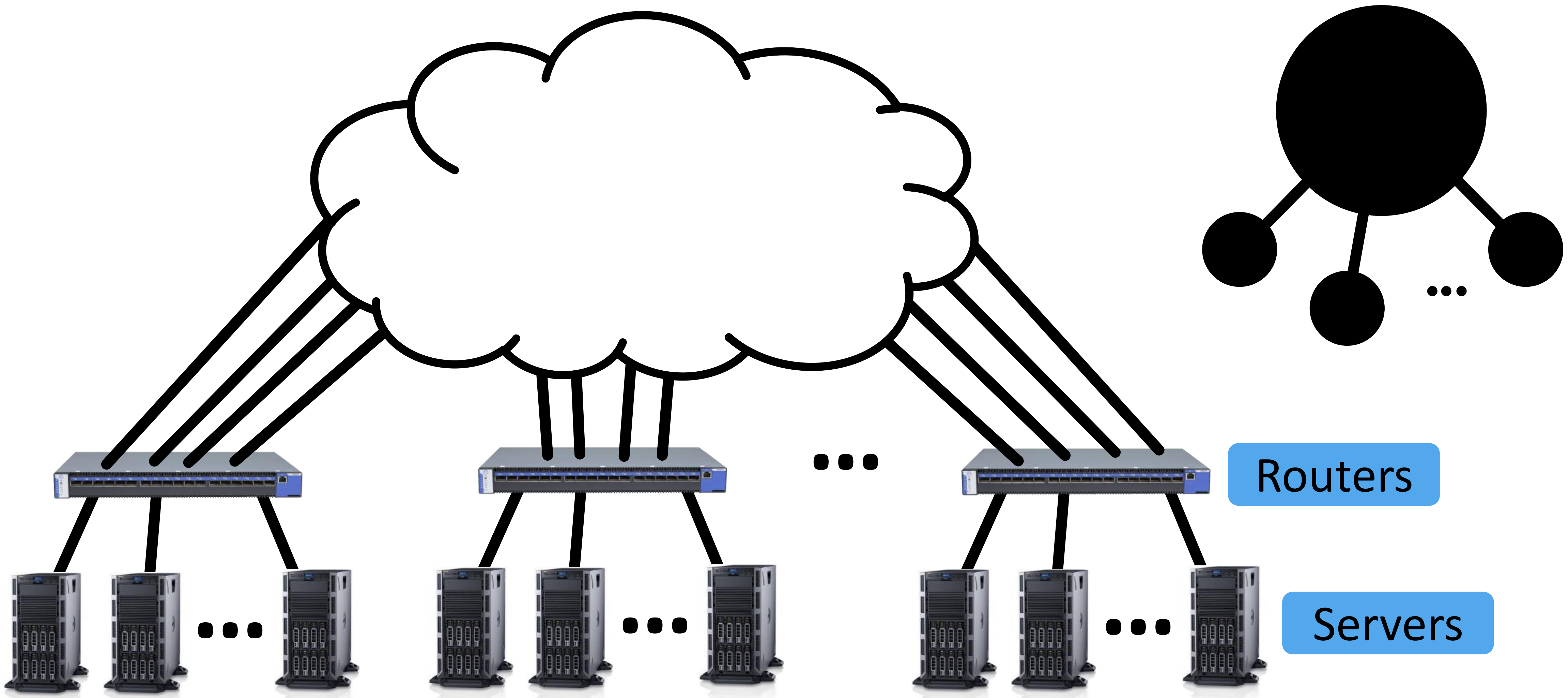








Network Topologies : Routing



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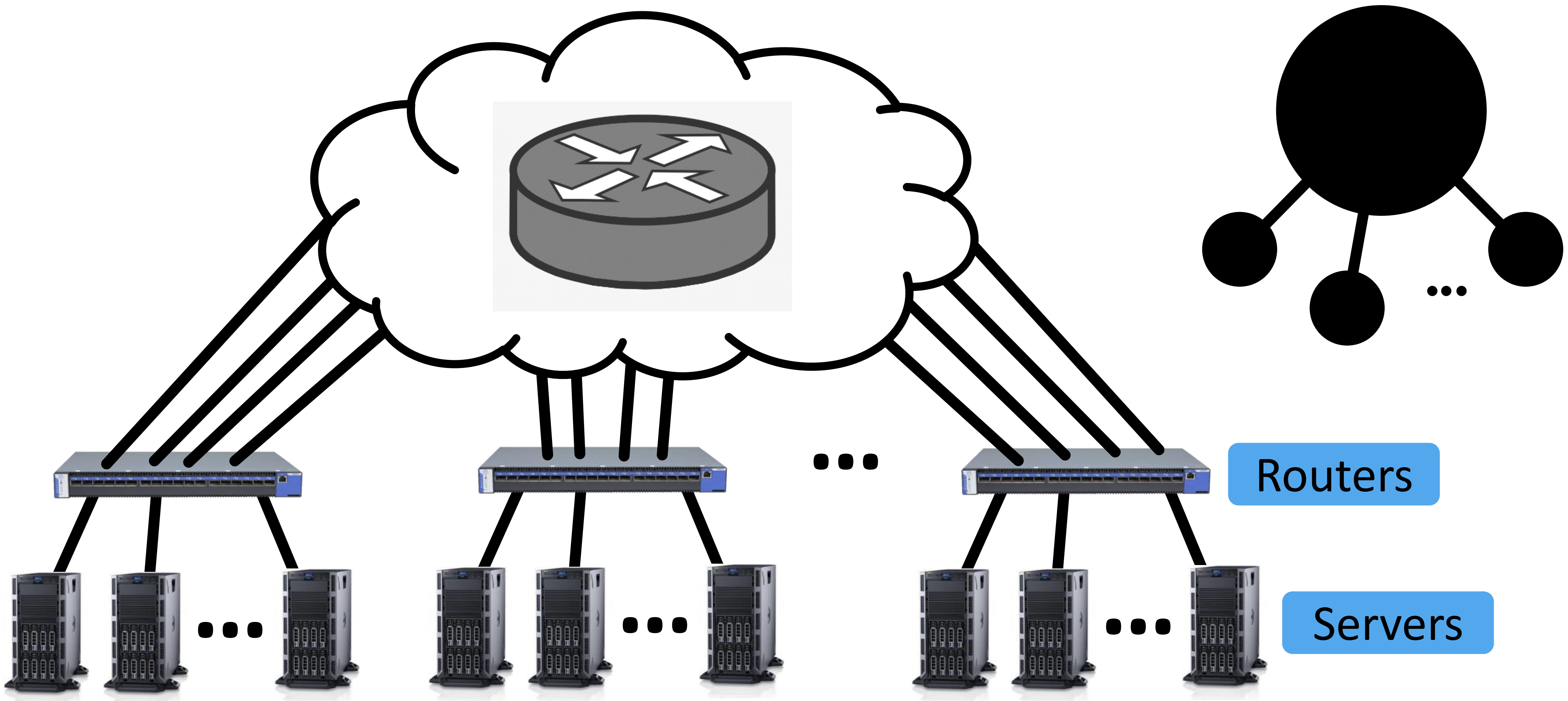
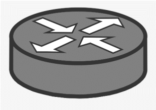


Routing in Fat Trees 

ROUTING IN FAT TREES

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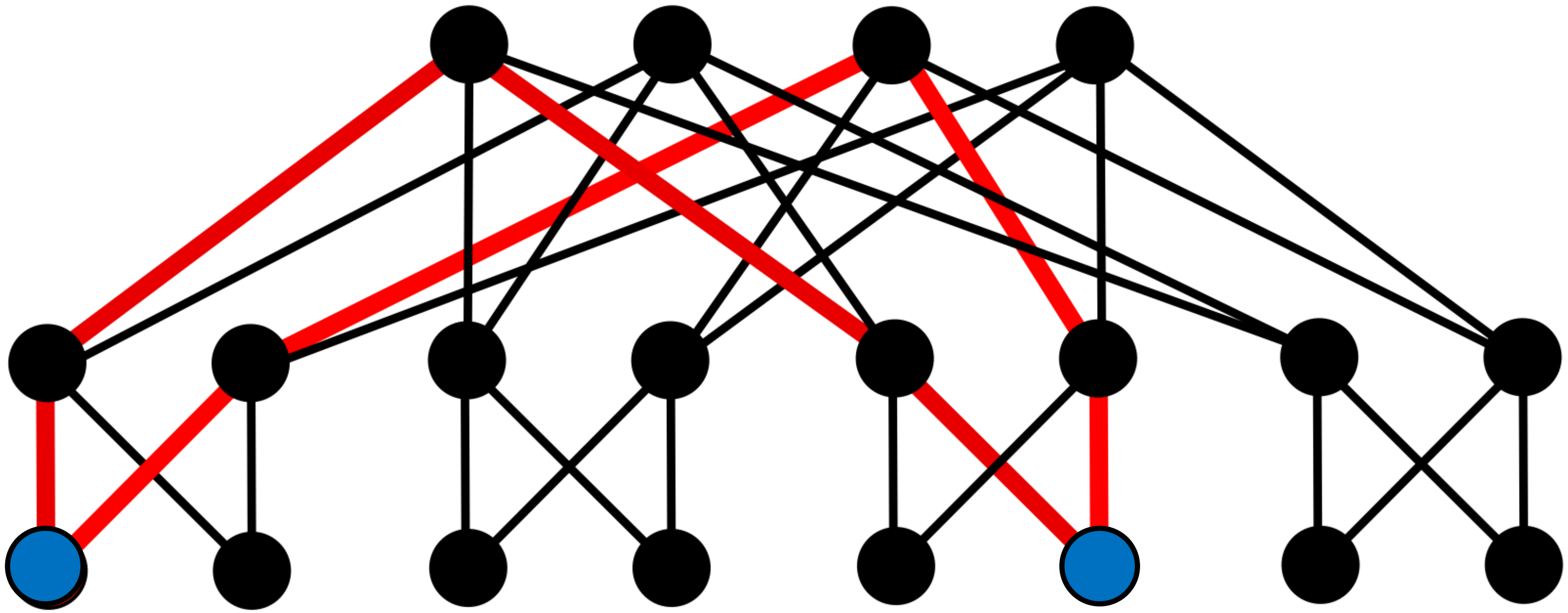

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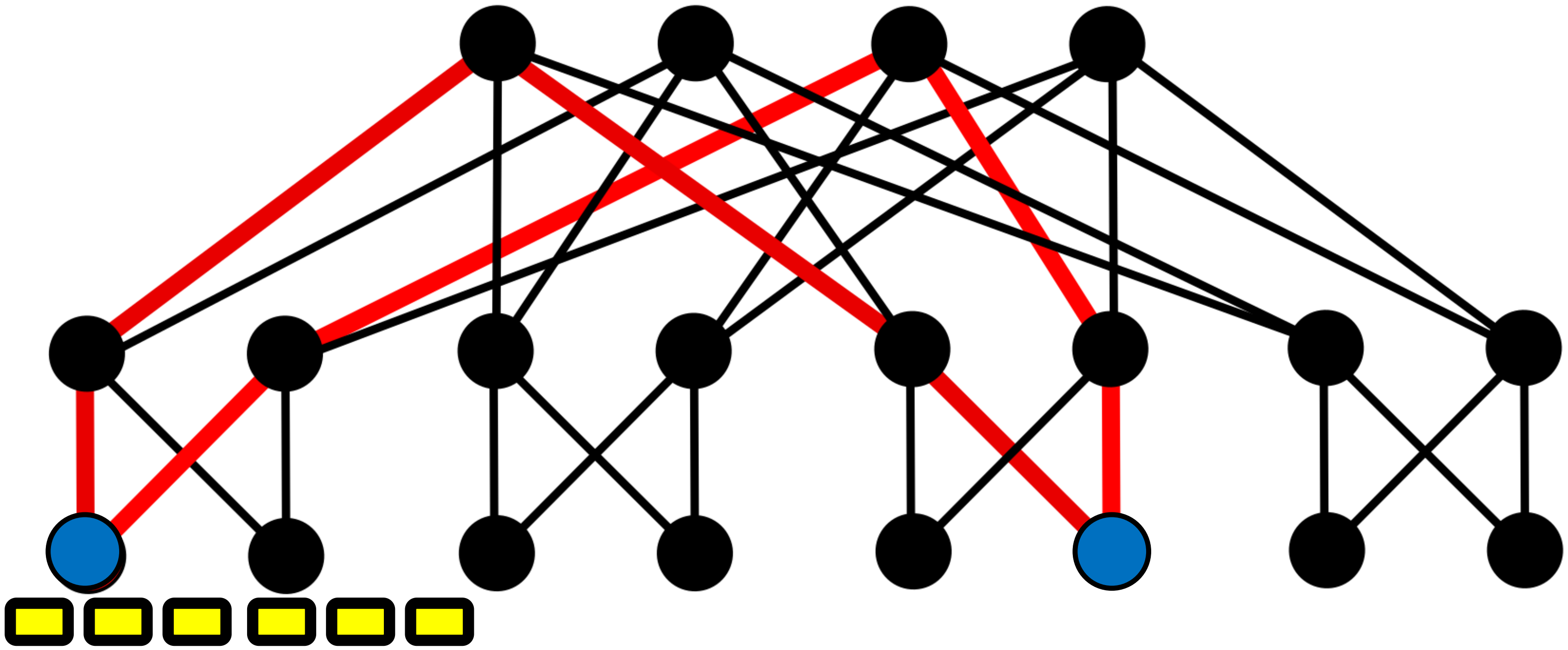

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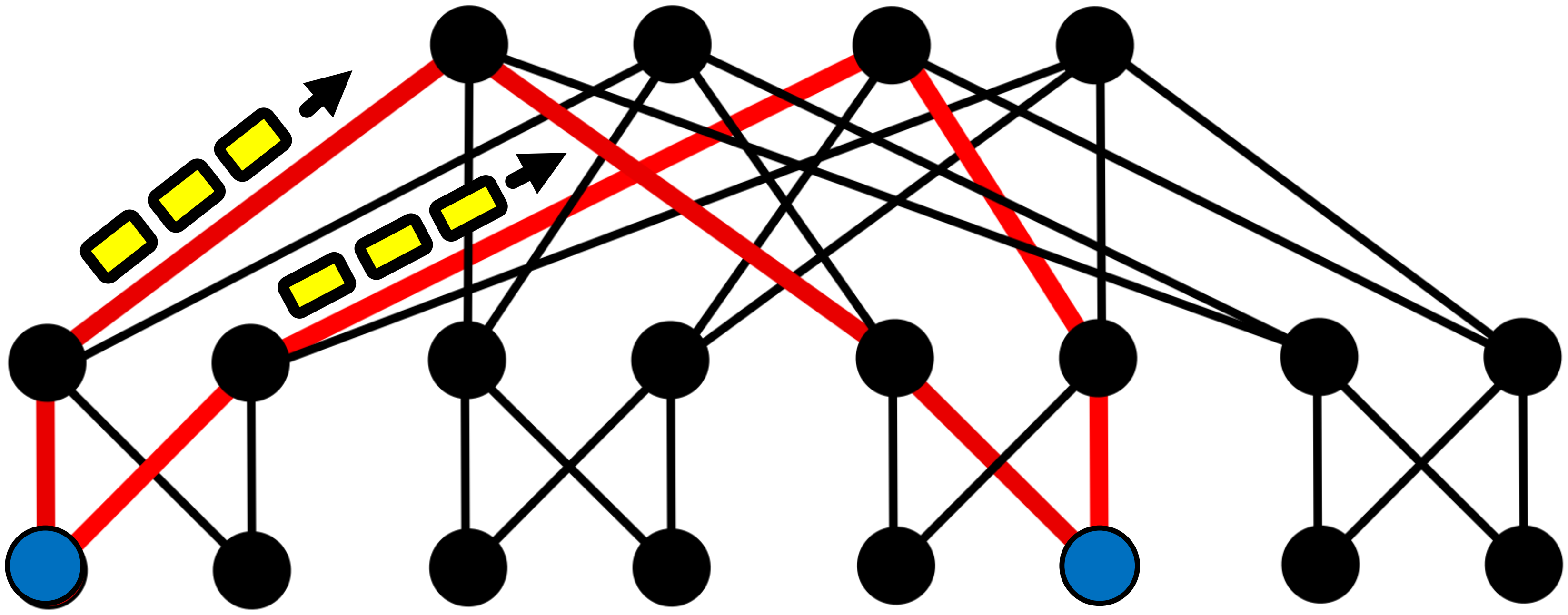

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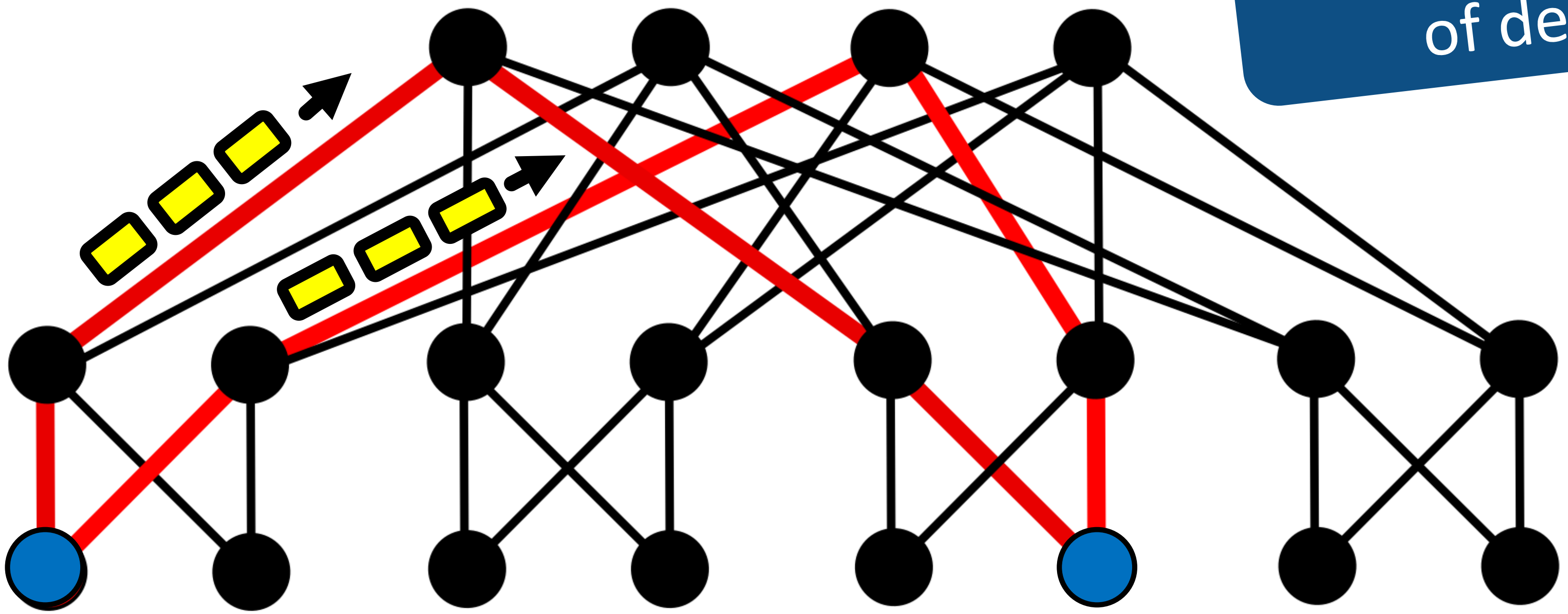
Established techniques for using multipathing & plethora of designs available



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INFORMATIONAL

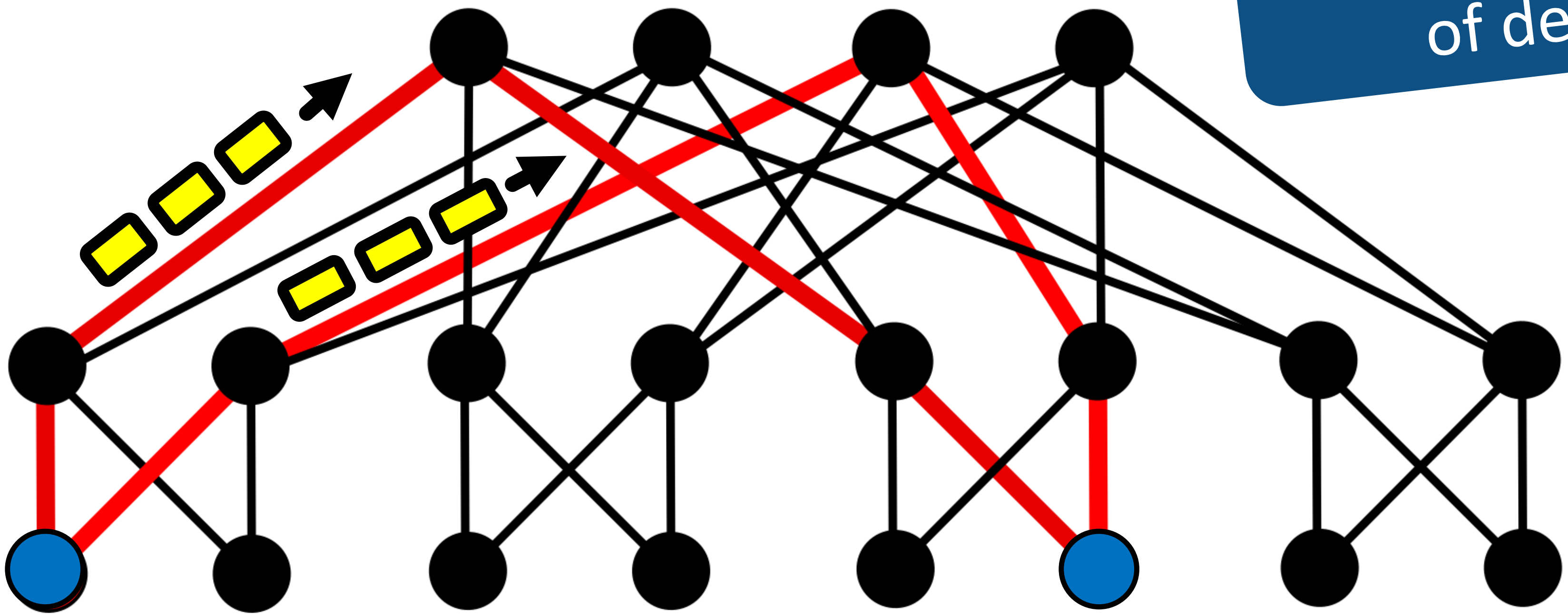
Network Working Group
Request for Comments: 2992
Category: Informational

ECMP

C. Hopps
NextHop Technologies
November 2000

Analysis of an Equal-Cost Multi-Path Algorithm

Established techniques for using multipathing & plethora of designs available



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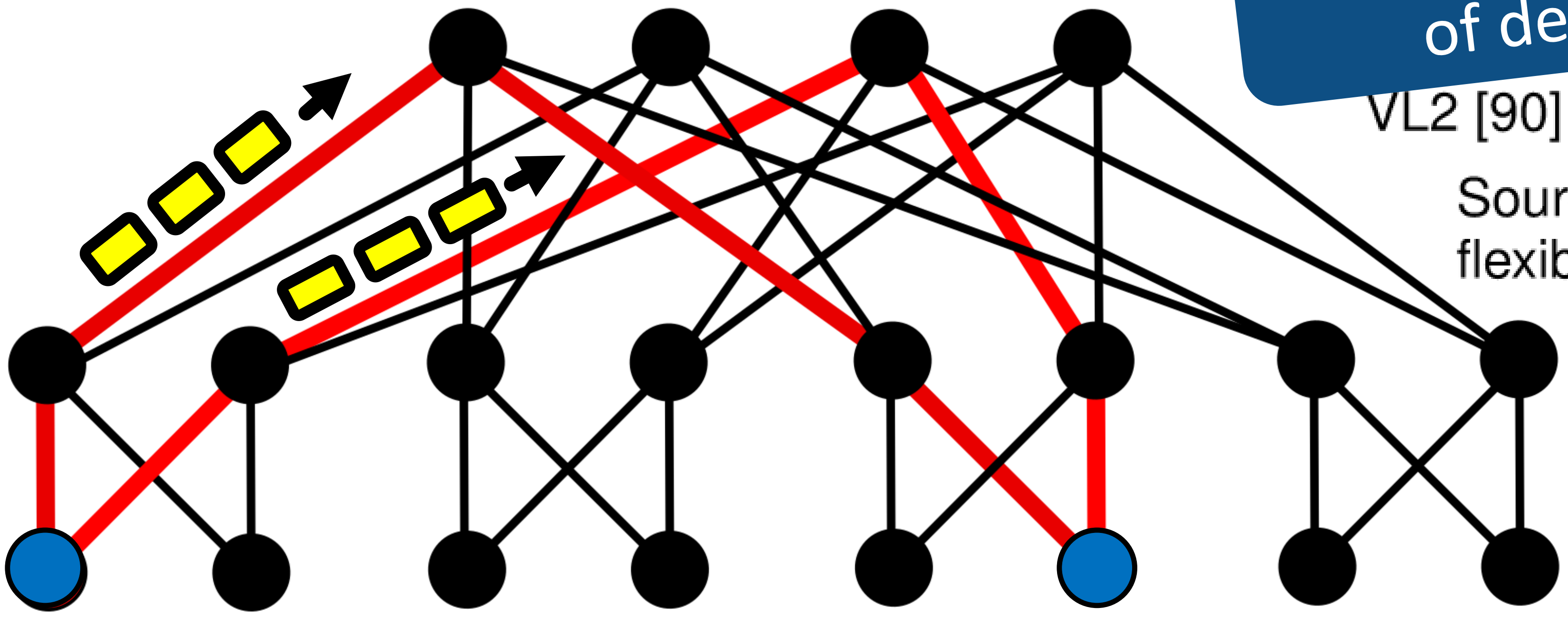


Work by Al-Fares et al. [7]

VL2 [90]

WCMP for DC [233]

Source routing for flexible DC fabric [117]

Monsoon [91]

PortLand [160]

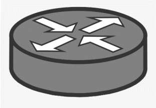
SPAIN [158]

ECMP-VLB [123]

Work by Linden et al. [215]

Work by Suchara et al. [204]

ROUTING IN LOW-DIAMETER TOPOLOGIES?



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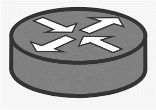

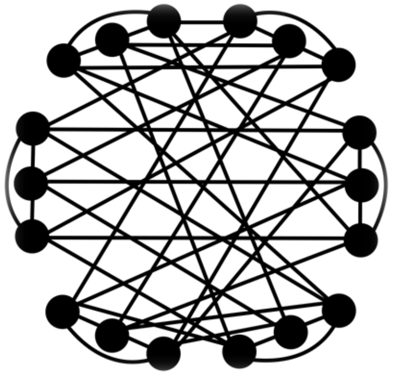

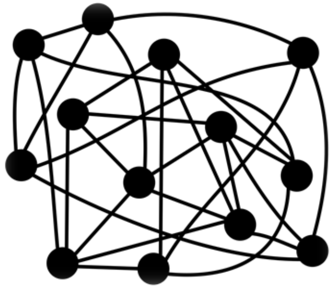

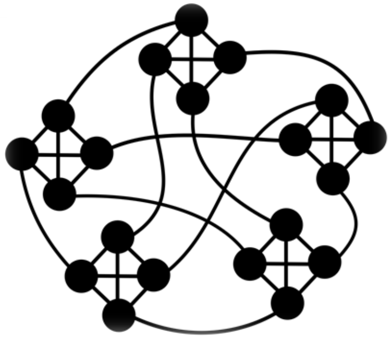

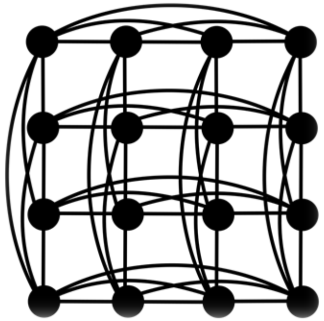

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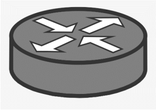
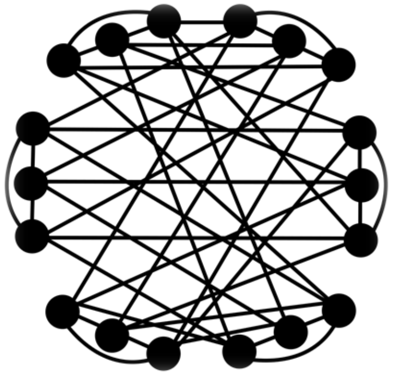
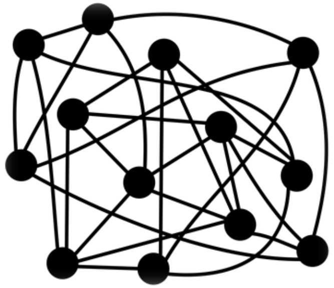
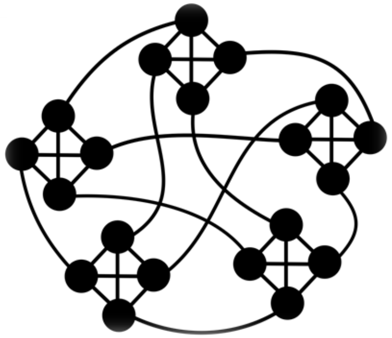
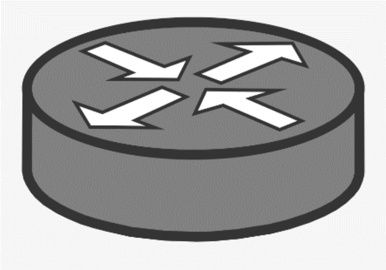


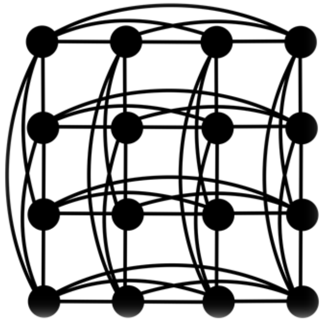




How to route modern low diameter topologies using multipathing?







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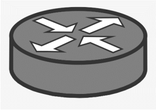
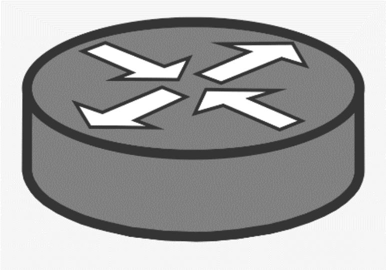
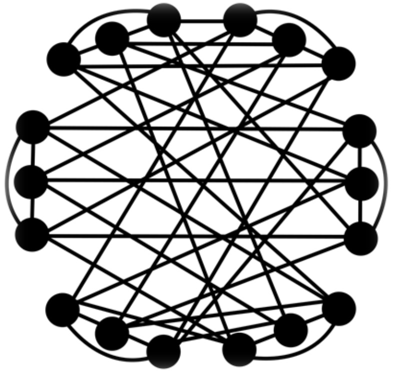
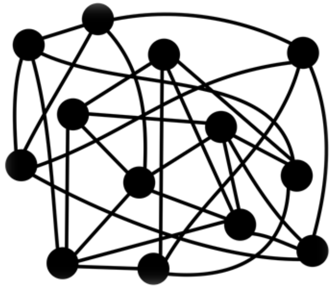


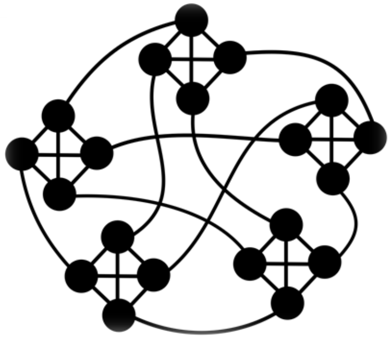
How to route modern low diameter topologies using multipathing?

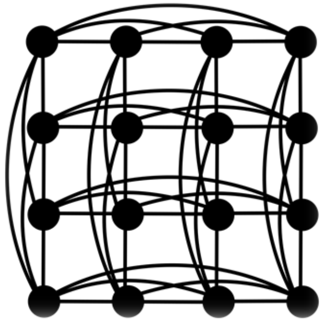
The driving question of this whole work











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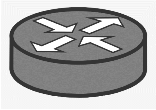
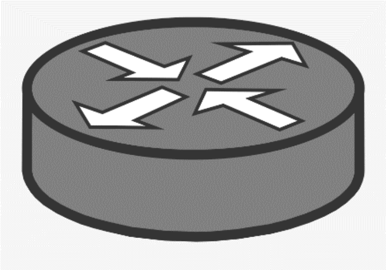
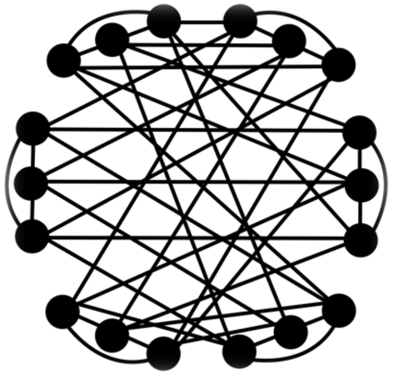


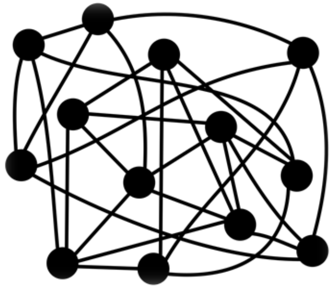
How to route modern low diameter topologies using multipathing?

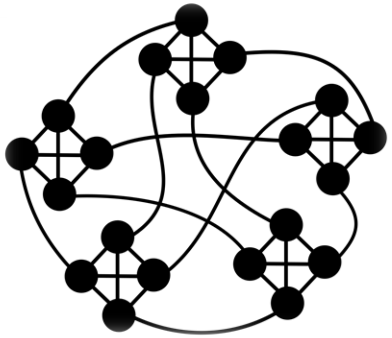
The driving question of this whole work

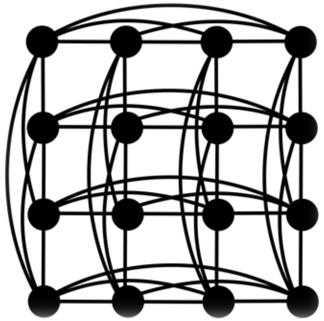


...but it touches on many aspects. Let's go!

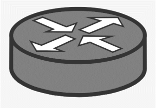








MULTIPATH ROUTING: MOTIVATION



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What are the problems that we want to tackle with multipathing?

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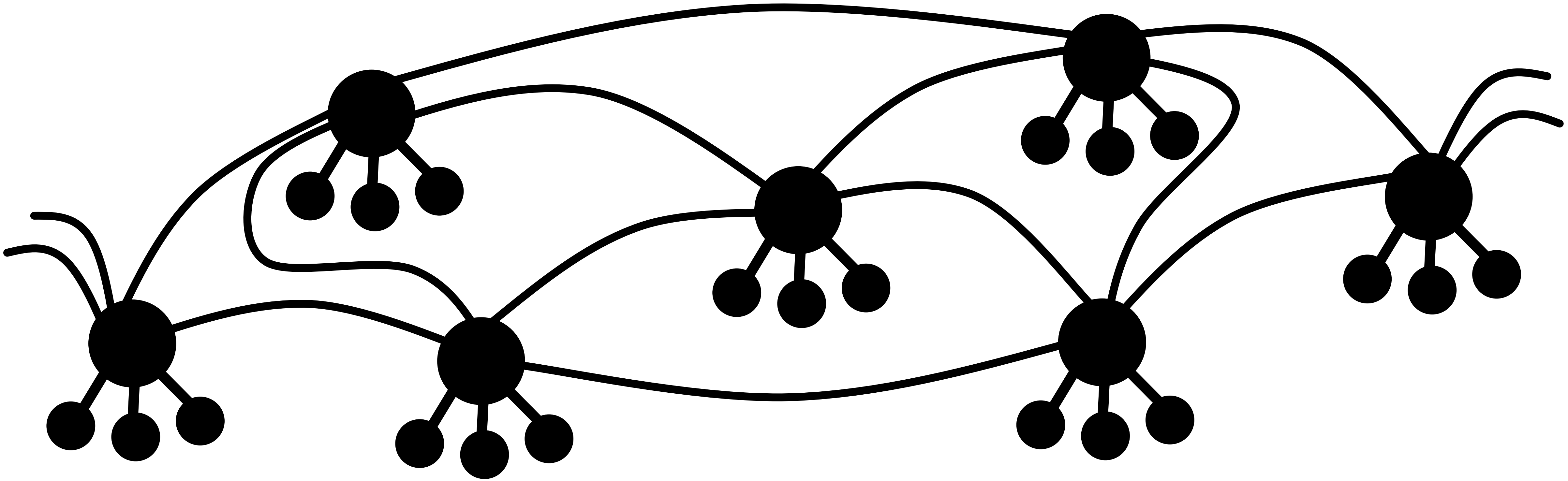

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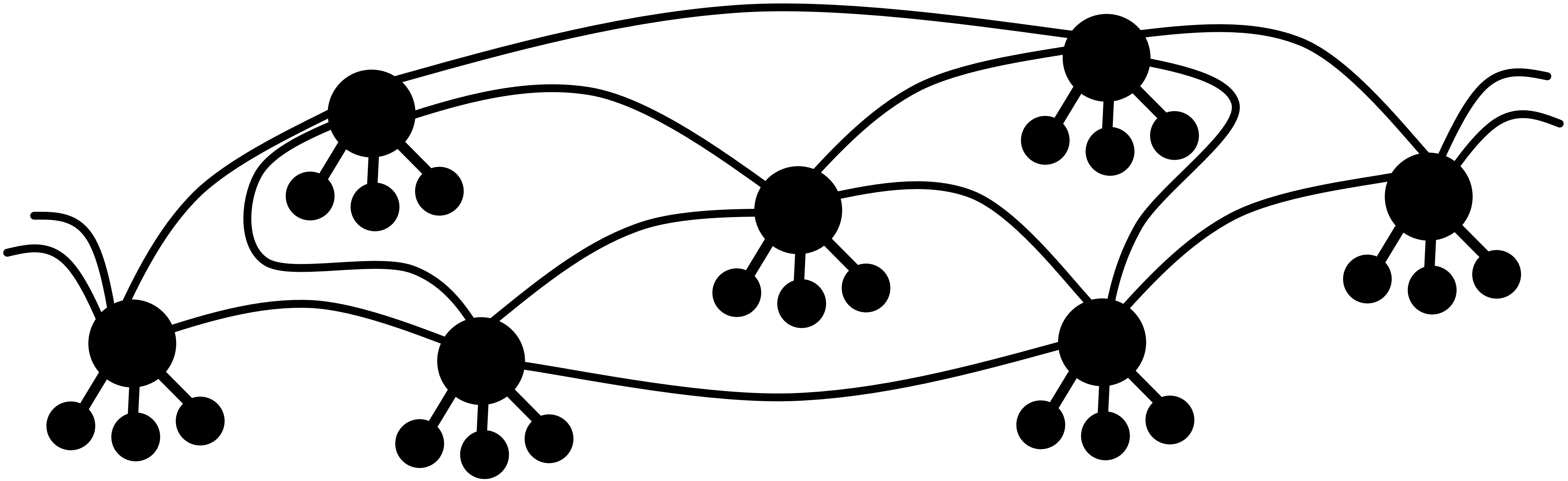

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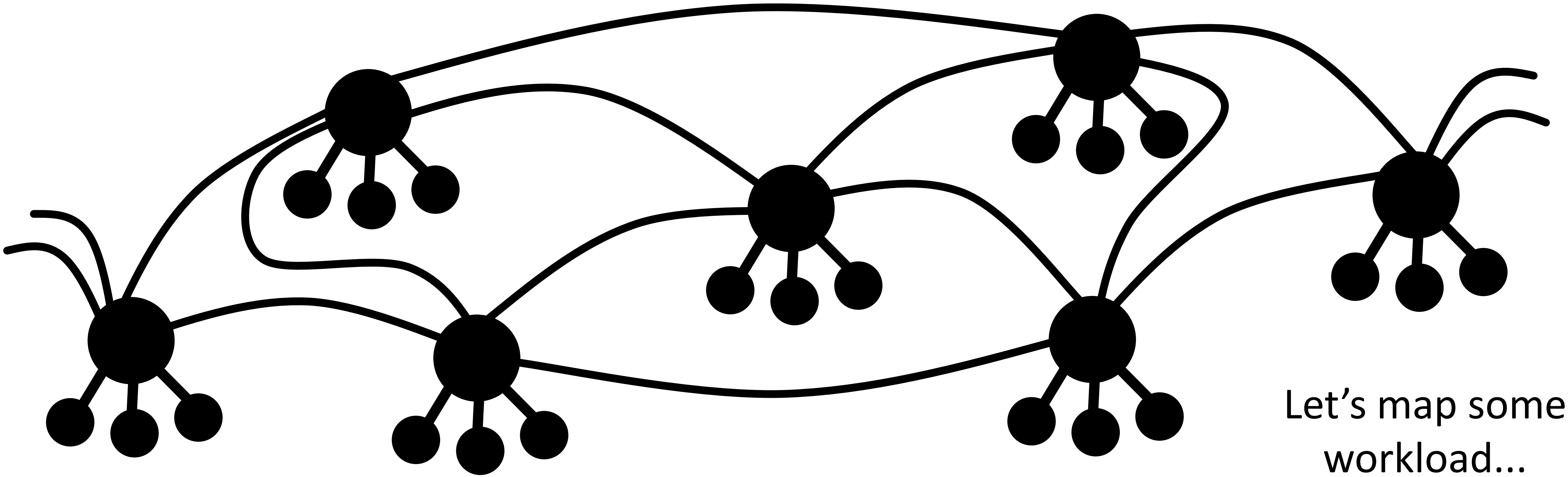

Let's map some workload...

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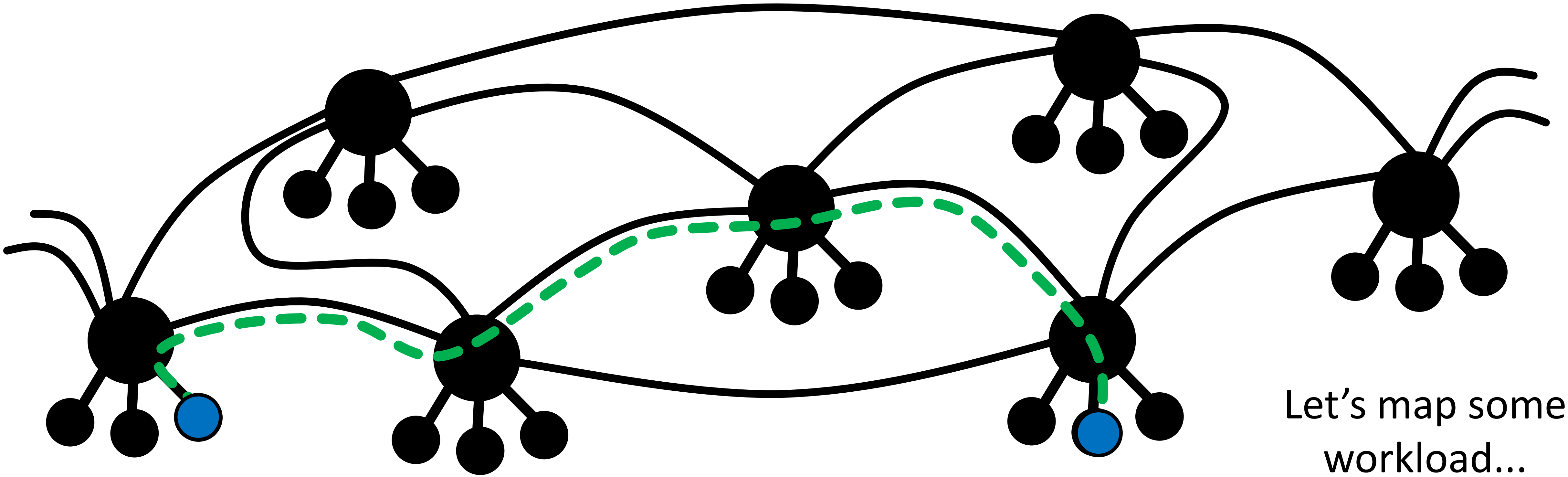

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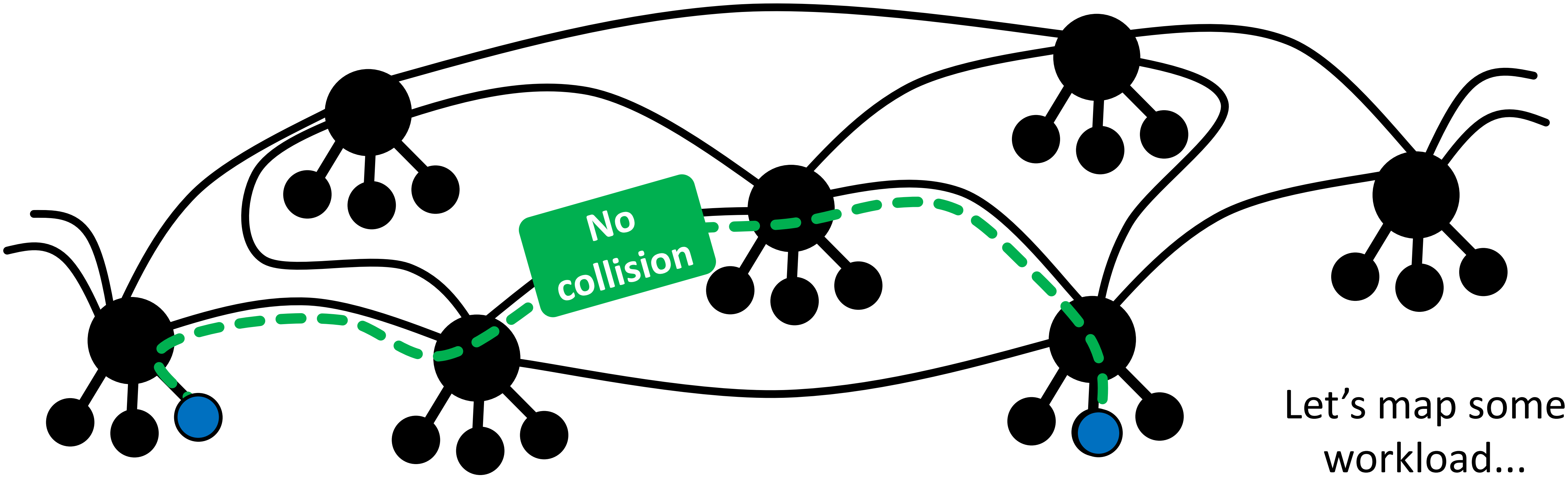

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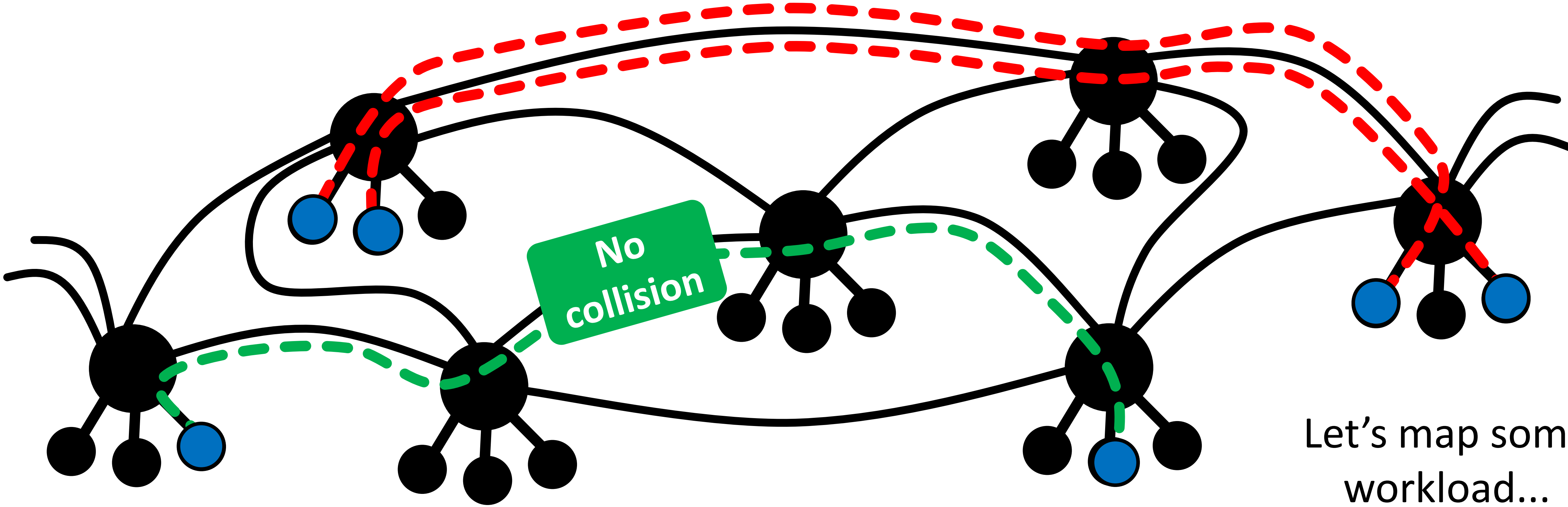

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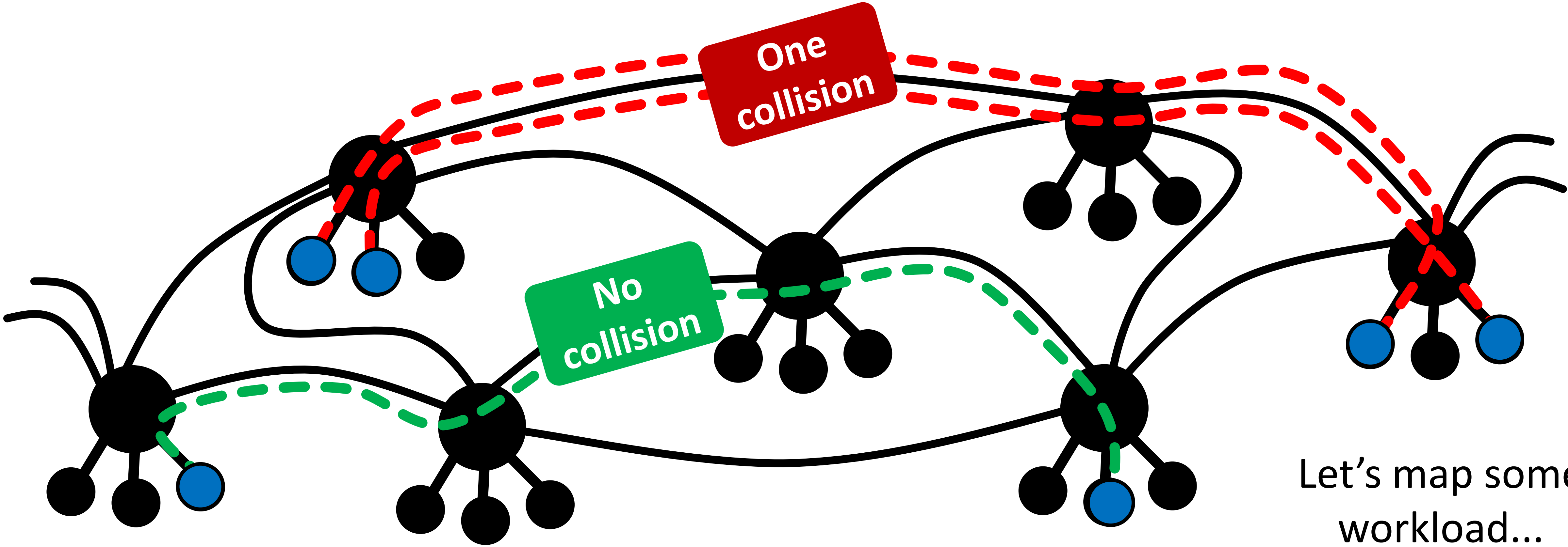

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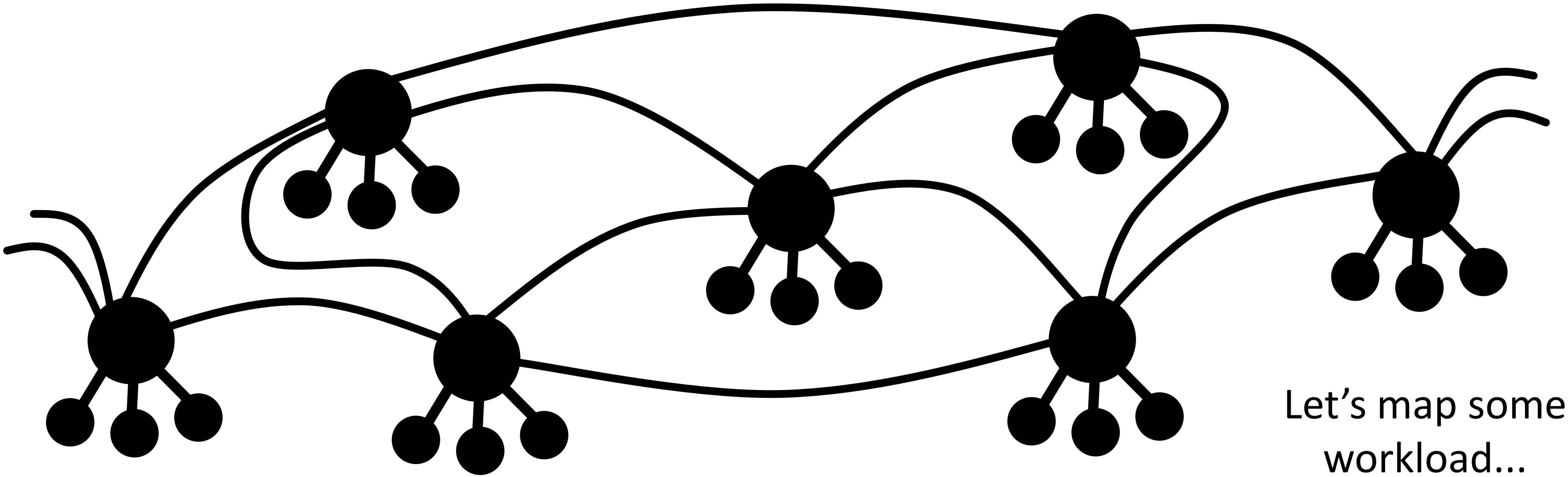

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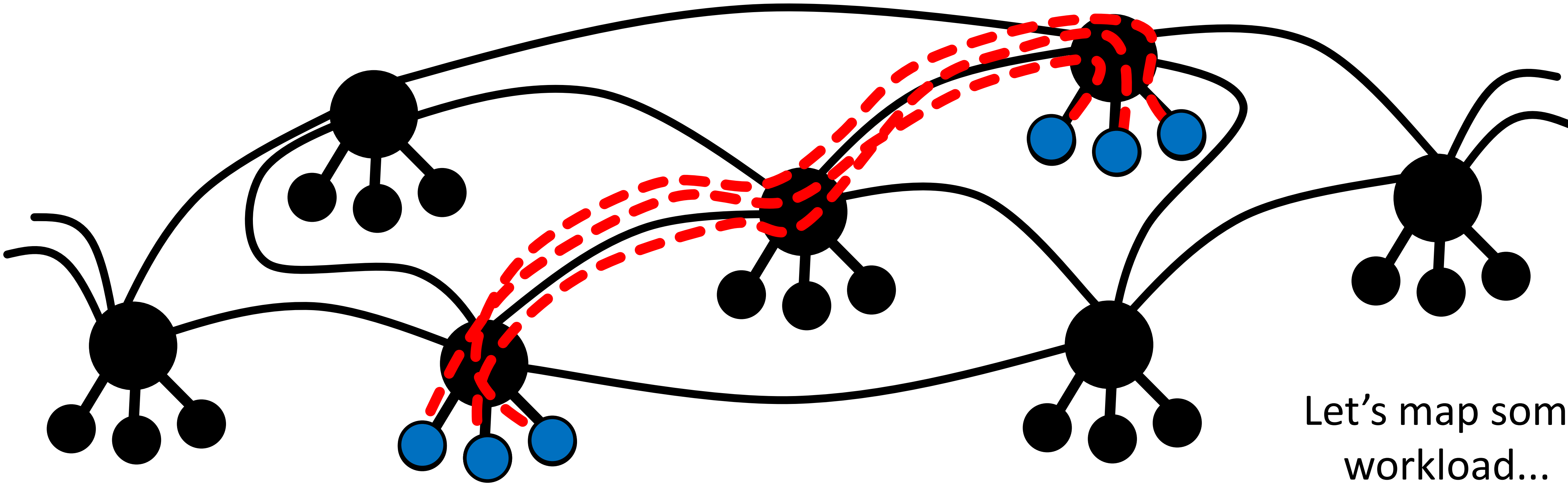

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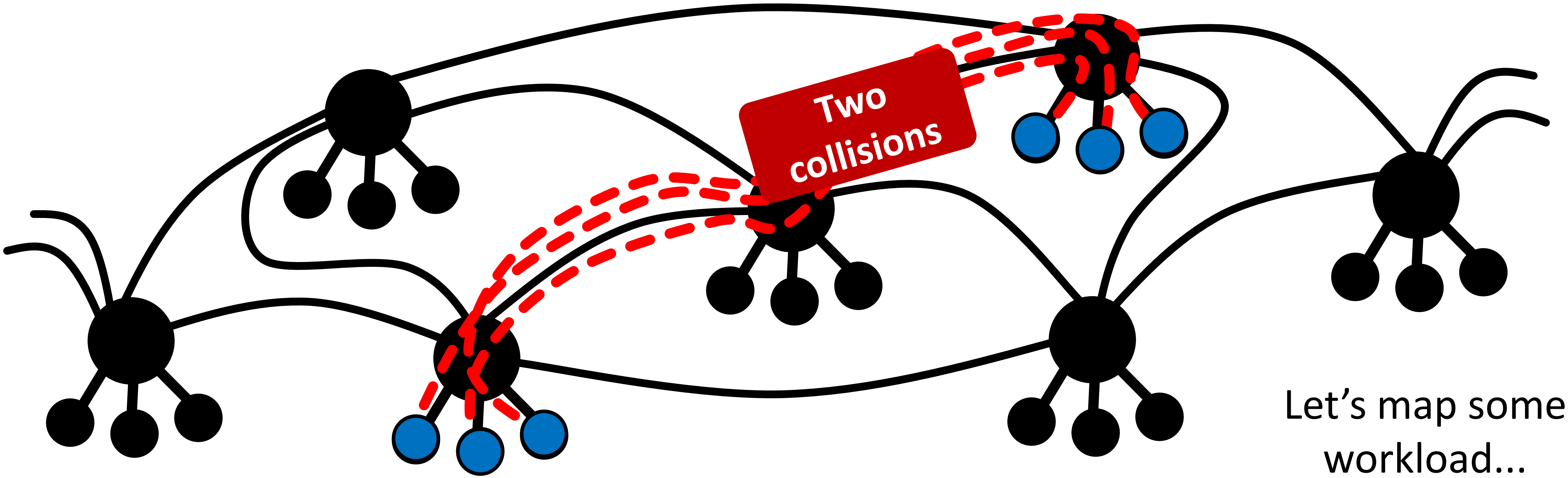

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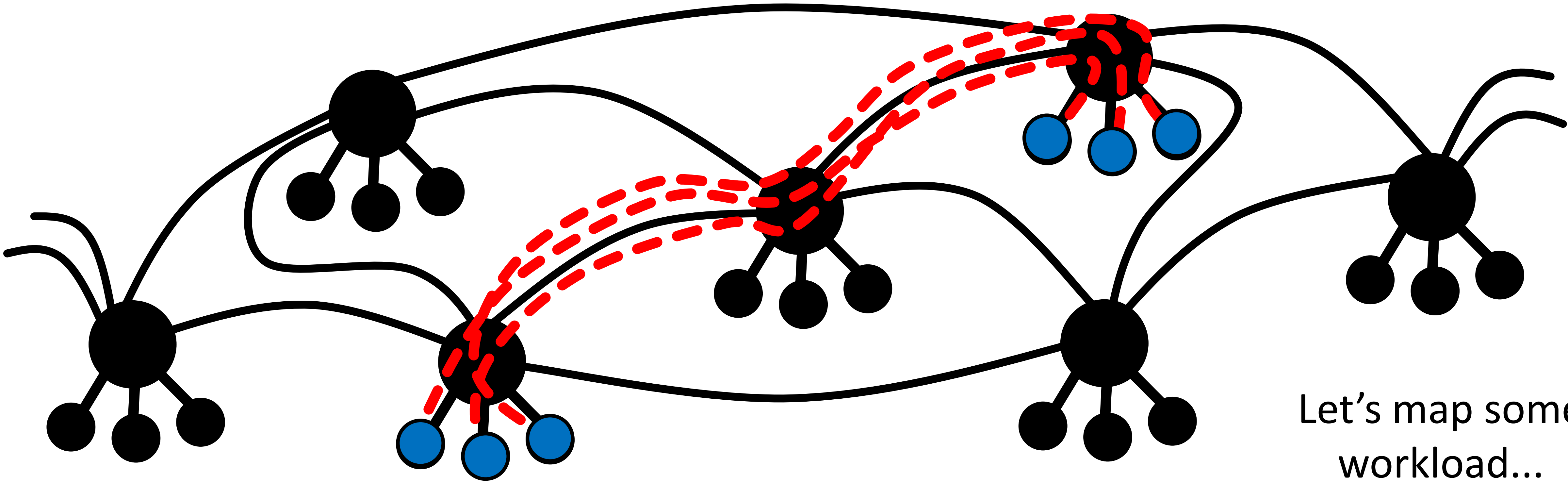

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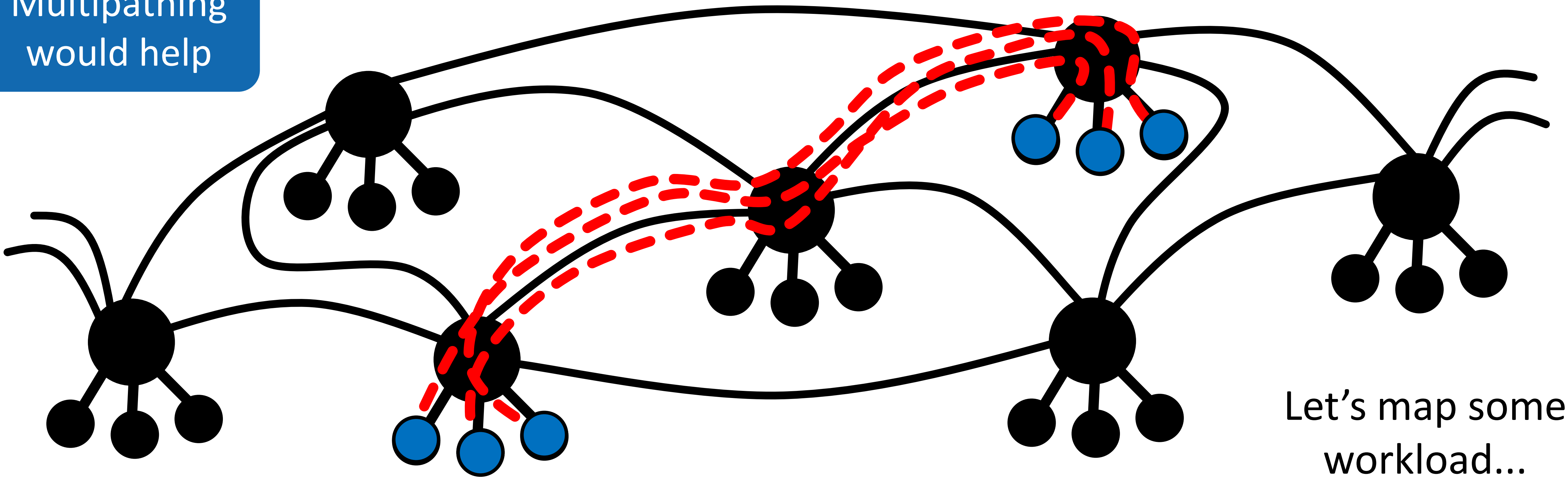

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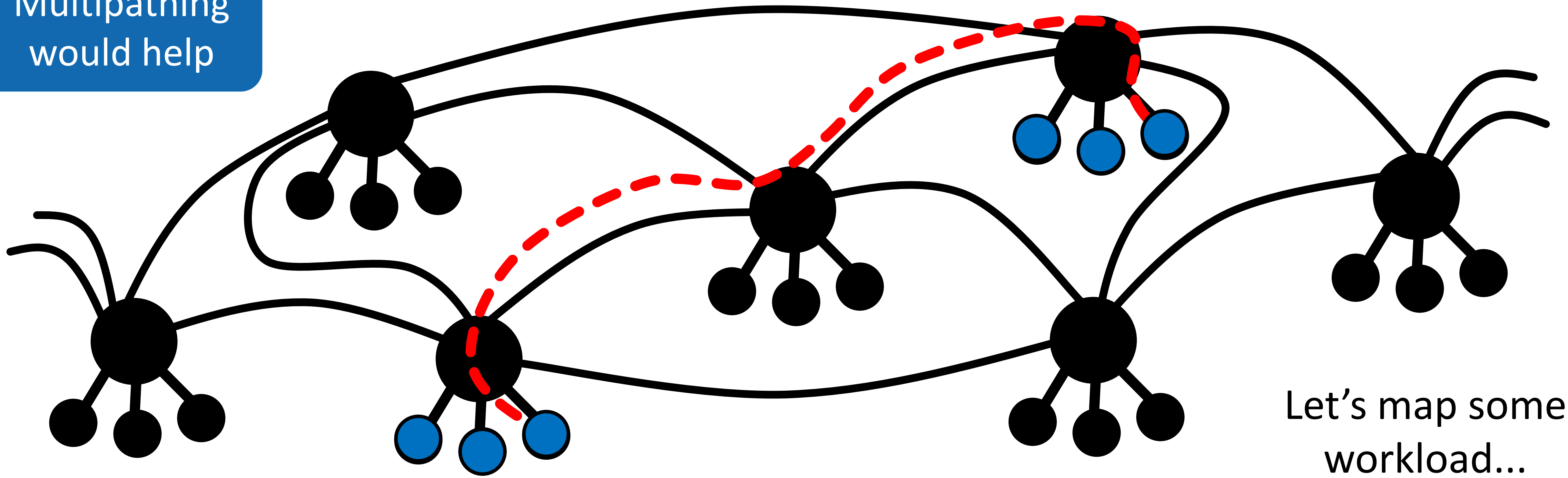

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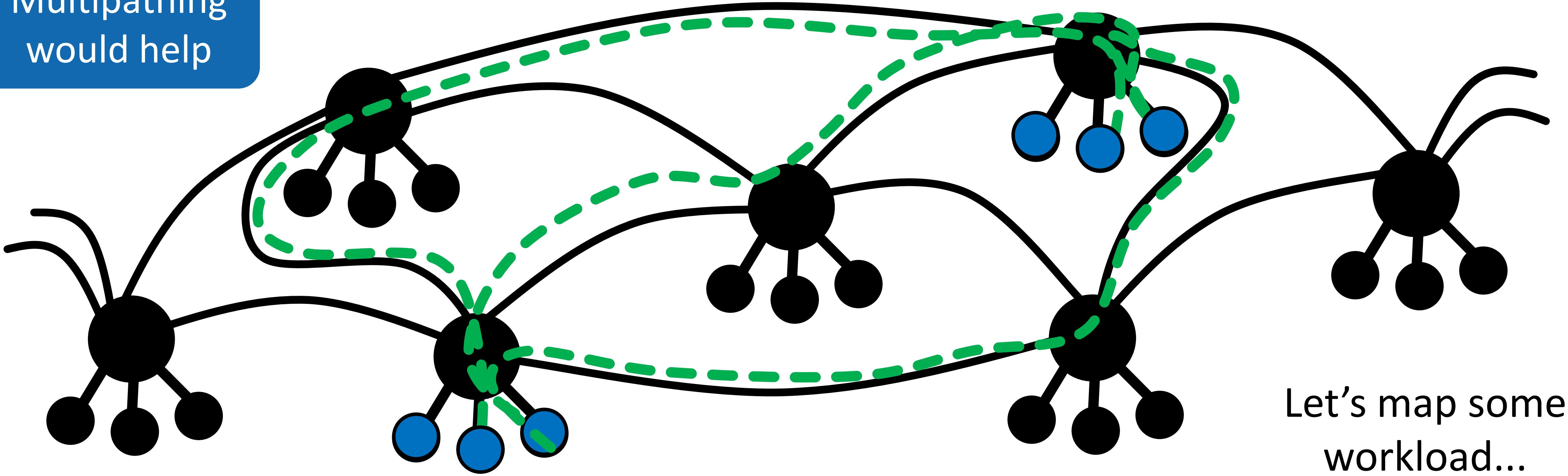

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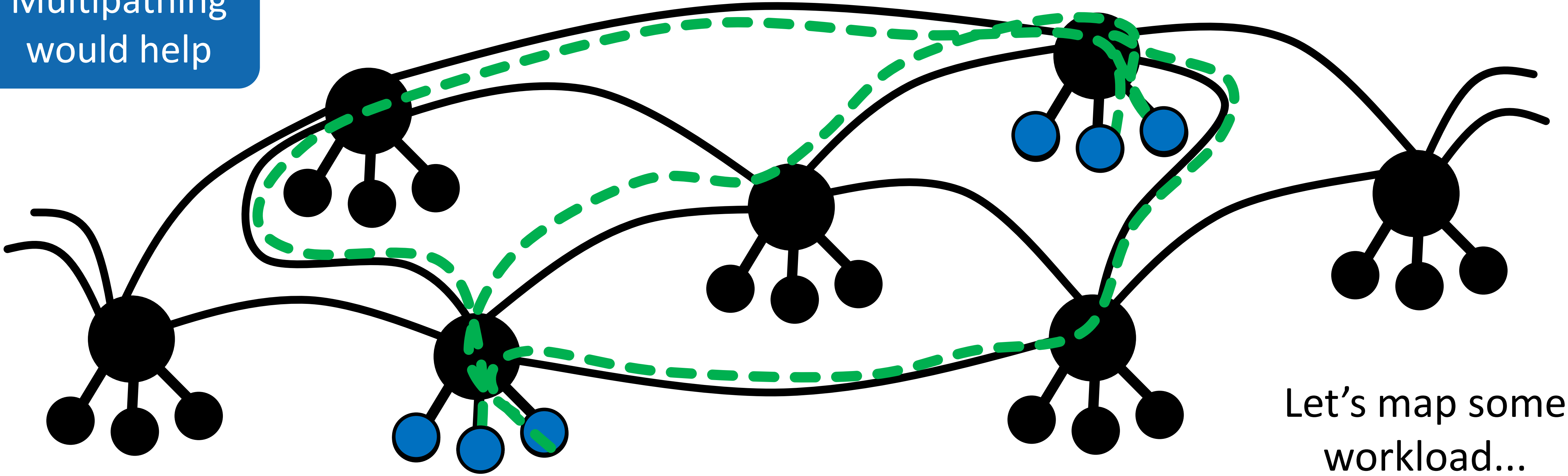

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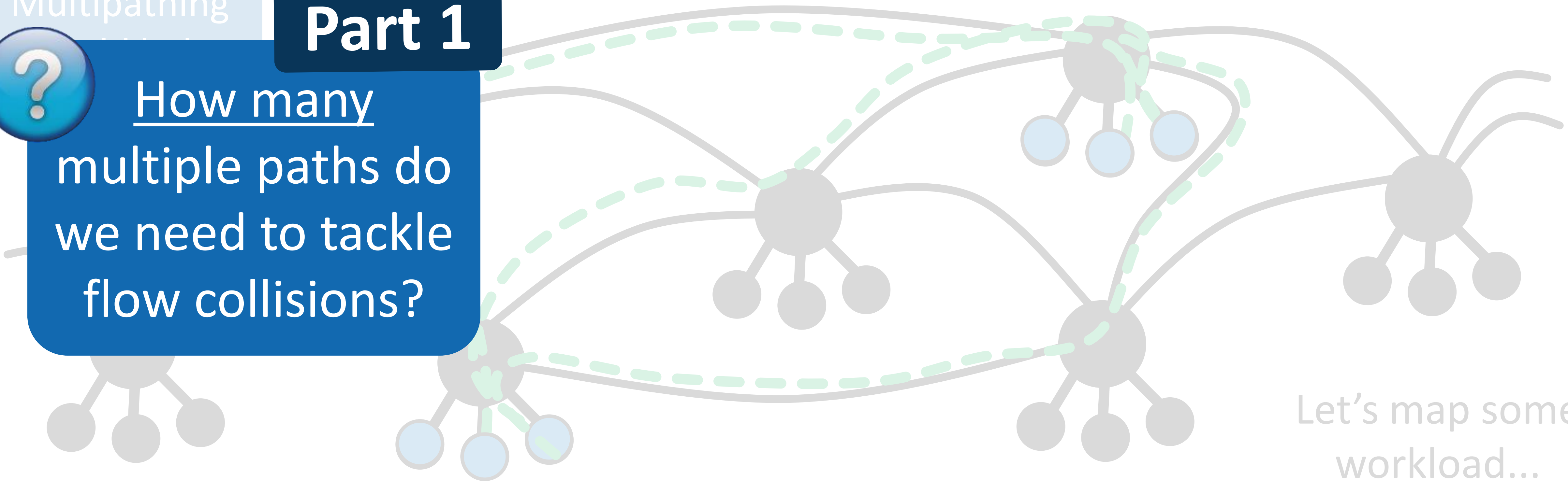

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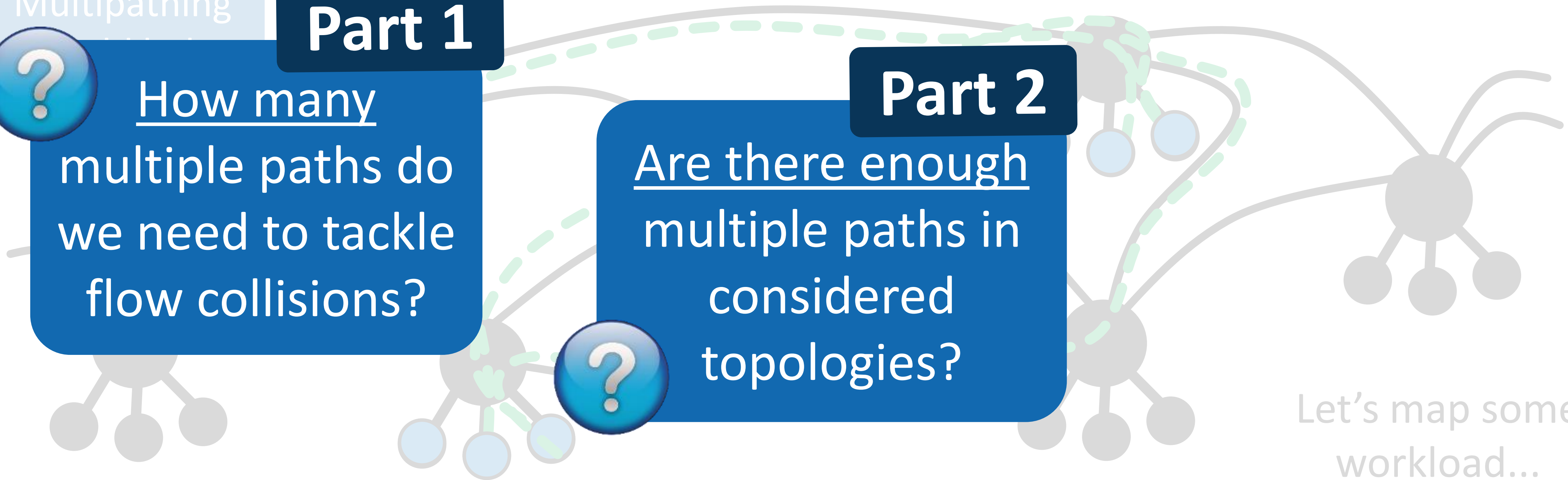

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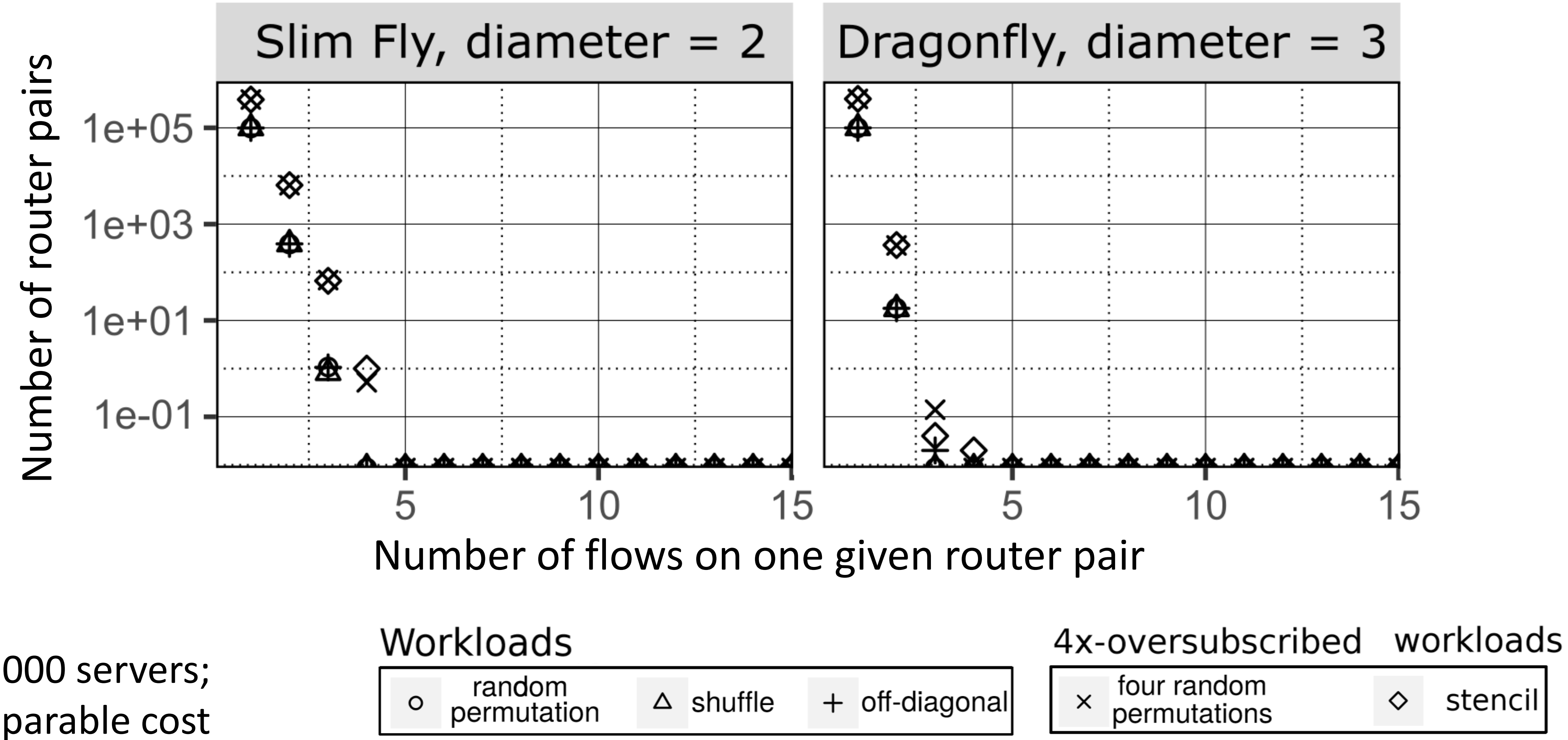

≈10,000 servers; comparable cost

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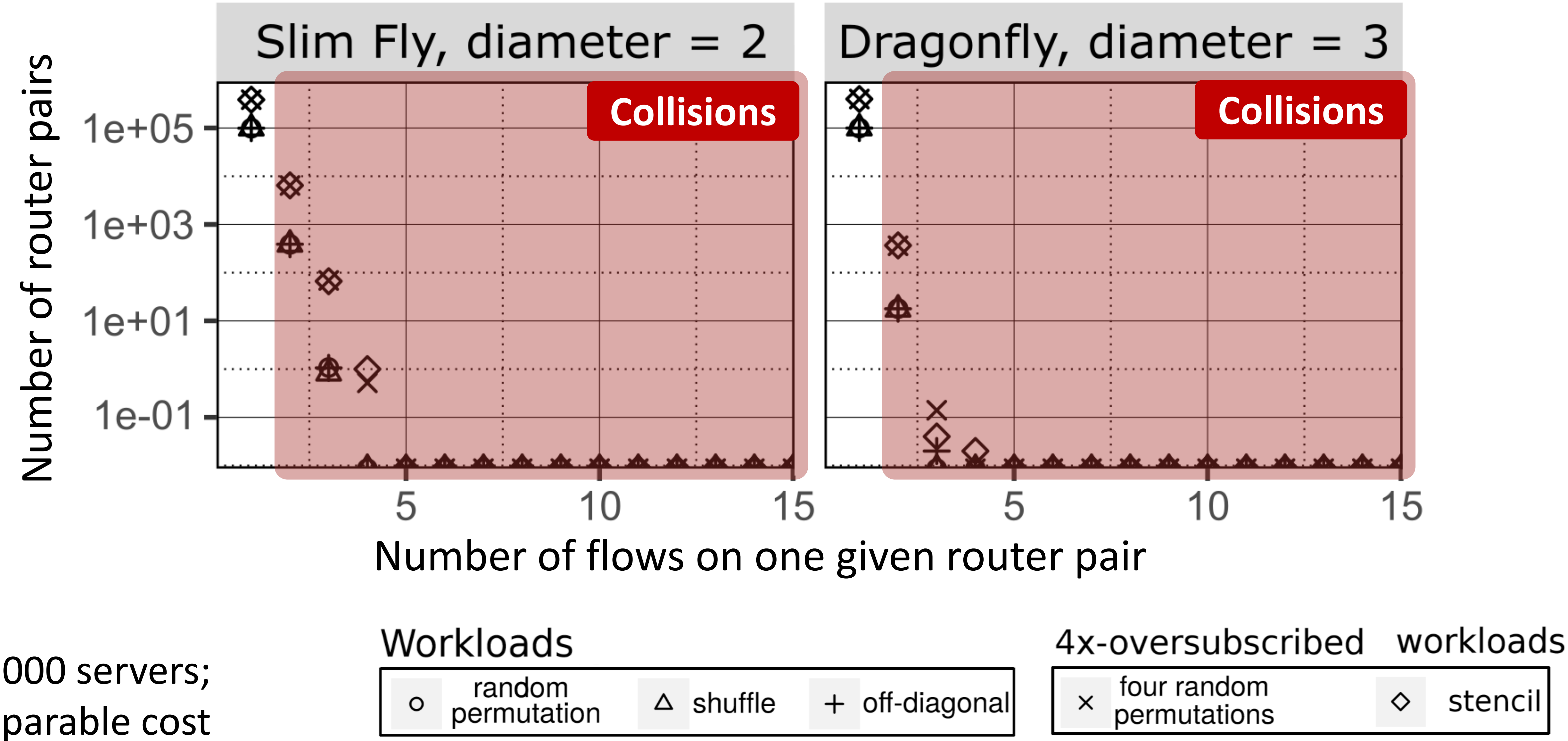

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HOW MANY MULTIPLE PATHS DO WE NEED TO TACKLE FLOW COLLISIONS?

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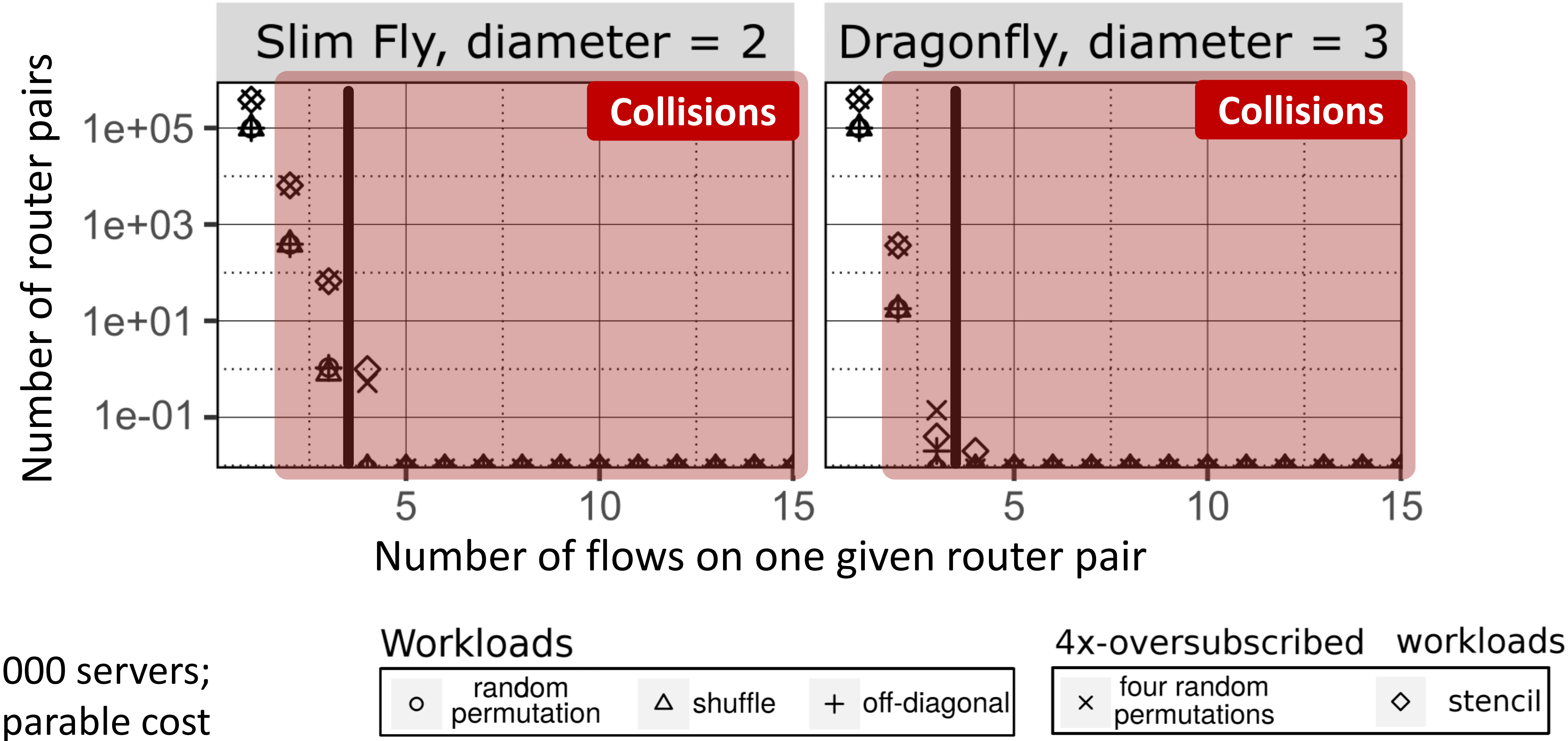

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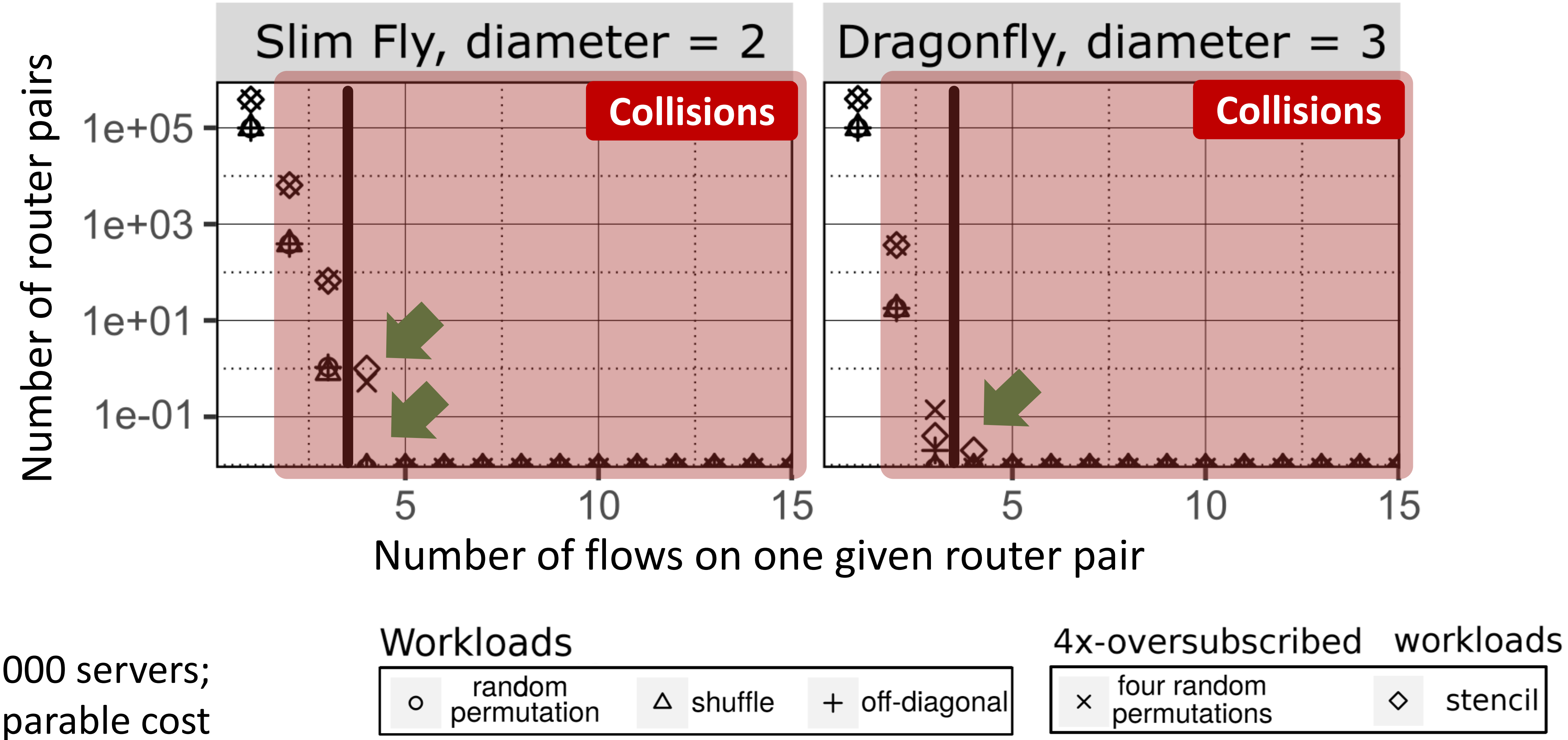

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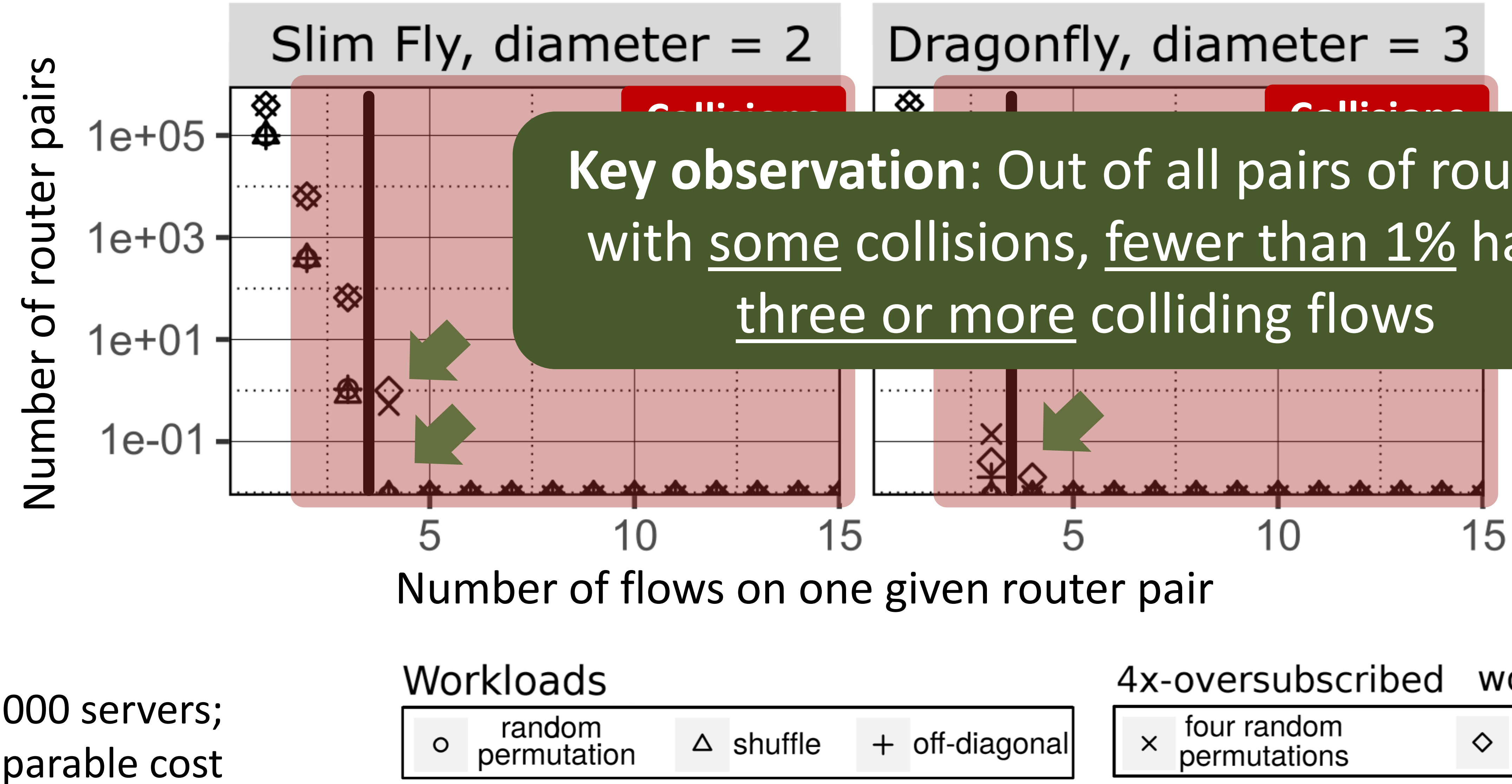

Key observation: Out of all pairs of routers with <u>some</u> collisions, <u>fewer than 1%</u> have <u>three or more</u> colliding flows

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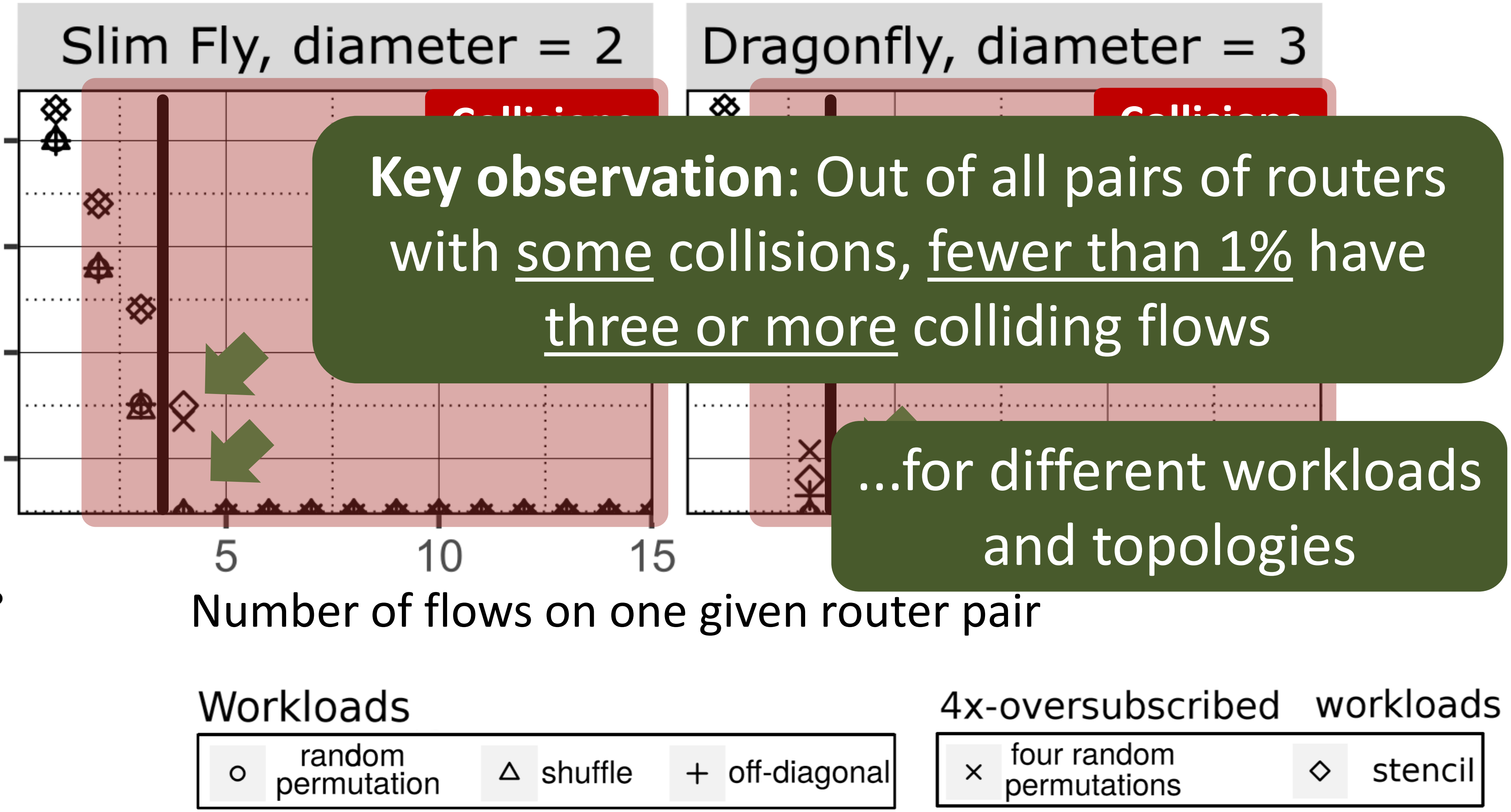

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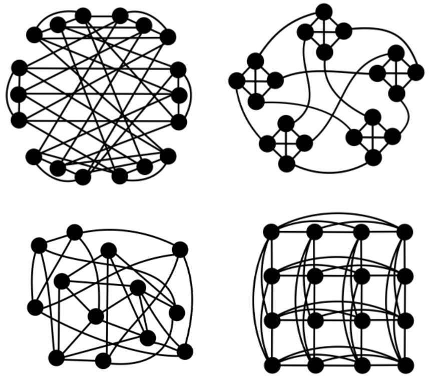
...for different workloads and topologies



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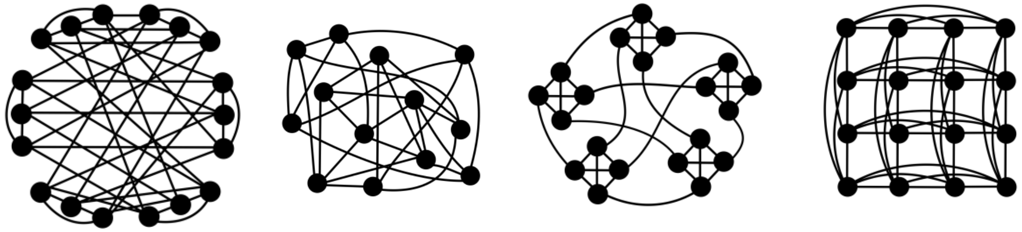
...For different topologies



...For different workloads

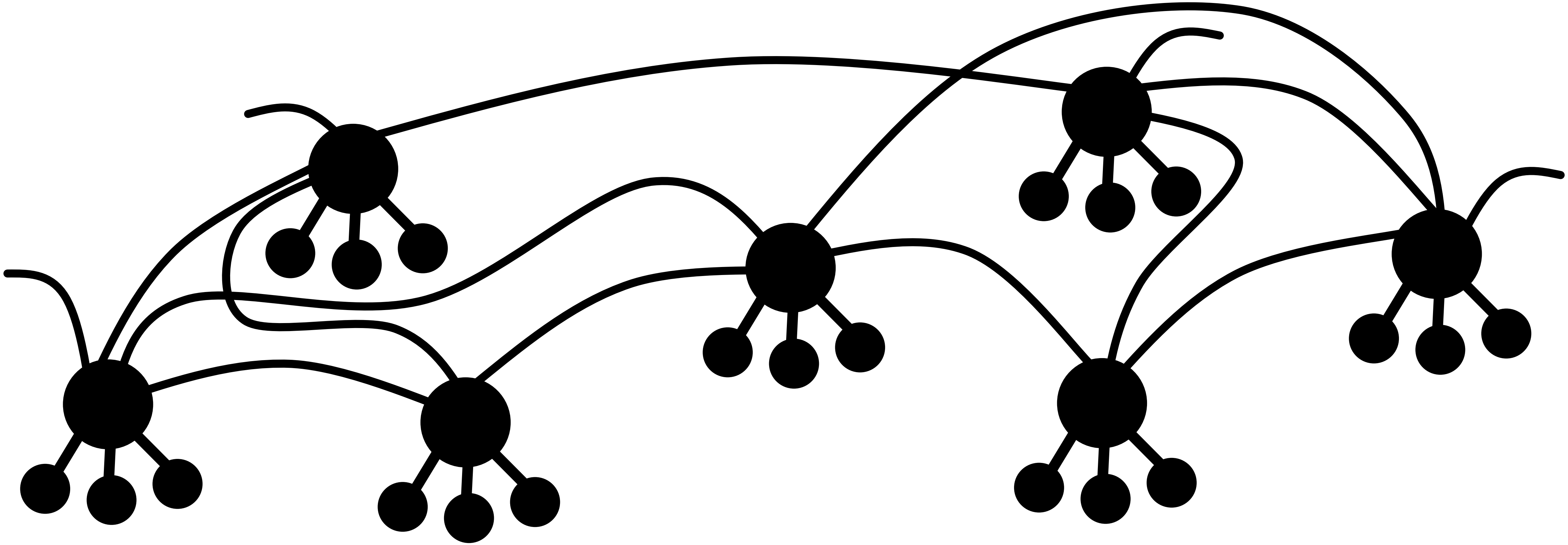
Random uniform

Off-diagonal

Stencil

Shuffle

...



How many multiple paths do we need to tackle flow collisions?

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Key Insight: We need **three** disjoint paths per router pair to handle [almost all] colliding flows

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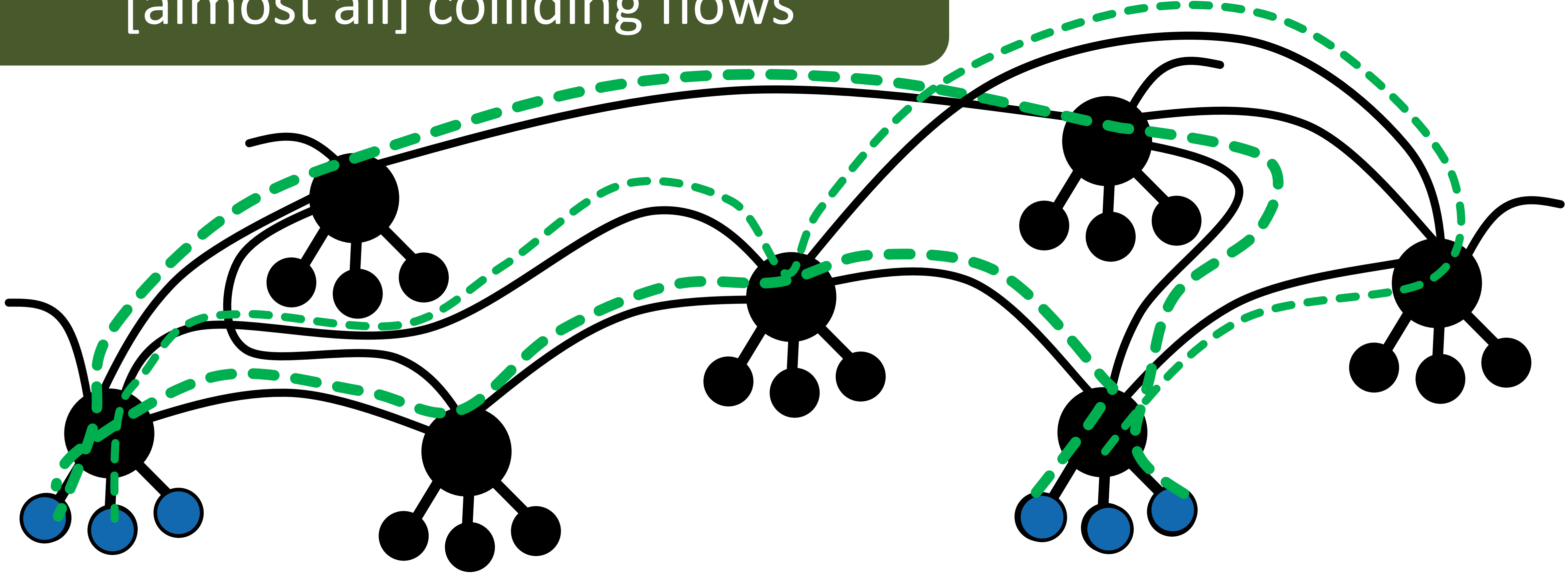

HOW MANY MULTIPLE PATHS DO WE NEED TO TACKLE FLOW COLLISIONS?

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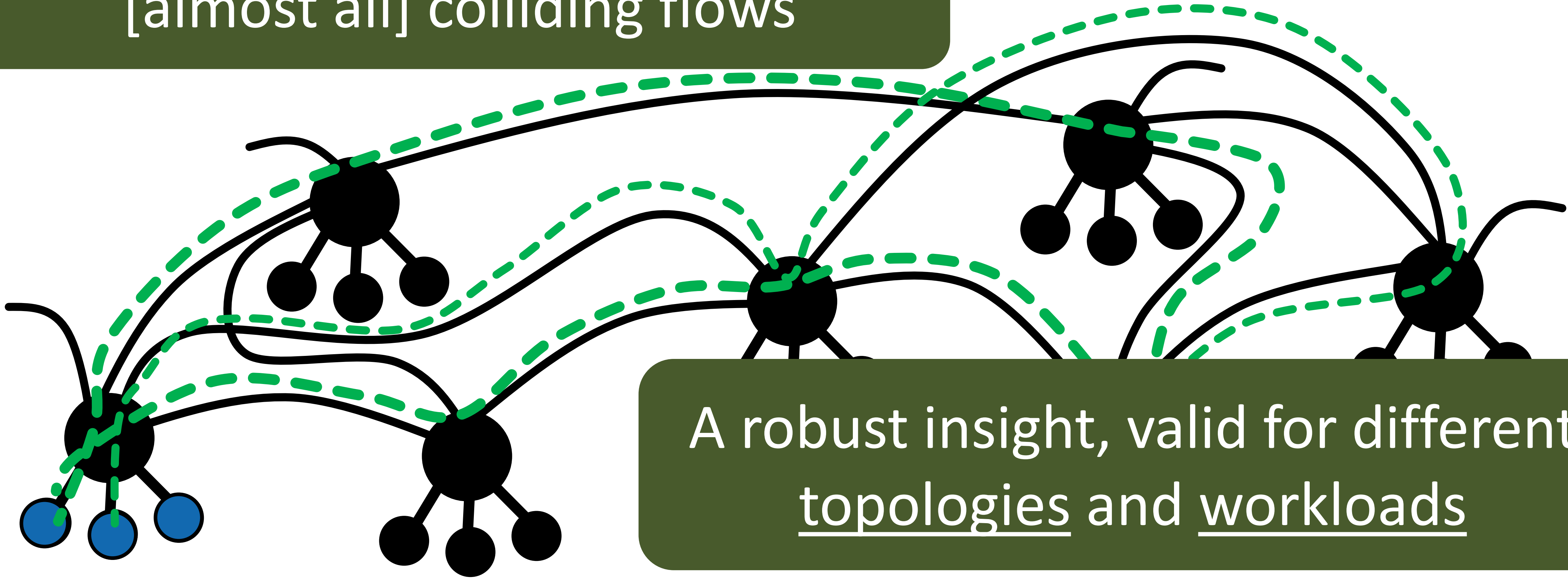

A robust insight, valid for different topologies and workloads

How many multiple paths do we need to tackle flow collisions?

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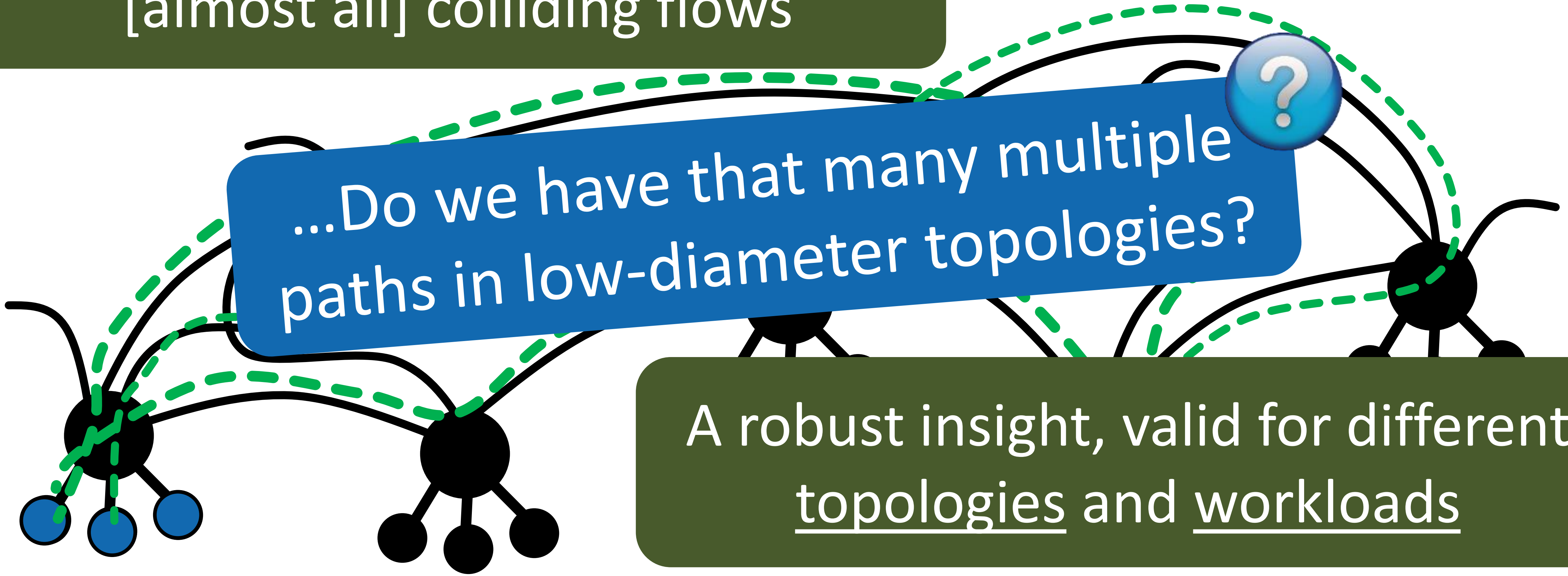

…Do we have that many multiple paths in low-diameter topologies?

A robust insight, valid for different topologies and workloads

ARE THERE ENOUGH MULTIPLE PATHS IN LOW-DIAMETER TOPOLOGIES?

Part 2

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Shortest paths

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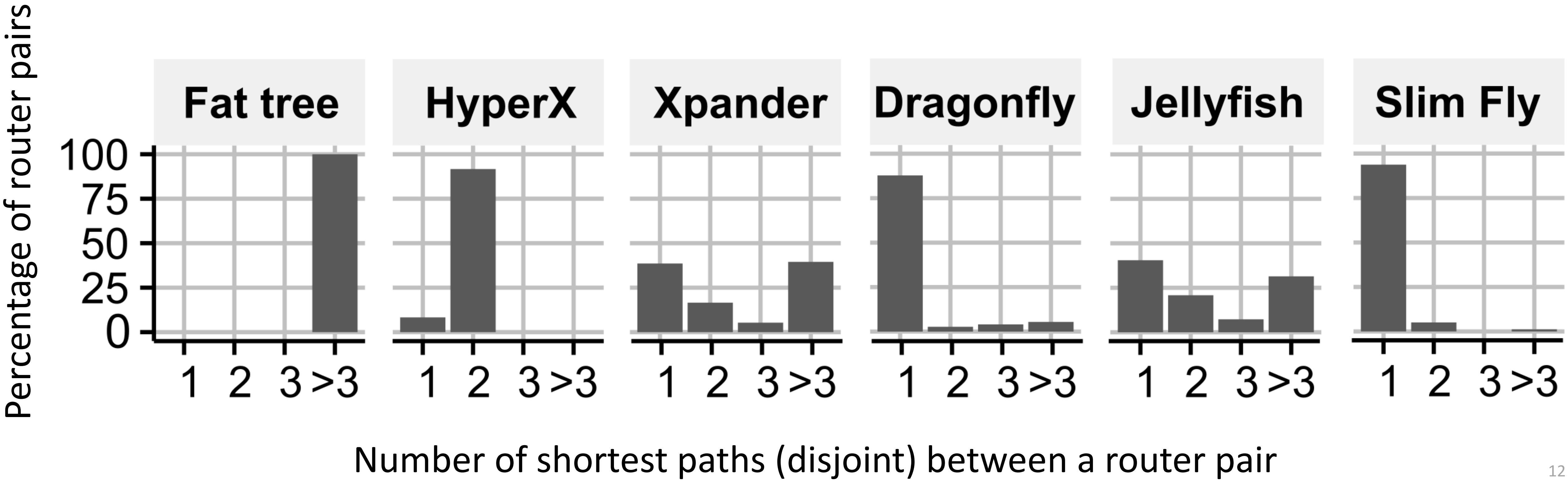

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≈10,000 servers;
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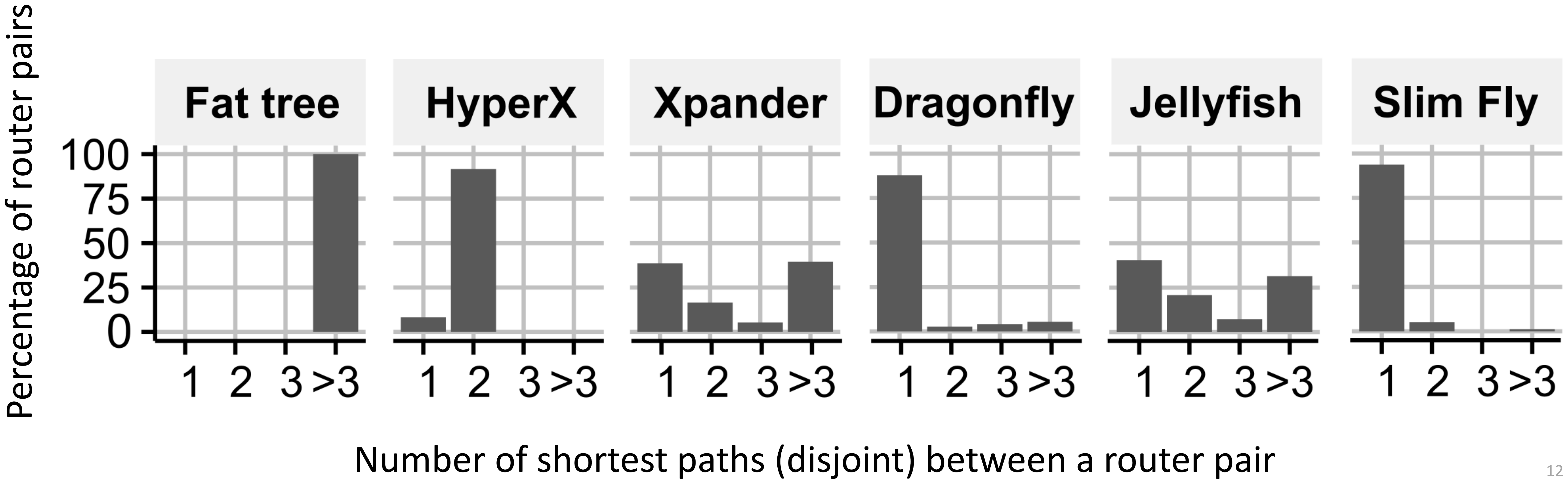

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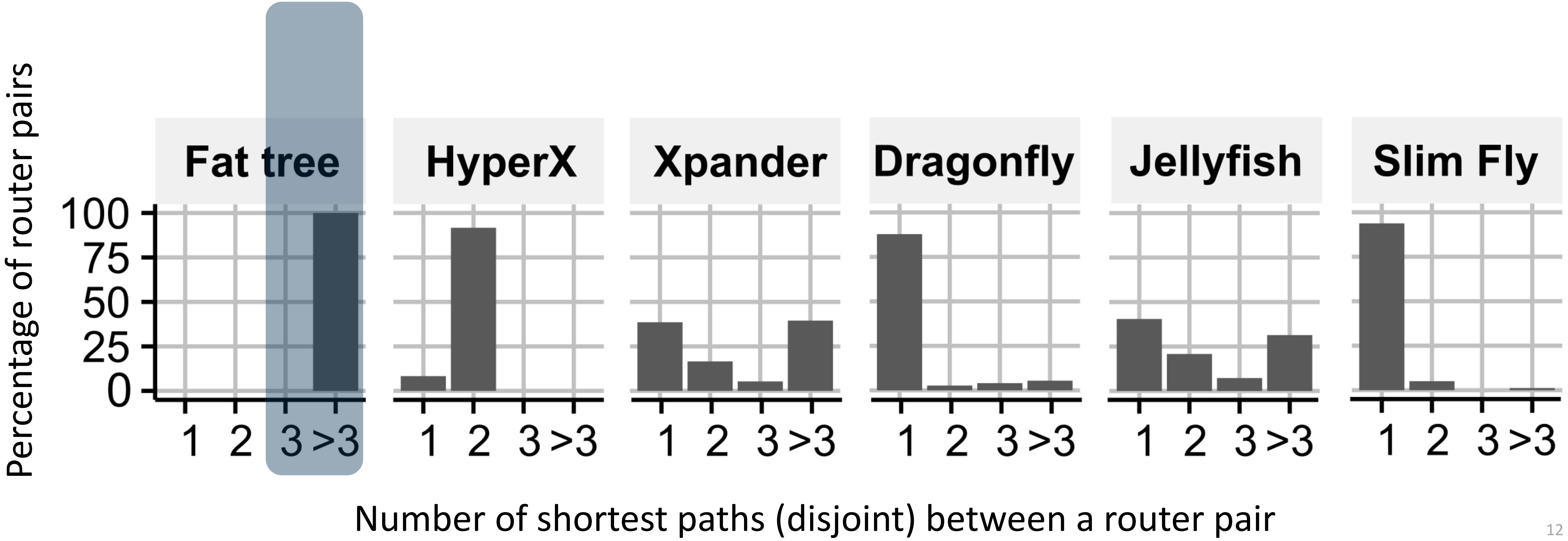

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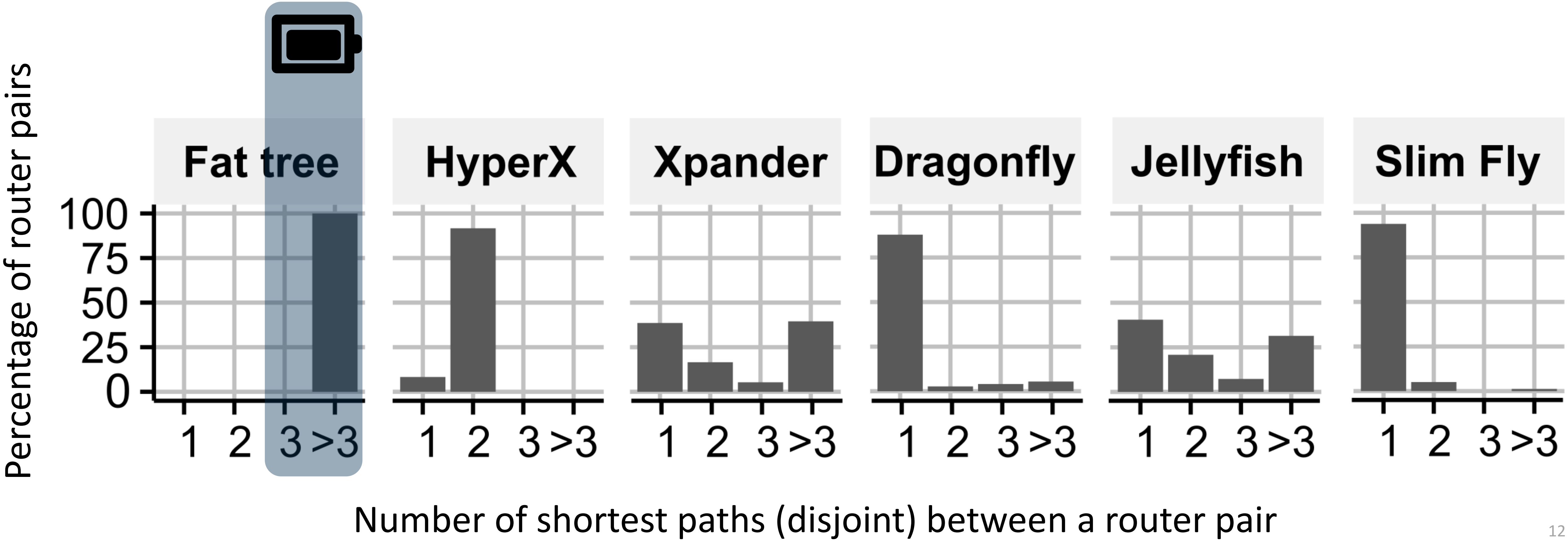

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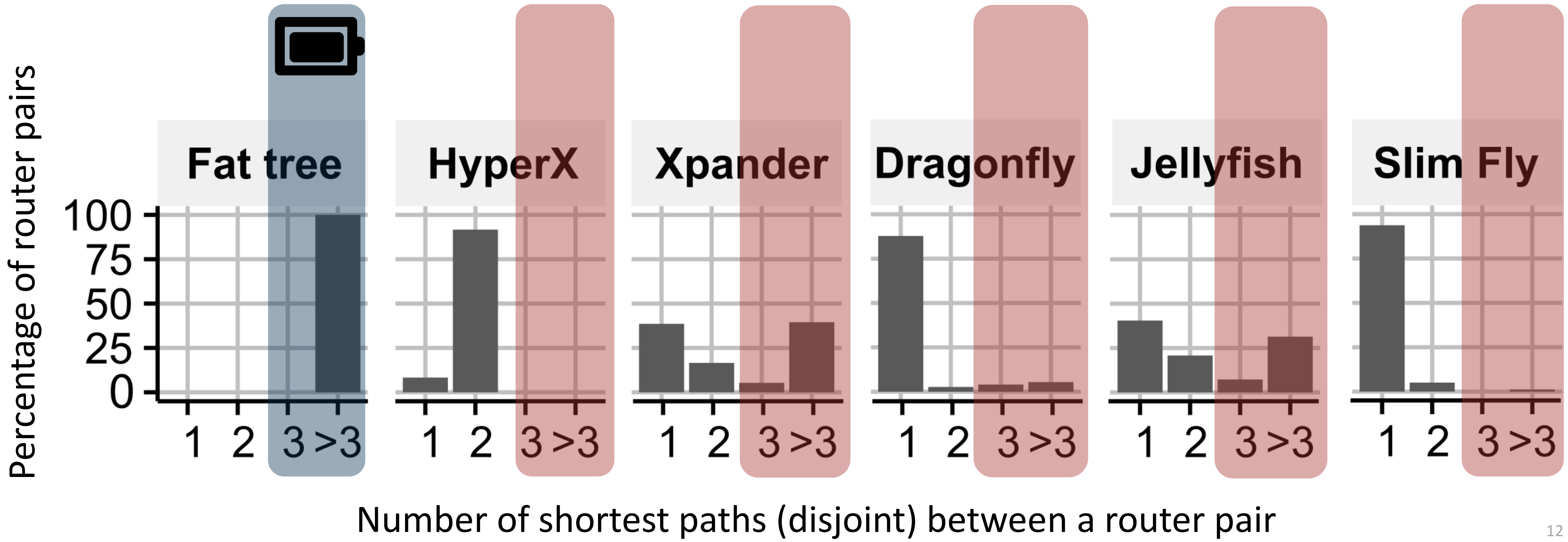

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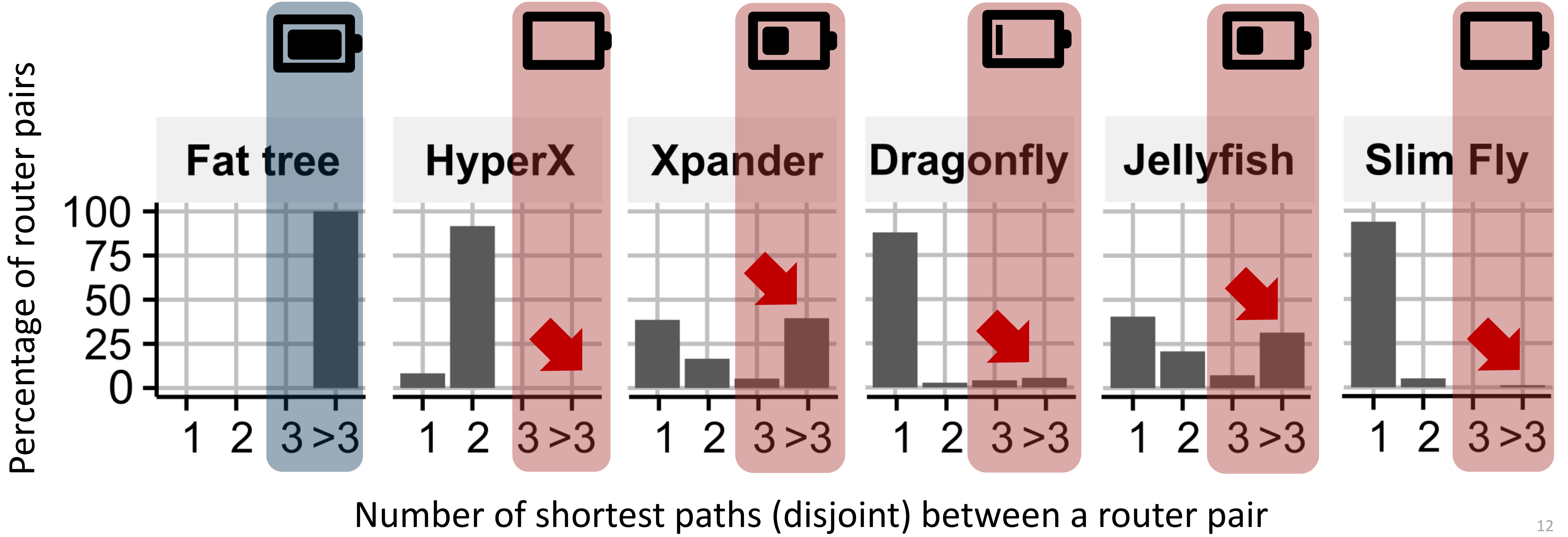

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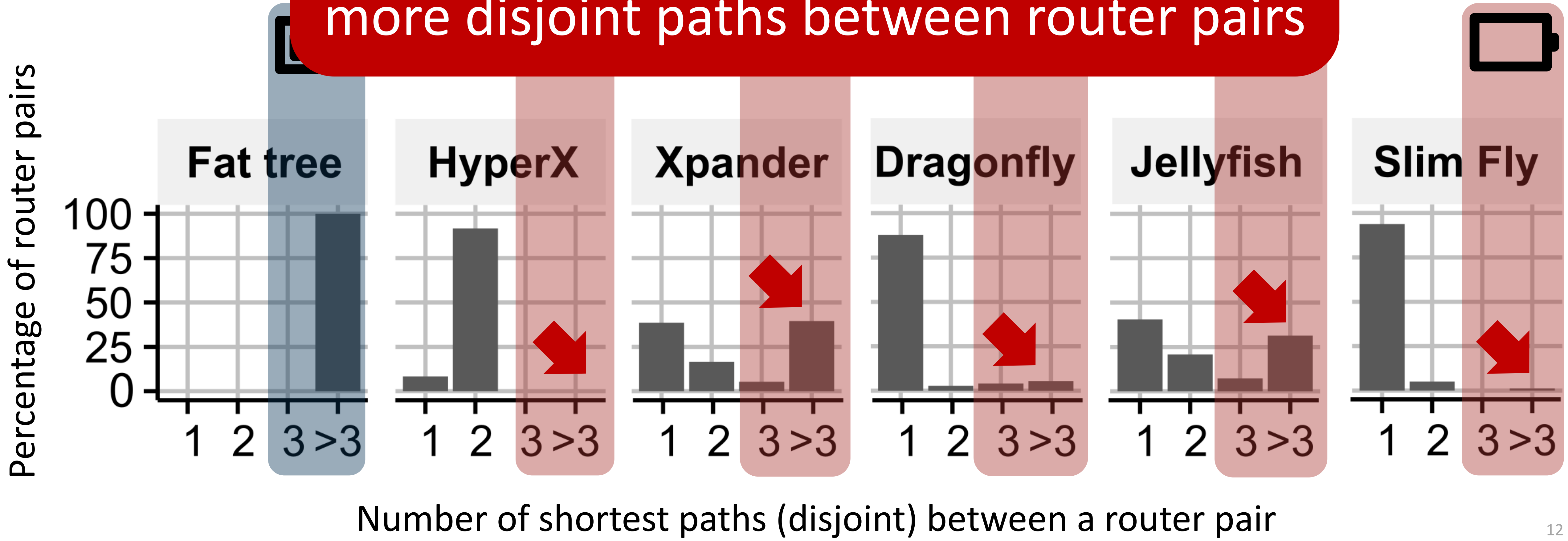
Key observation: In most cases, there is not enough path diversity for three or more disjoint paths between router pairs



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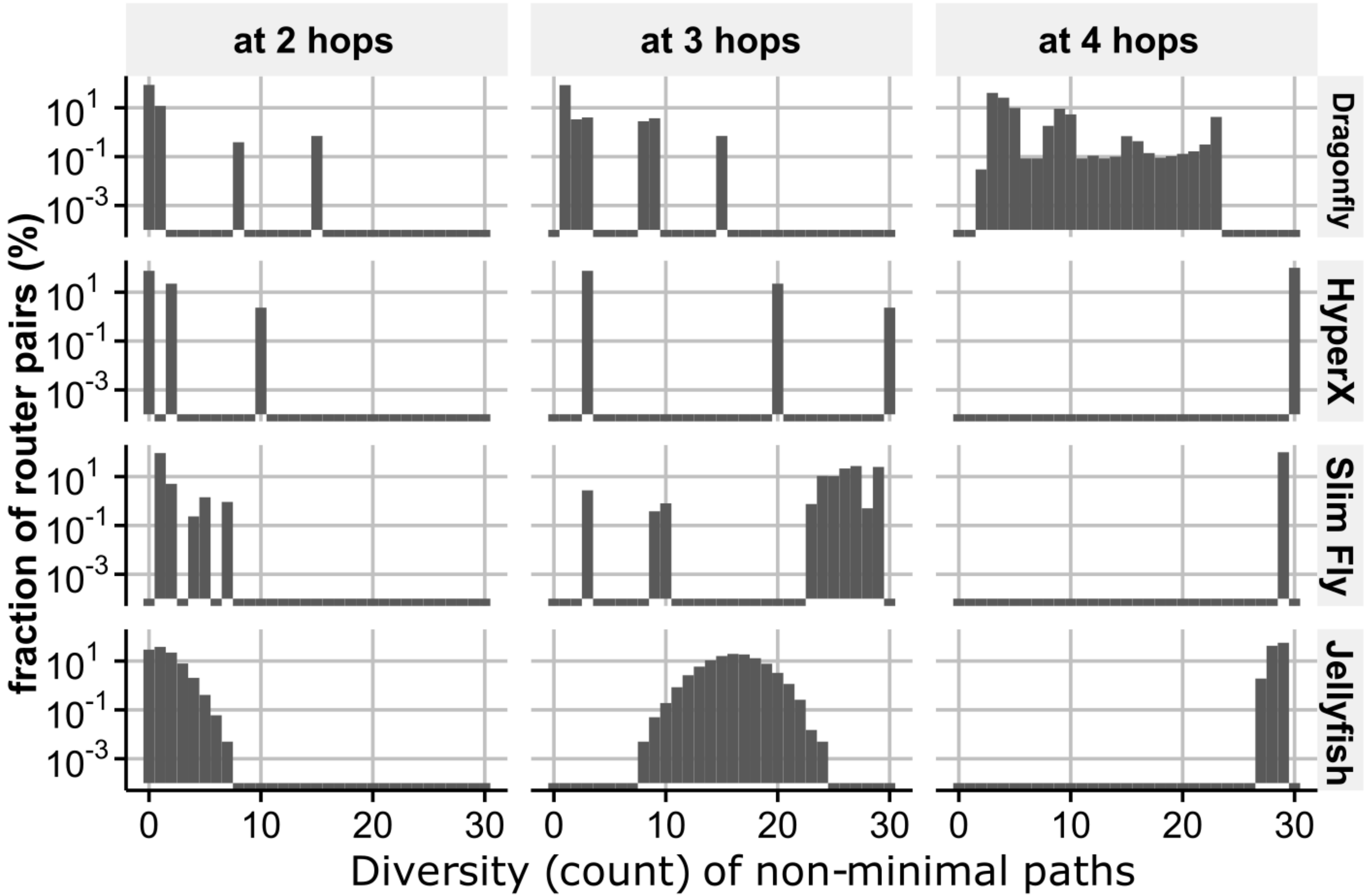

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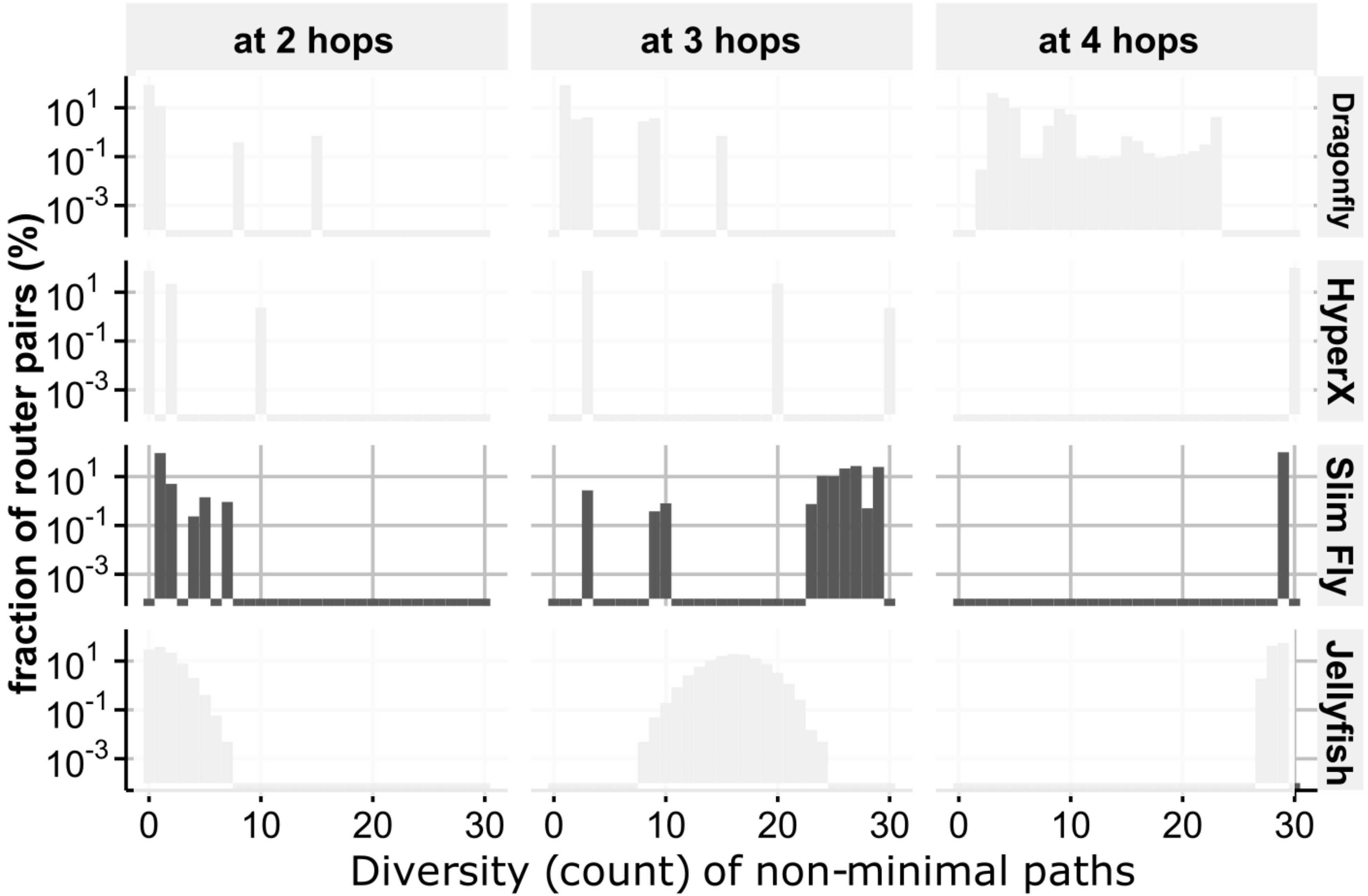

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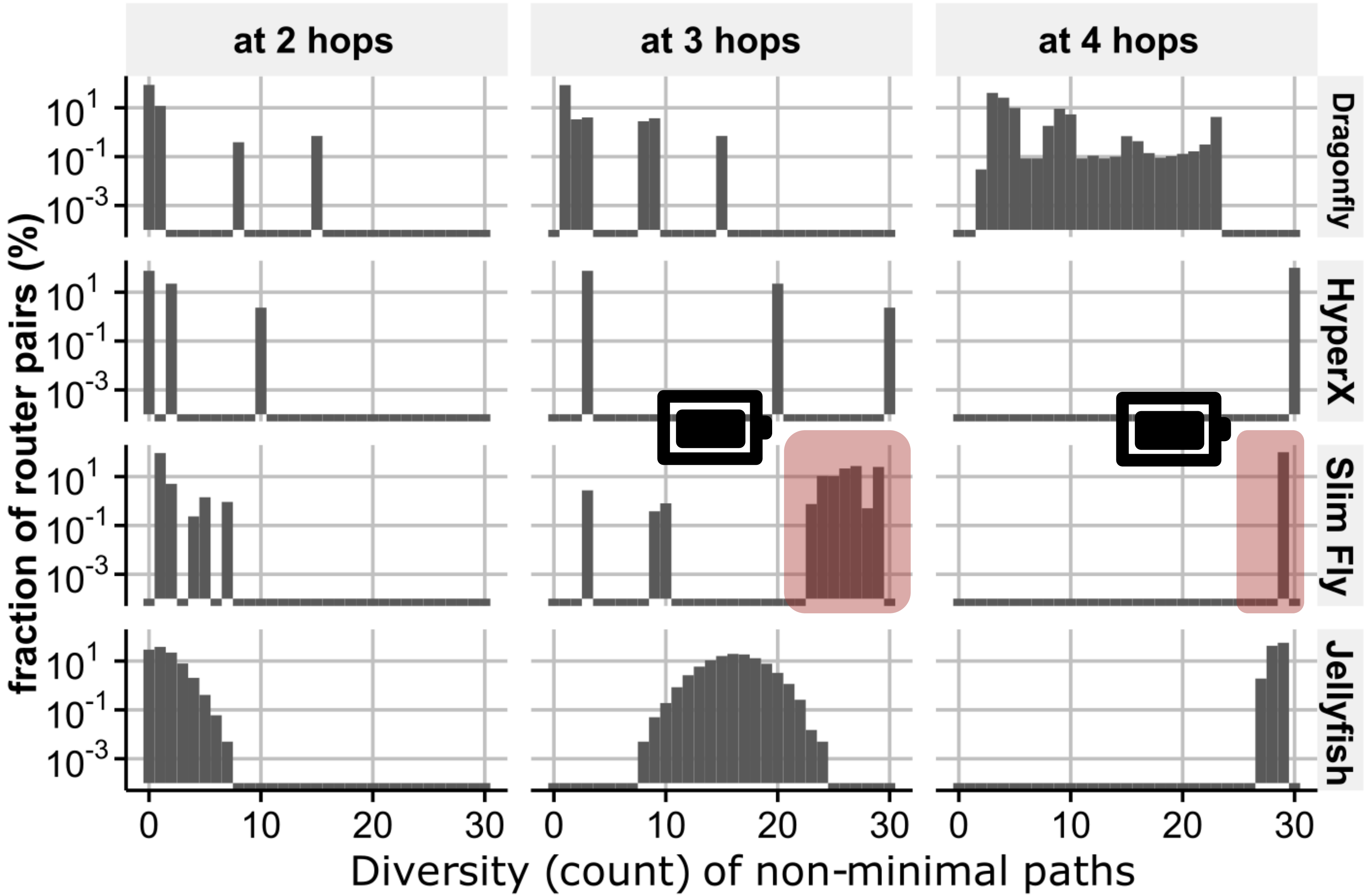

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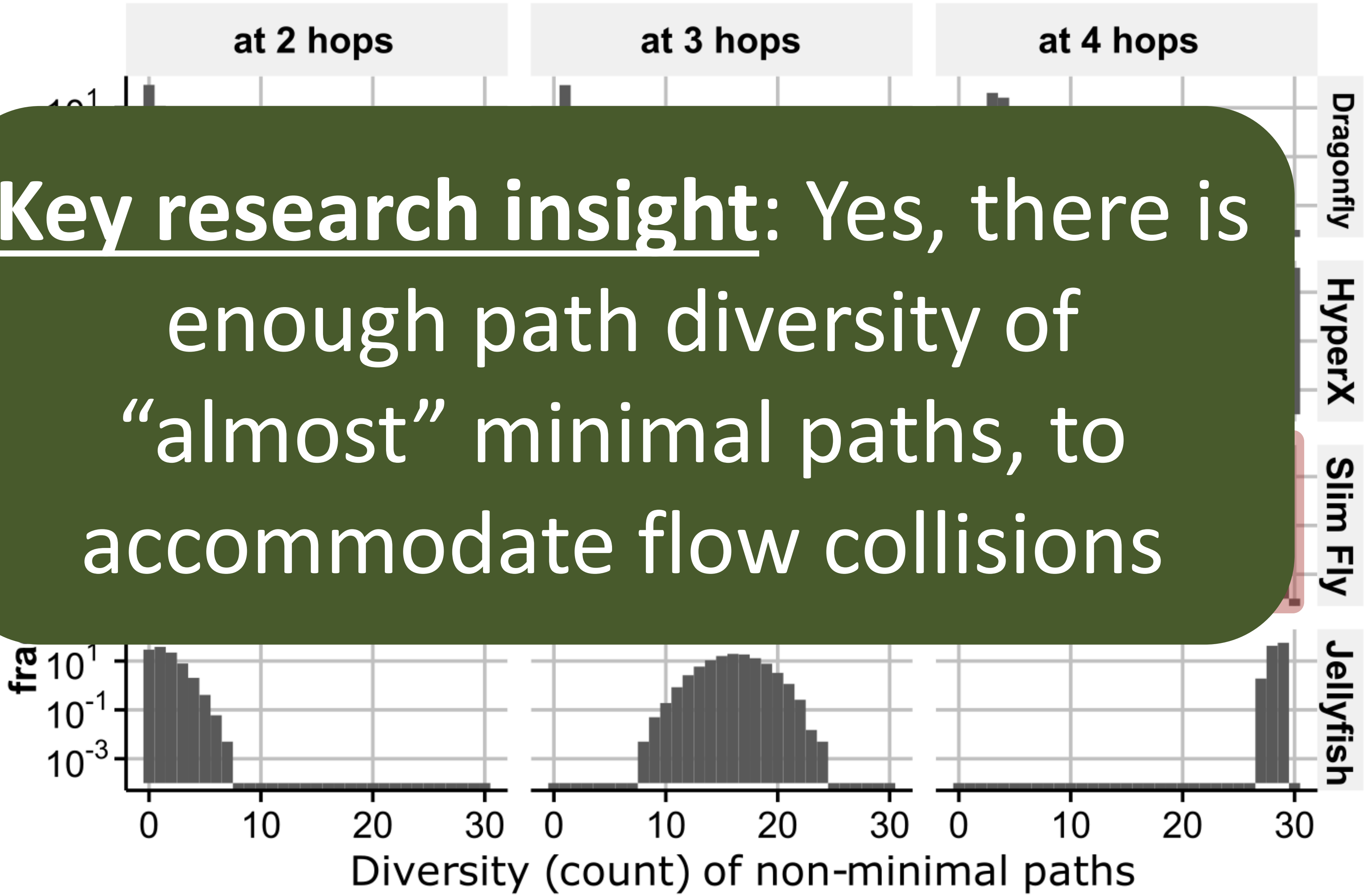

Key research insight: Yes, there is enough path diversity of "almost" minimal paths, to accommodate flow collisions

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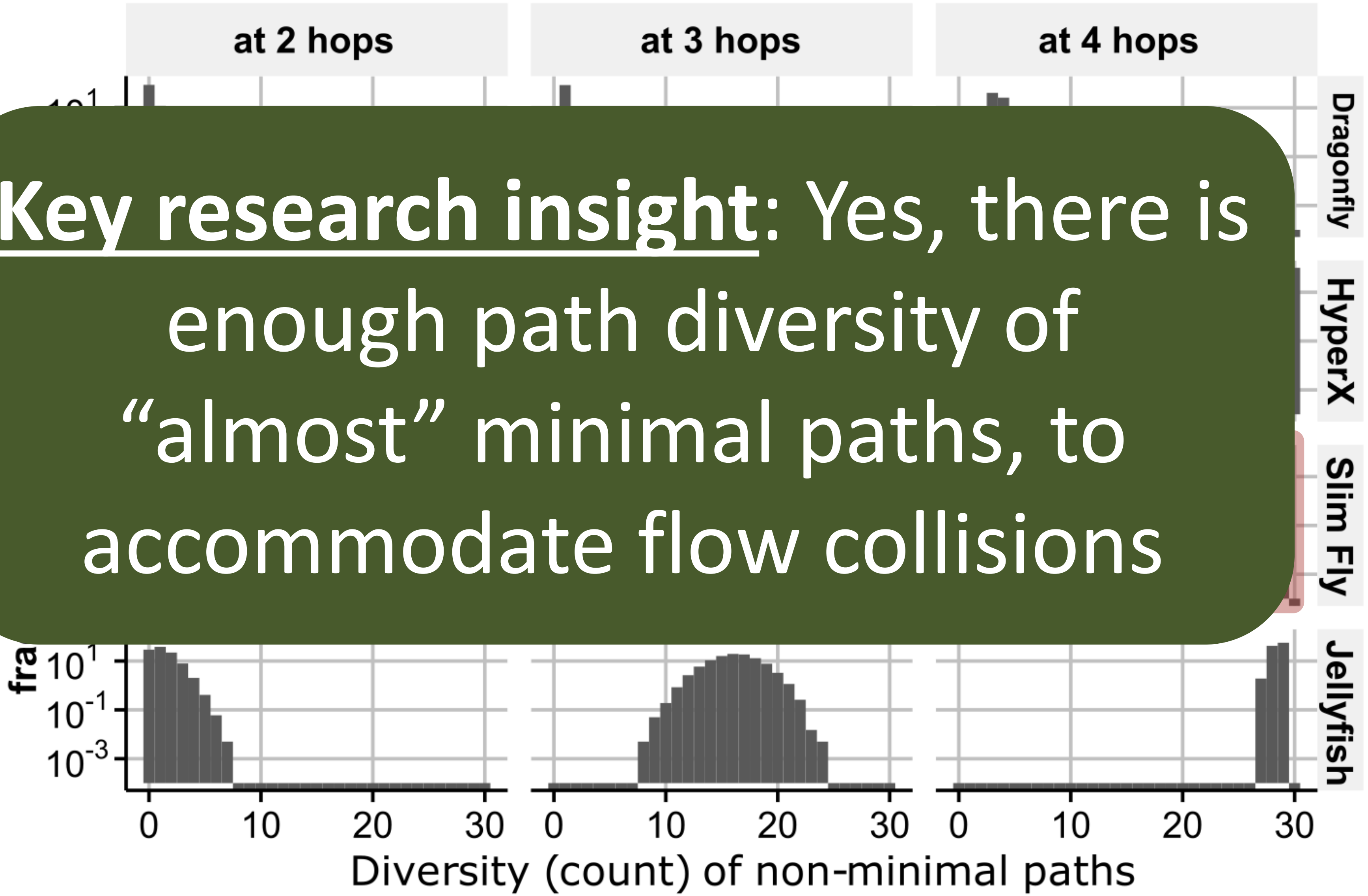

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Let's sum up...

Multipath Routing: Motivation

What are the problems that we want to tackle with multipathing?

Flows collide!

How many paths (in the network) do we need to „accommodate" collisions?

Multipathing

One collision

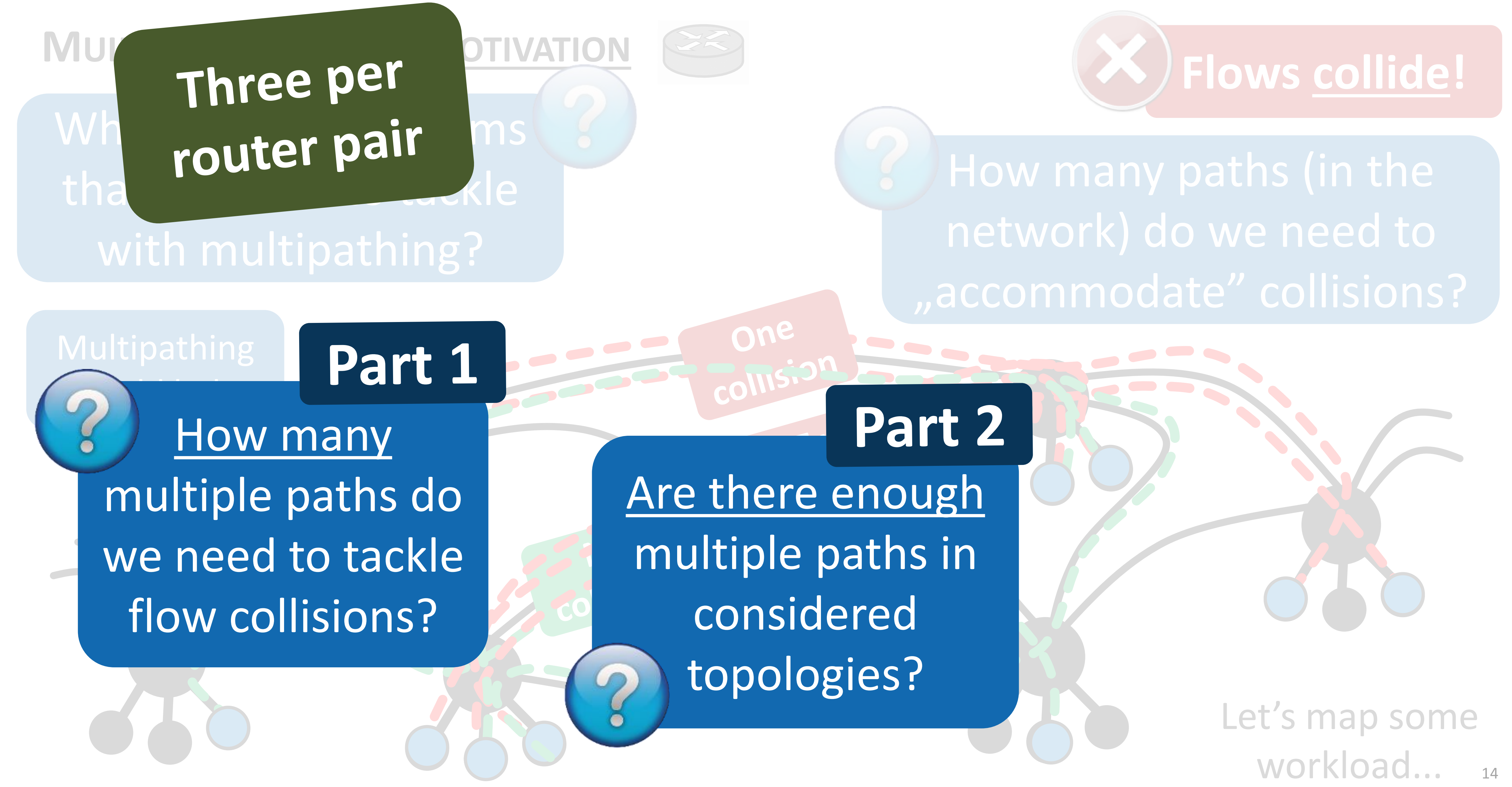
Part 1

How many multiple paths do we need to tackle flow collisions?

Part 2

Are there enough multiple paths in considered topologies?

Let's map some workload...



Three per router pair
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One collision
Part 1
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Part 2
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Let's map some workload...

spcl.inf.ethz.ch
@spcl_eth
ETH zürich

MU... OTIVATION

Wh... ms tha... tackle with multipathing?

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Part 2

Are there enough multiple paths in considered topologies?

Part 3

How to use such multiple paths in considered topologies?

One collision

workload...

Three per router pair

Yes

Let's develop a multipathing-focused routing architecture using these insights

Part 1

How many multiple paths do we need to tackle flow collisions?

Part 2

Are there enough multiple paths in considered topologies?

Part 3

How to use such multiple paths in considered topologies?

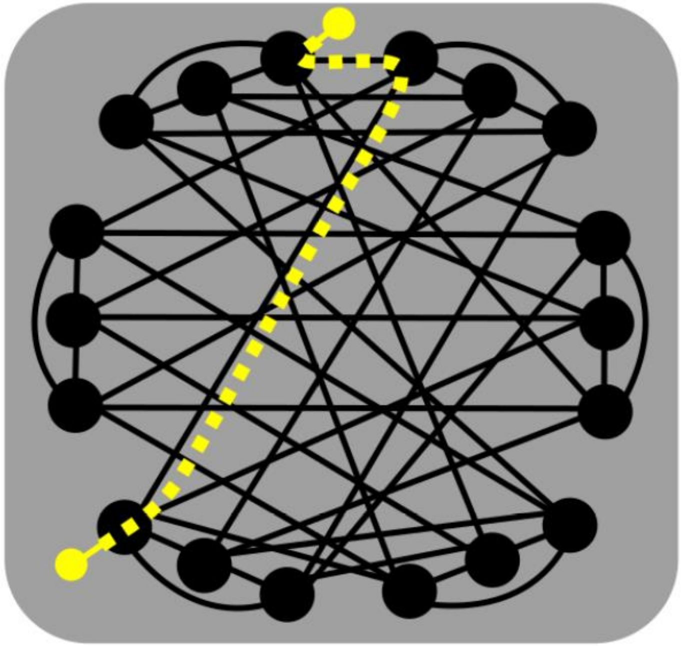
FatPaths architecture: layered routing protocol

Part 3.1

FATPATHS ARCHITECTURE: LAYERED ROUTING PROTOCOL

Part 3.1

Default topology
Shortest path: 2 hops



Default topology
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FatPaths architecture: Layered routing protocol

Part 3.1

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(a.2) Create a layer by removing a fraction of edges (e.g., random uniform sampling)

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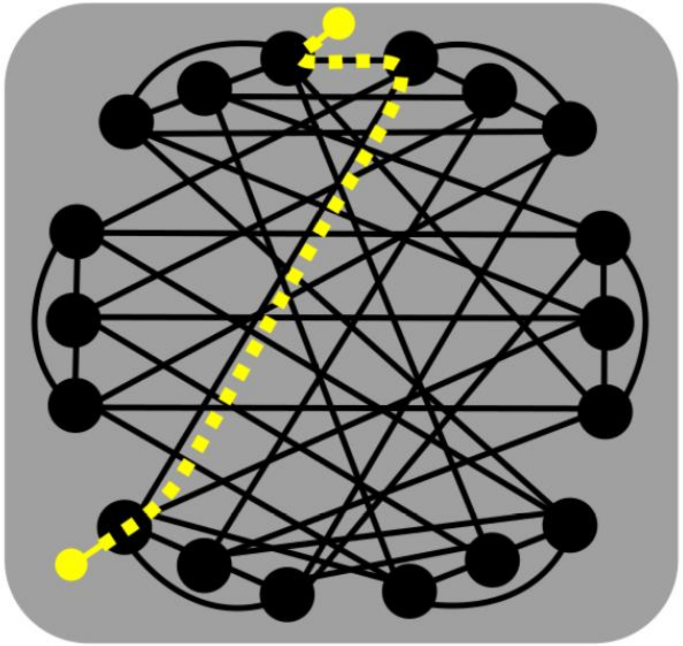

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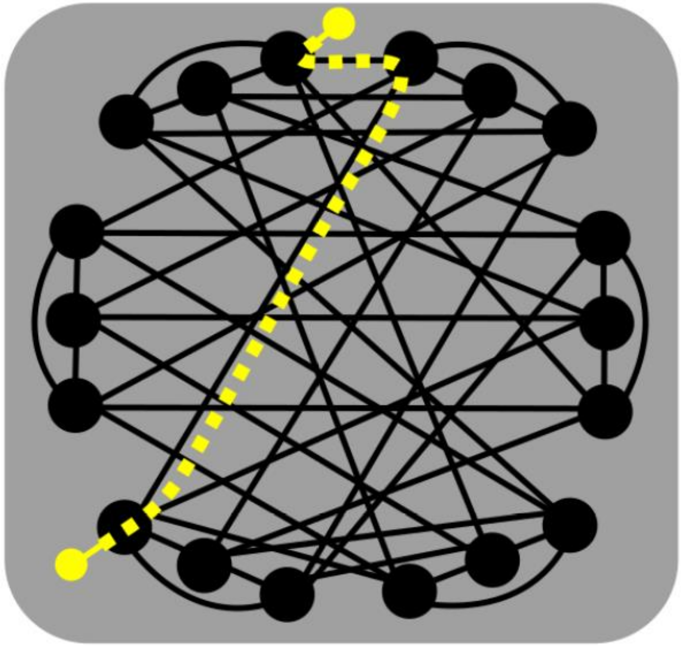

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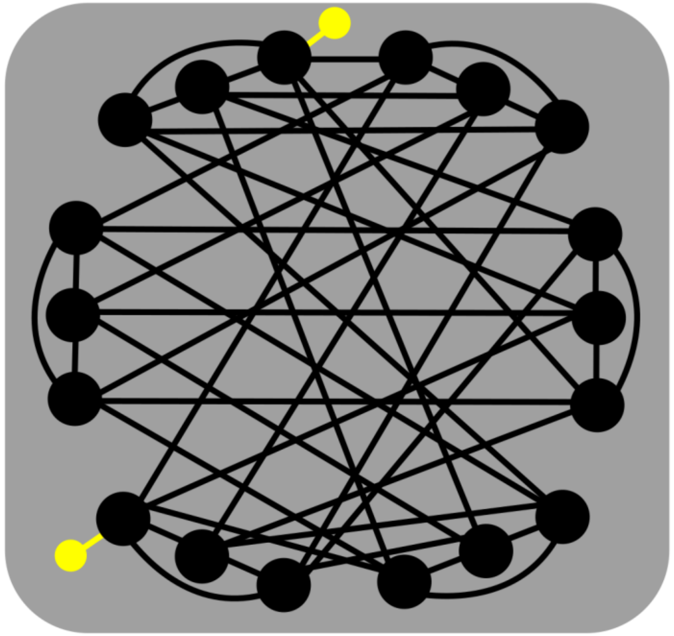

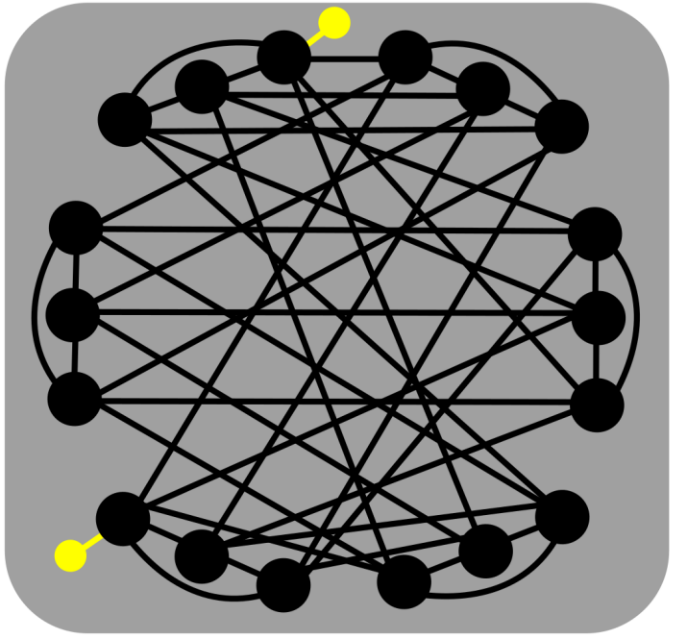

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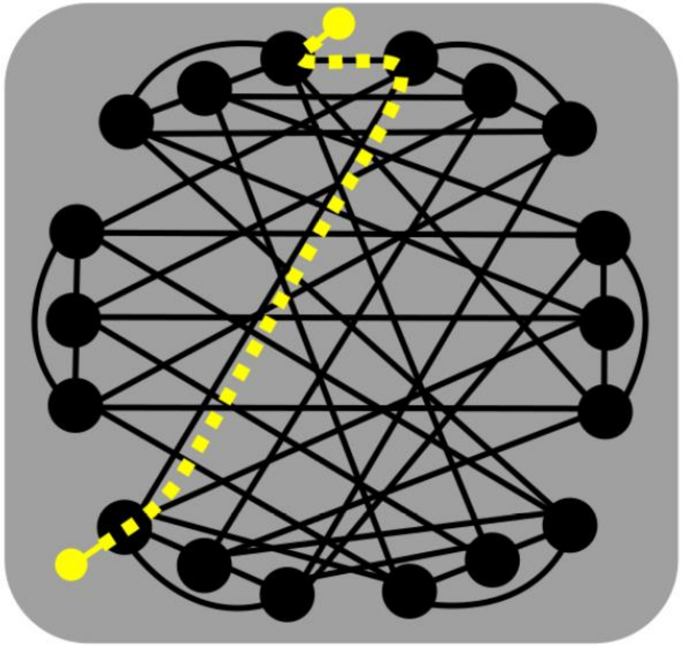
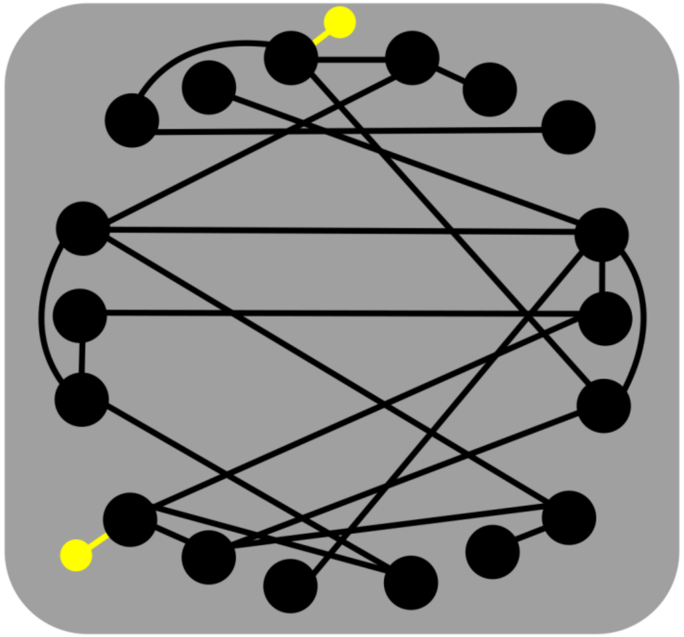


Layer 1: "Almost"-
-shortest path: 3 hops
Default topology



Layer 2: "Almost"-
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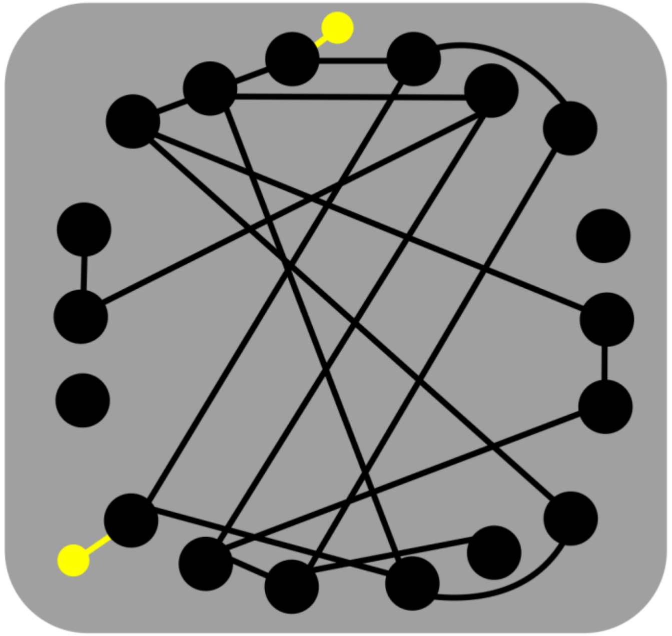

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FatPaths architecture: Layered routing protocol

Part 3.1

(a.1) Divide links into subsets (layers).

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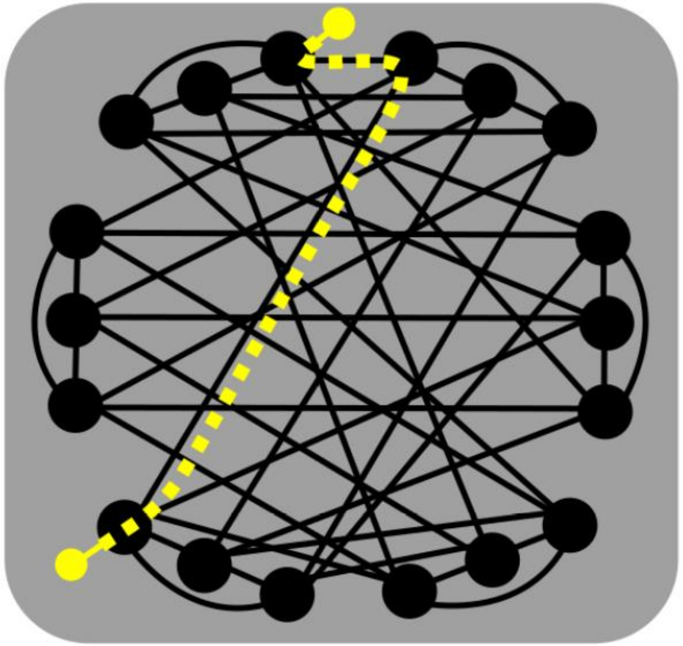
(b) Divide one flow into subflows and send subflows across different layers

Default topology
Shortest path: 2 hops



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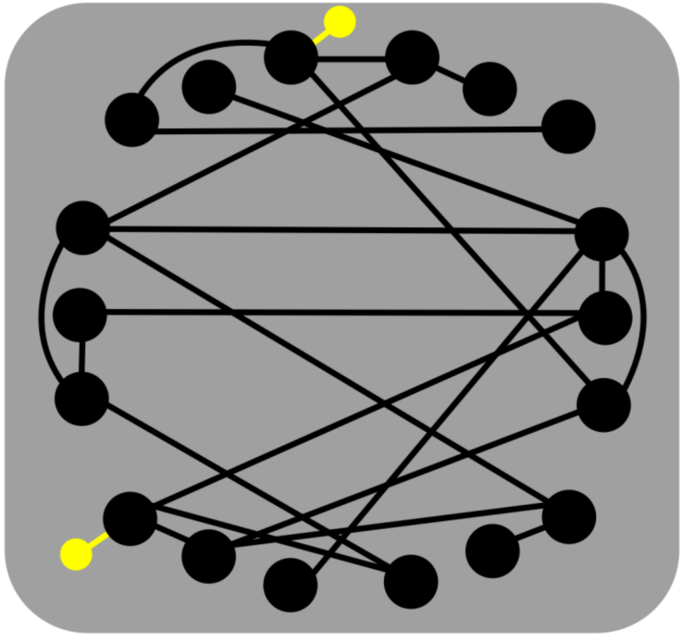

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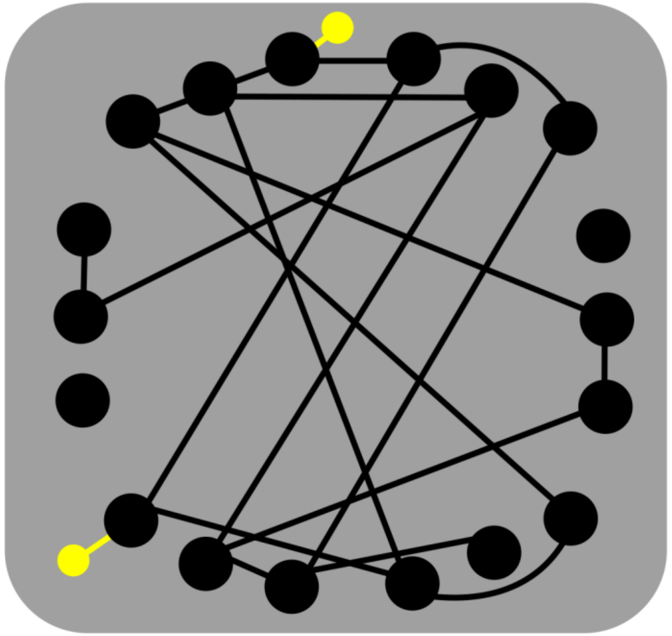

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FATPATHS ARCHITECTURE: LAYERED ROUTING PROTOCOL

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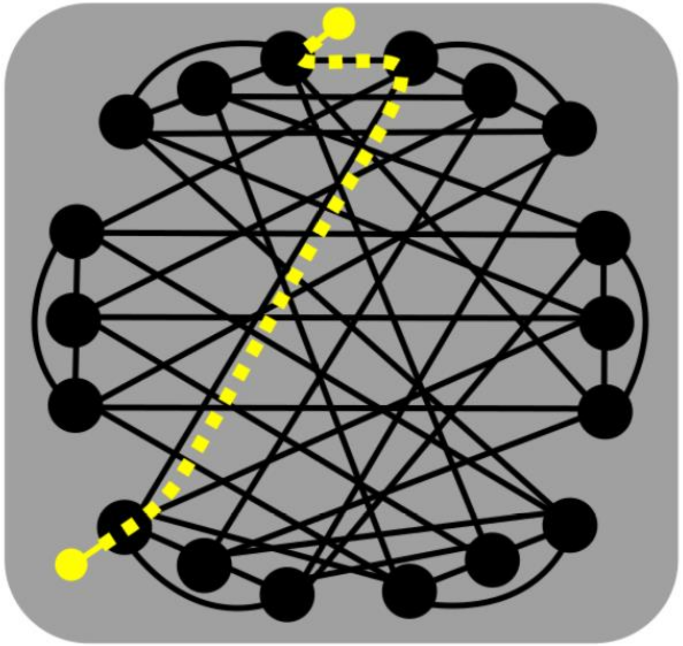

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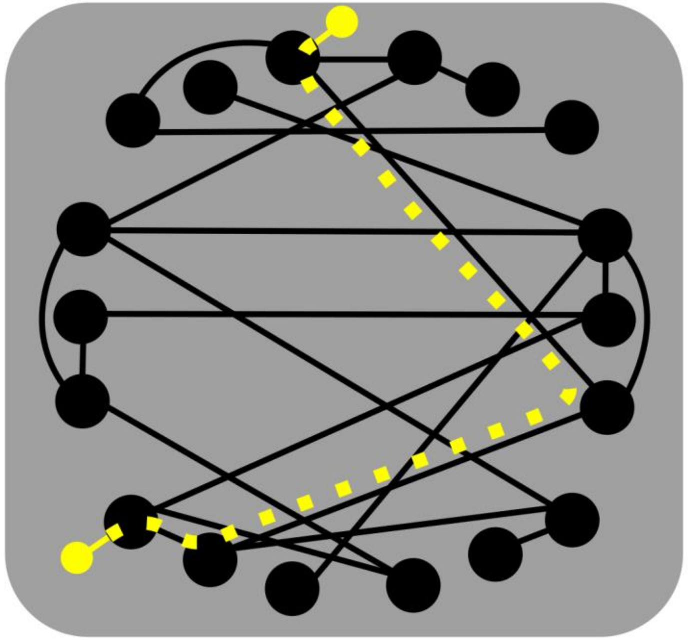

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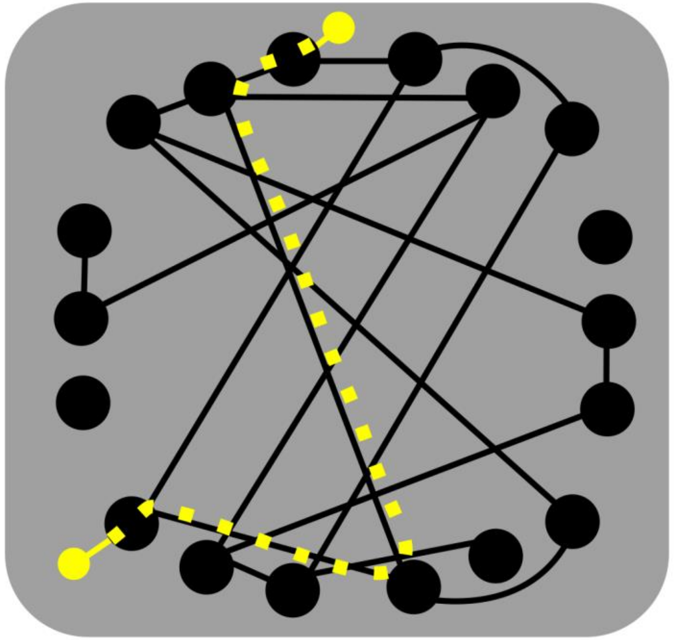

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FatPaths architecture: layered routing protocol

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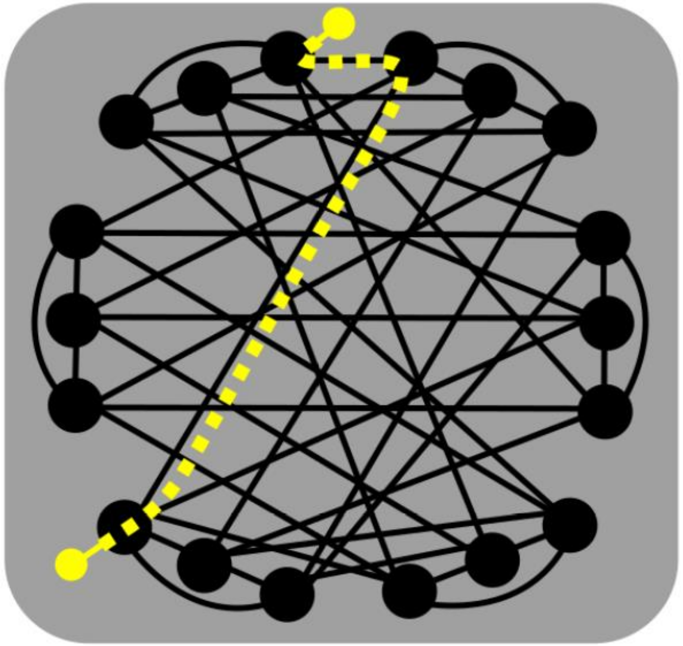
(c) Route minimally in each layer. A minimal route in one layer is often non-minimal when considering all links

Default topology
Shortest path: 2 hops



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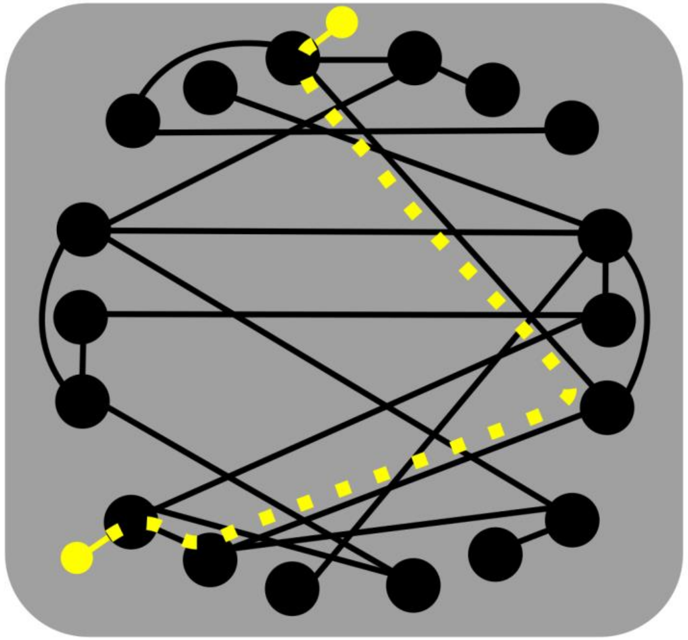

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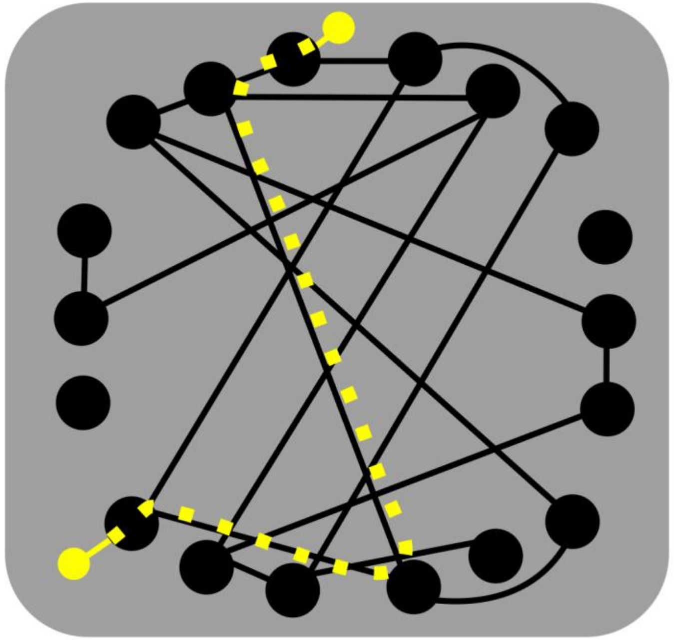

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FatPaths Architecture: Layered Routing Protocol

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Design justification: Different layers enable multipathing

Default topology
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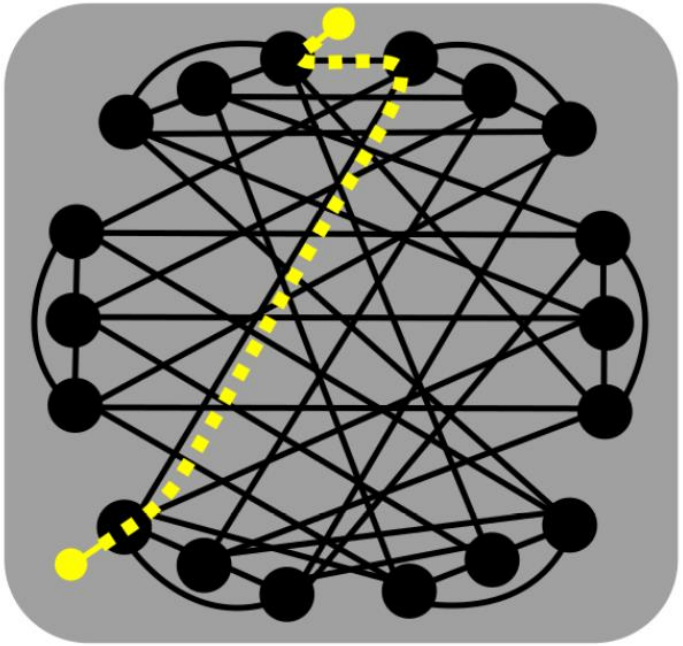

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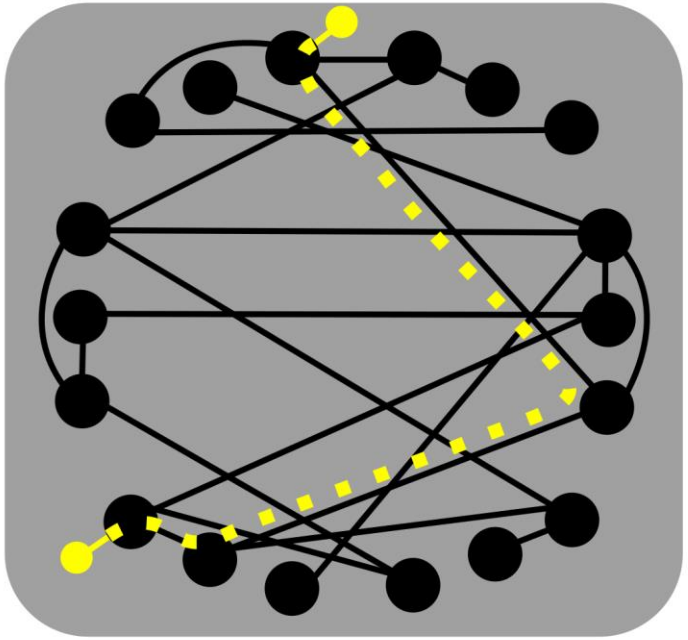

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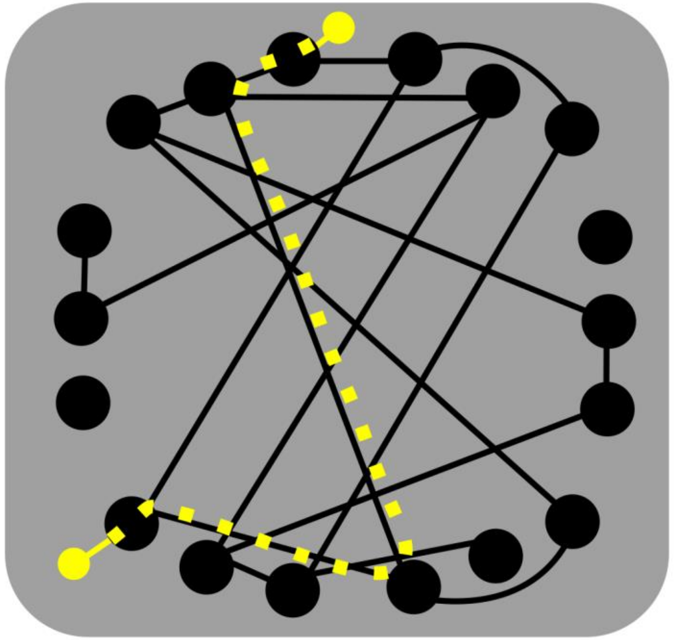

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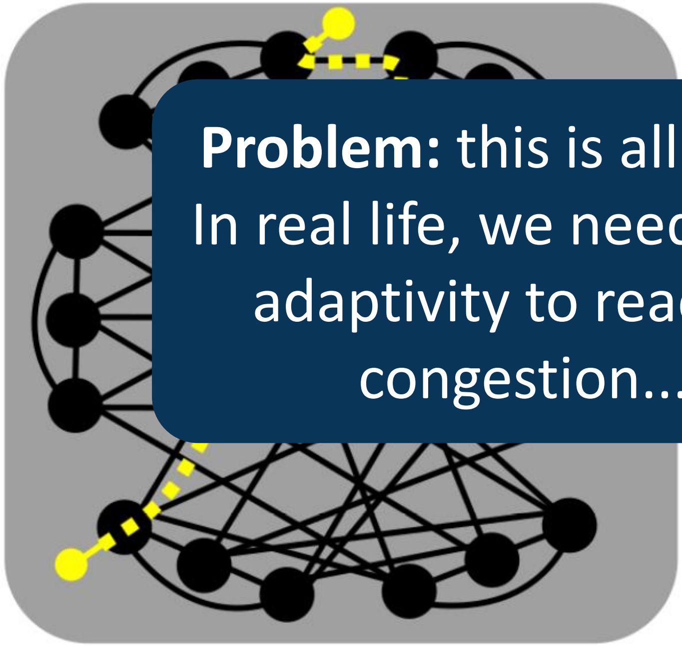

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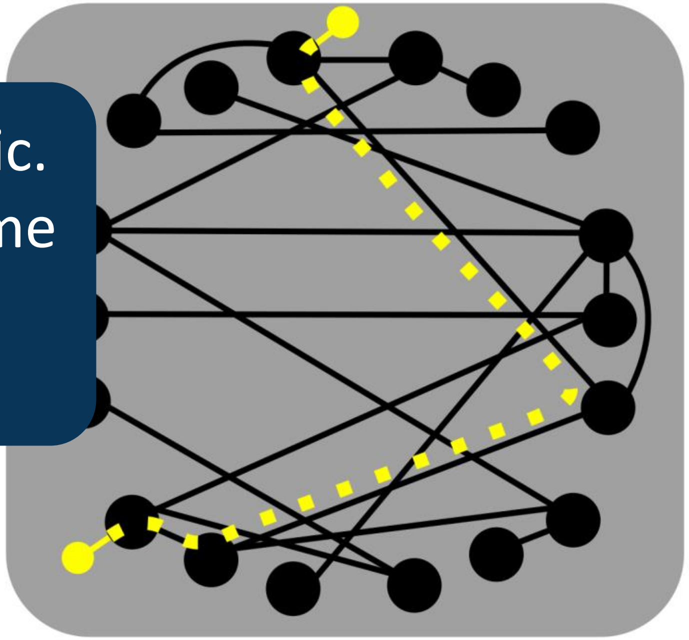

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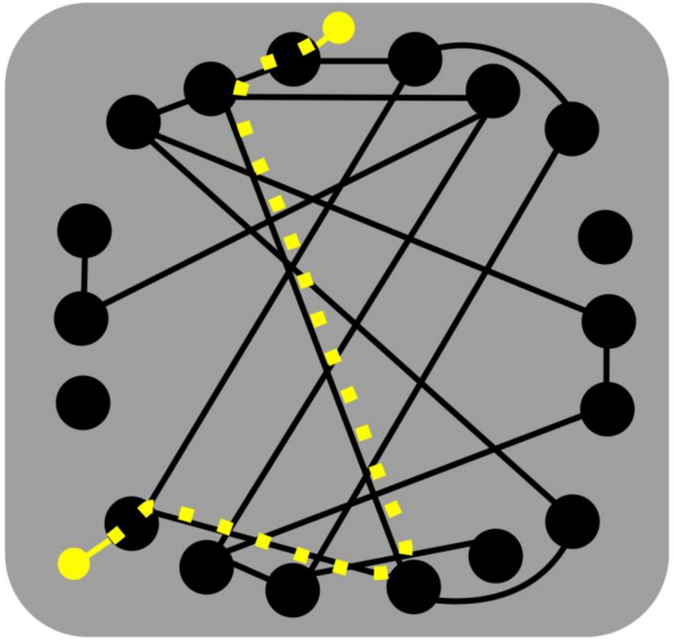

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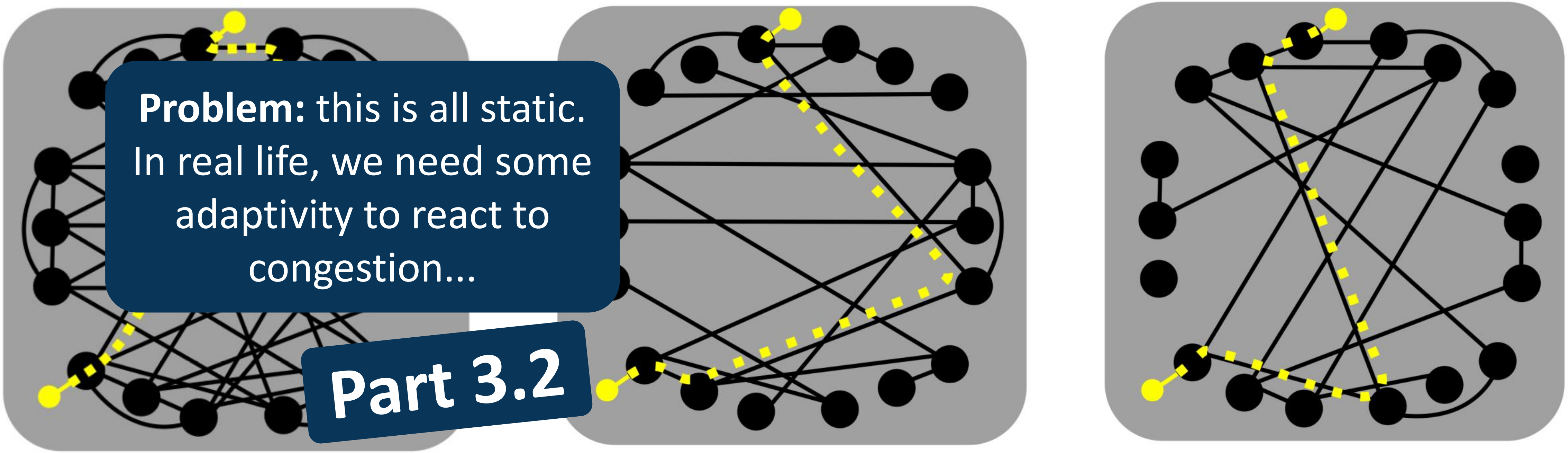

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Part 3.2

FatPaths architecture: load balancing with flowlets

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How to load balance traffic over different paths of different lenghts?

FatPaths Architecture: Load Balancing with Flowlets

A flowlet [1,2] is a sequence of packets within one flow, separated from other flowlets by sufficient time gaps, which prevents packet reordering at the receiver.

How to load balance traffic over different paths of different lenghts?

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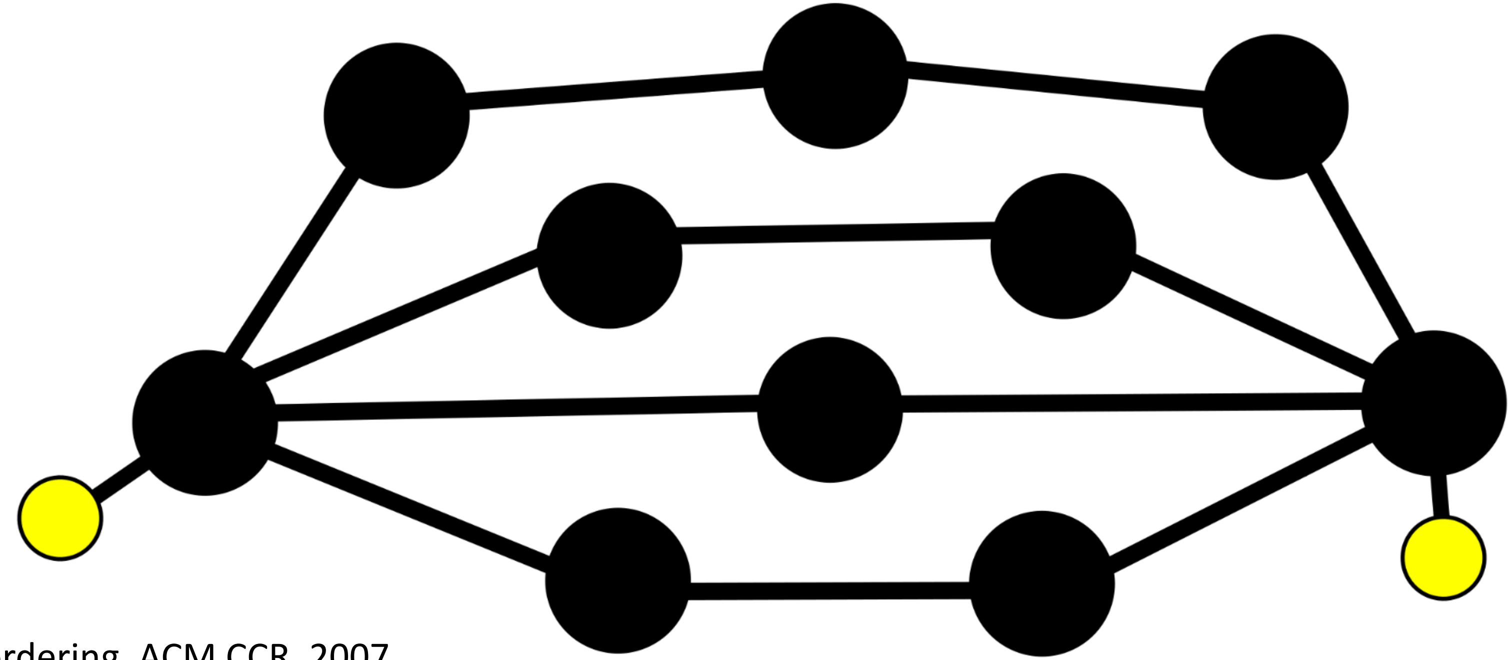

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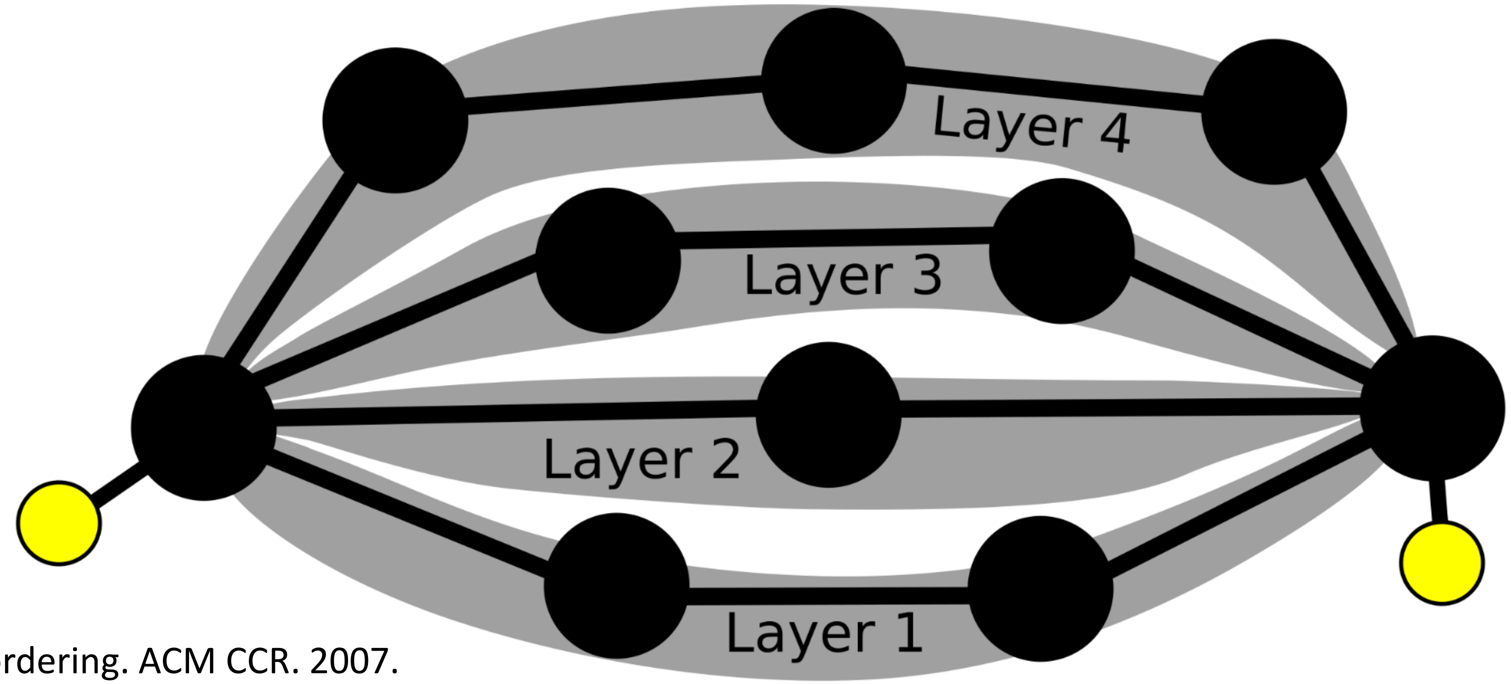

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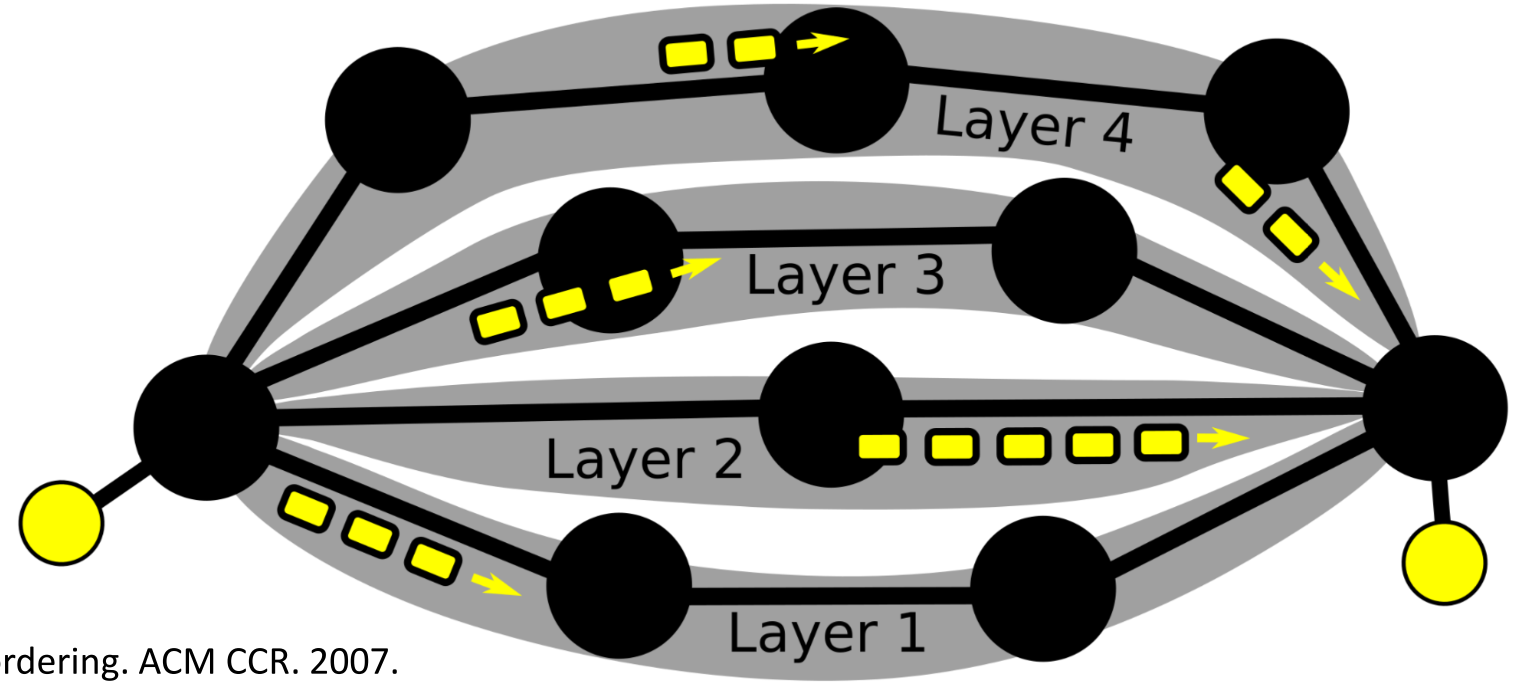

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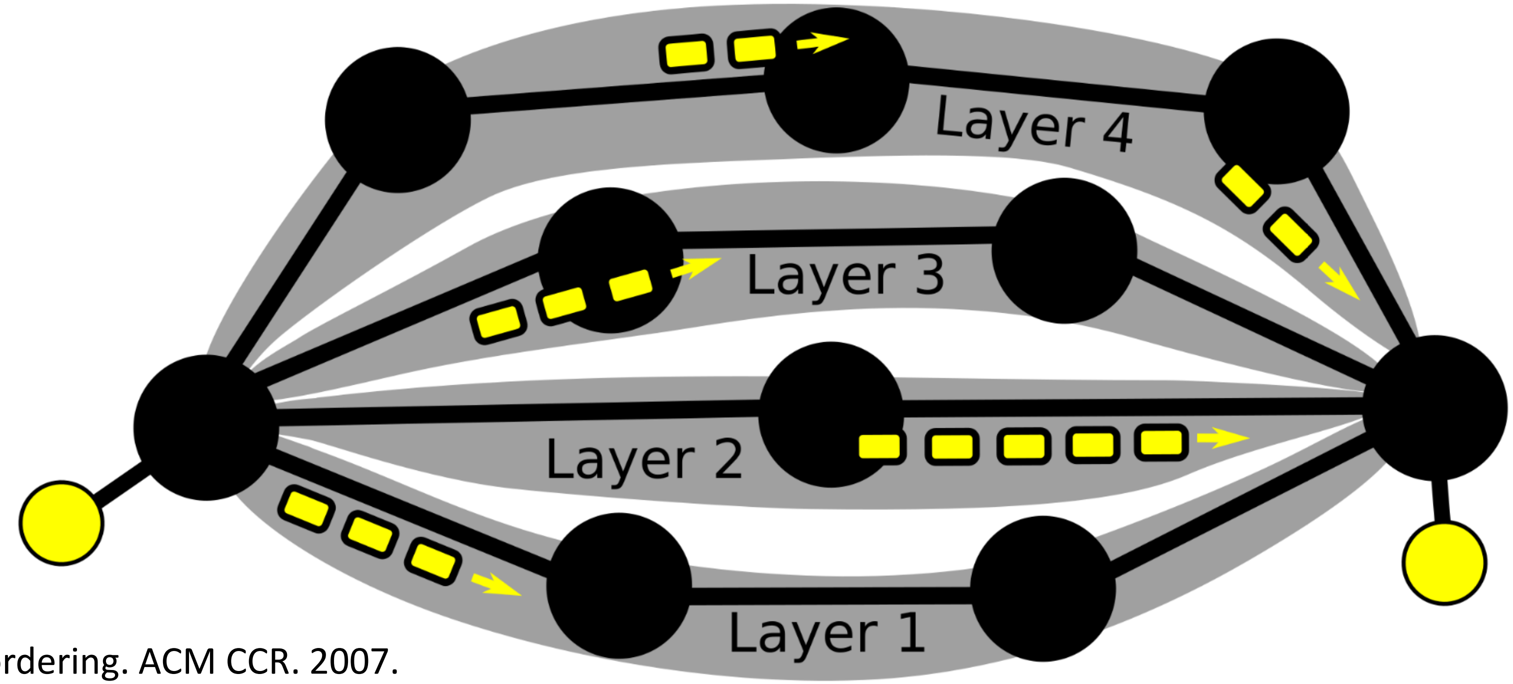
Very simple load balancing: when one detects congestion, a router just picks a random path (layer) for the packets to be sent (they become a new flowlet)



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Size of flowlets changes automatically based on conditions in the network

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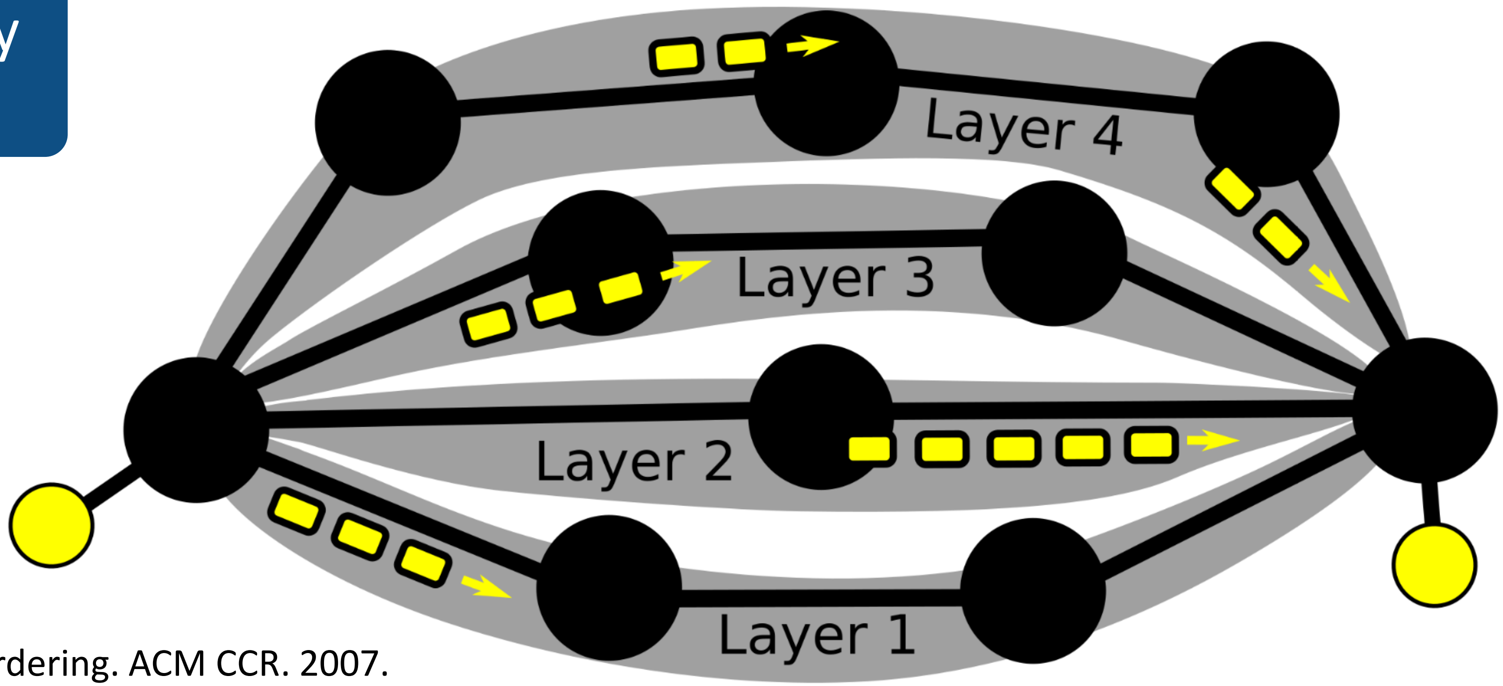

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FatPaths architecture

Design details

FatPaths architecture

Design details

```
L = {E} //Init a set of layers L; we start with E that corresponds to σ_1.
Π = {π_1(V), ..., π_{n-1}(V)} //Generate n-1 random permutations of vertices.

//Init a matrix W containing weights of edges (u,v) ∈ E.
W = {[w_uv] | ∀u,v ∈ V : w_uv = 0}

foreach π ∈ Π do: //One iteration of the main loop derives one layer.
  E' = create_layer(π, E, W, L_min, L_max) //Generate a layer.
  L = L ∪ {E'} //Record the layer

//Derive a layer that corresponds to some σ_i.
create_layer(π, E, W, L_min, L_max):
  //A condition "π(u) < π(v)" ensures layer's acyclicity.
  V = {(u,v) ∈ V × V : π(u) < π(v)}
  //Init a priority queue Q. One queue element is a pair of vertices from V.
  Q.init(V)
  incidence_G =incidence_matrix(G) //Generate an incidence matrix of G.
  p_cnt = 0 //Init path count variable p_cnt.
  while (V ≠ ∅ and p_cnt < M) do:
    (u,v) = Q.pop() //Get a pair of vertices with lowest priority (lowest number of added paths).
    path = (v_1, v_2 ..., v_d) ←find_path(u, v, W, incidence_G, L_min, L_max) //Find path from u to v, with path of
         length ∈ [L_min, L_max], minimizing the sum of edge weights, such that for i < j: π(v_i) < π(v_j) and the
         available edges are given by the incidence_G matrix.
      th exists: //Check if u and v are connected, in the graph given by the incidence_G matrix.
        = p_cnt + 1
      each link ∈ path do:
        = E' ∪ {link} //Add each edge from path to the current layer.
      ach v_i, v_j ∈ path where |i - j| > 1 do:
        idence_G[v_i][v_j] = 0 //Exclude all edges, which will force the traffic from v_1 to v_d to use a
          different path than one that was found.
      each v_i, v_j ∈ path where j - i < L_min do:
        V = V \ (v_i, v_j) // Even if an additional path from v_i to v_j of length at least L_min will be added,
          there will still exist this shorter path between these vertices (the one contained by the
          path (v_1, v_2, ... v_d)), therefore the pair (v_i, v_j) should be further excluded from the V set.

ath(src, dst, W, incidence_G, L_min, L_max):
  path = null //Init variable containing the path with lowest cost.
   //Init an empty queue.
  (src)
  Q ≠ ∅ do:
  = Q.pop()
  th.last() == dst then:
```

Creating layers

```
L = {E} //Init a s
P = {π_1(V), ..., π_n
foreach π ∈ P do: //One iter
  E' = {}; foreac
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Deploying layers (VLAN, ...)

FatPaths architecture

Design details

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```

Populating forwarding entries

```
//Input: E'_i, i ∈ {1,...,n}: the specification of each layer. E'_i are router-router links in each layer i,
//produced by FatPaths layer construction algorithms specified in Listing 1 or Listing 2.
//Output: F_{i,s}: a forwarding table in router s ∈ V within layer i (1 ≤ i ≤ n).
//F_{i,s}[t] ∈ {1,...,k'} is a port number (in router s ∈ V) that leads to router t ∈ V (within layer i (1 ≤ i ≤ n)).

//Compute shortest paths between routers in each layer i. First, initialize the function σ_i.
//σ_i(s,t) is a port number (in router s) that leads to router t (in layer i); d is an auxiliary structure.
foreach i ∈ {1,...,n} do: //For each layer...
  foreach (s,t) ∈ V × V do: //For each router pair...
    if s == t then:
      d_st = 0 //The distance between u and v is zero, if u == v.
      σ_i(s,t) = s
    else if (s,t) ∈ E'_i then:
      d_st = 1 //The distance between directly connected routers is 1.
      σ_i(s,t) = t
    else:
      d_st = +∞ //The initial distance between non-adjacent routers is infinity.
      σ_i(s,t) = null

  //For each layer, derive the routing functions:
  foreach z ∈ |V| do:
    foreach s ∈ |V| do:
      foreach t ∈ |V| do:
        if d_st > d_sz + d_zt then:
          d_st = d_sz + d_zt
          σ_i(s,t) = σ_i(s,z)

  //Once σ_i is computed, populate a f...
  foreach s ∈ V do: //For every router...
    F_s = {} //Initialize the forwarding...

  //Build a forwarding table within la... ...the previously devised structures:
  foreach s ∈ V do:
    foreach t ∈ V, t ≠ s do:
      F_s[t] = σ_i(s,t)
```

FatPaths architecture

Design details

Creating layers

Deploying layers (VLAN, ...)

Populating forwarding entries

Flow control

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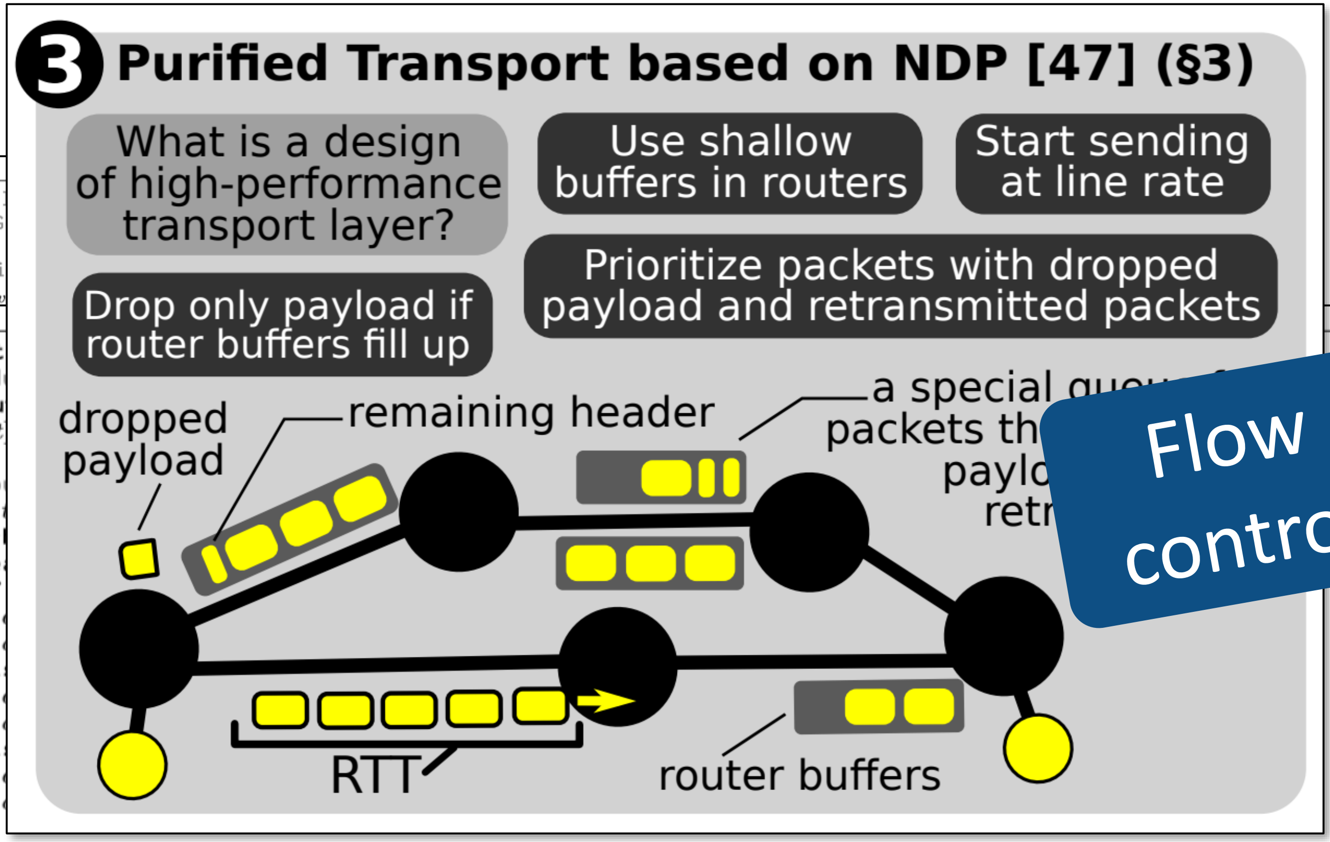
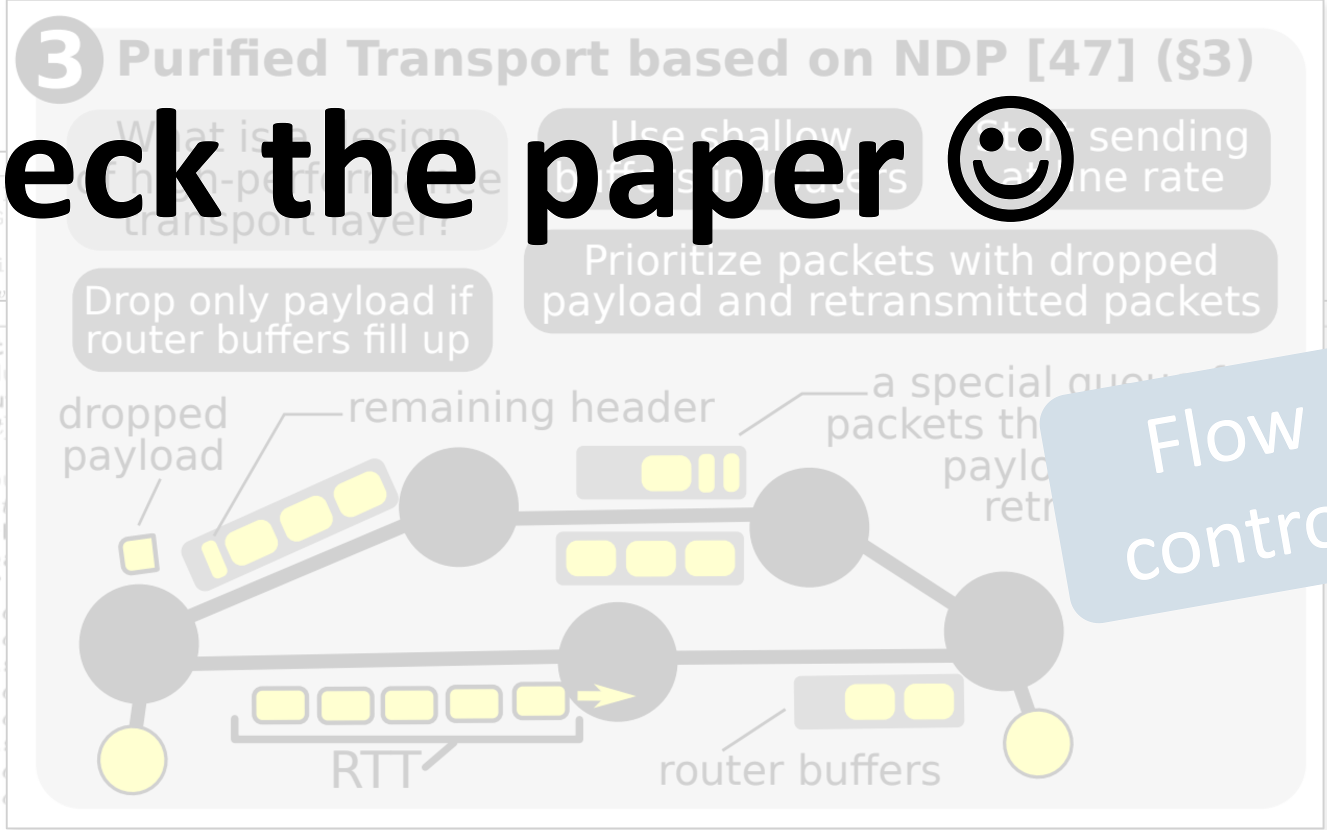


FatPaths architecture

Design details

Check the paper ☺



Flow control

Creating layers

Deploying layers (VLAN, ...)

Populating forwarding entries

FatPaths architecture

Design details

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Key design insight: Layered routing enables (1) easy encoding of the diversity of multiple minimal and non-minimal paths, and (2) enables simple and robust load balancing

EVALUATION

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<u>Question 1:</u> Can we get more performance on low-diameter networks than on Fat trees?

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<u>Question 2:</u> Does Fatpaths give more performance than existing routing schemes?

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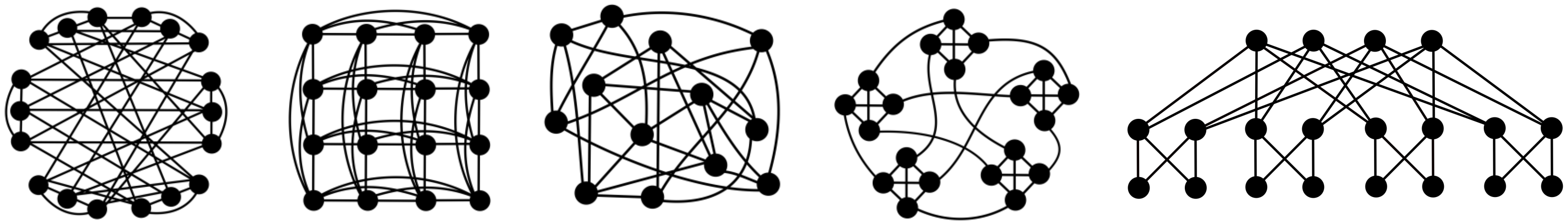
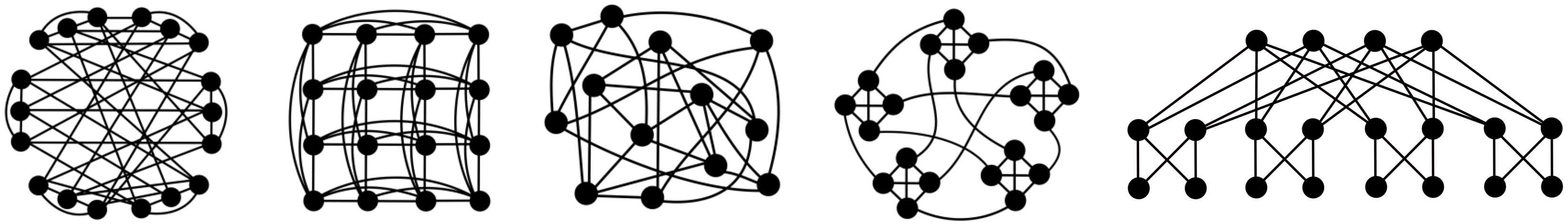


Evaluation



We pick Ethernet as a setting to accelerate as many Top500 systems as possible

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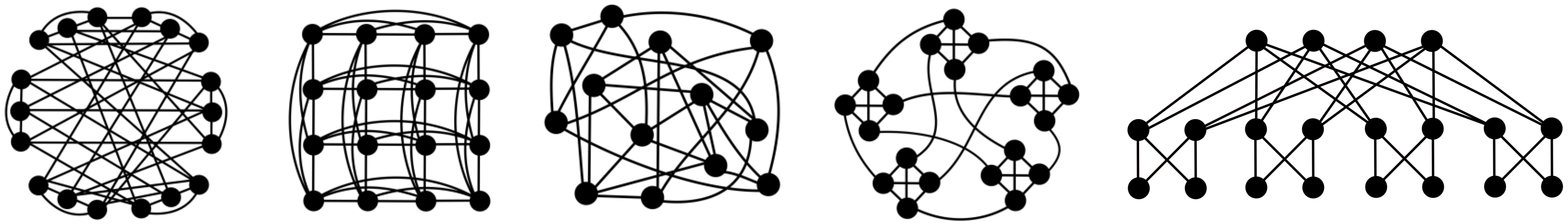

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(more than 50% of systems in Top500 use Ethernet. However, they are not as efficient as InfiniBand and others (details in the paper)

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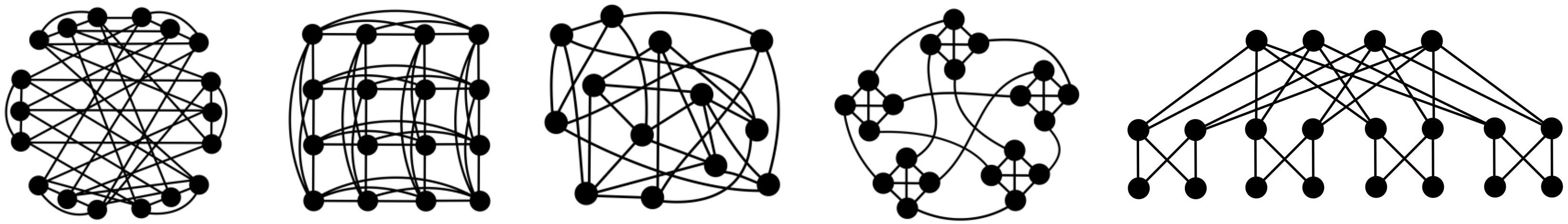

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<u>Setting 1 „Bare Ethernet”</u>

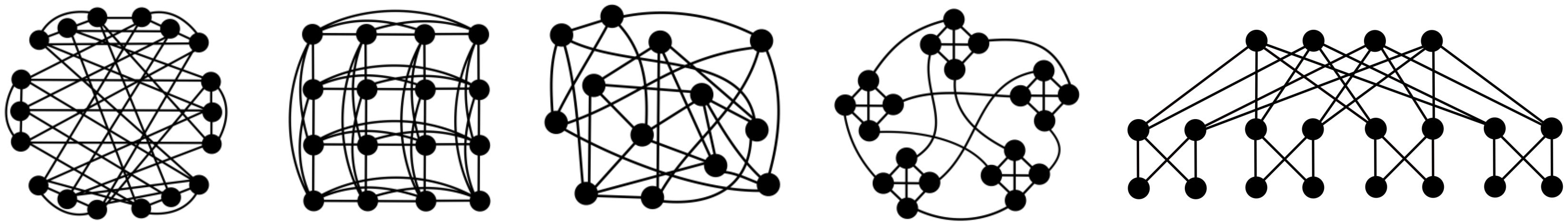
Ethernet, but no TCP.

Simulator: htsim [1].

NDP [1]: a very recent baseline, originally for fat trees.

[1] M. Handley et al. Re-architecting datacenter networks and stacks for low latency and high performance. SIGCOMM’17.

EVALUATION



We pick Ethernet as a setting to accelerate as many Top500 systems as possible

(more than 50% of systems in Top500 use Ethernet. However, they are not as efficient as InfiniBand and others (details in the paper)

Setting 1 „Bare Ethernet"
Ethernet, but no TCP.
Simulator: htsim [1].

NDP [1]: a very recent baseline, originally for fat trees.

Setting 2 „Full TCP"
Standard TCP and related.
Simulator: OMNeT++ [2].

ECMP [3]: traditional static load balancing.
LetFlow [4]: recent adaptive load balancing.

[1] M. Handley et al. Re-architecting datacenter networks and stacks for low latency and high performance. SIGCOMM'17.
[2] A. Varga et al. The OMNeT++ discrete event simulation system. ESM'01.
[3] C. Hopps. Analysis of an Equal-Cost Multi-Path Algorithm. RFC2992, 2000.
[4] E. Vanini et al. Let It Flow: Resilient Asymmetric Load Balancing with Flowlet Switching. NSDI'17.

EVALUATION

N ≈ 10,000; comparable cost; stencil (no remapping); “bare Ethernet” setting

NDP: a very recent baseline for fat trees [47]

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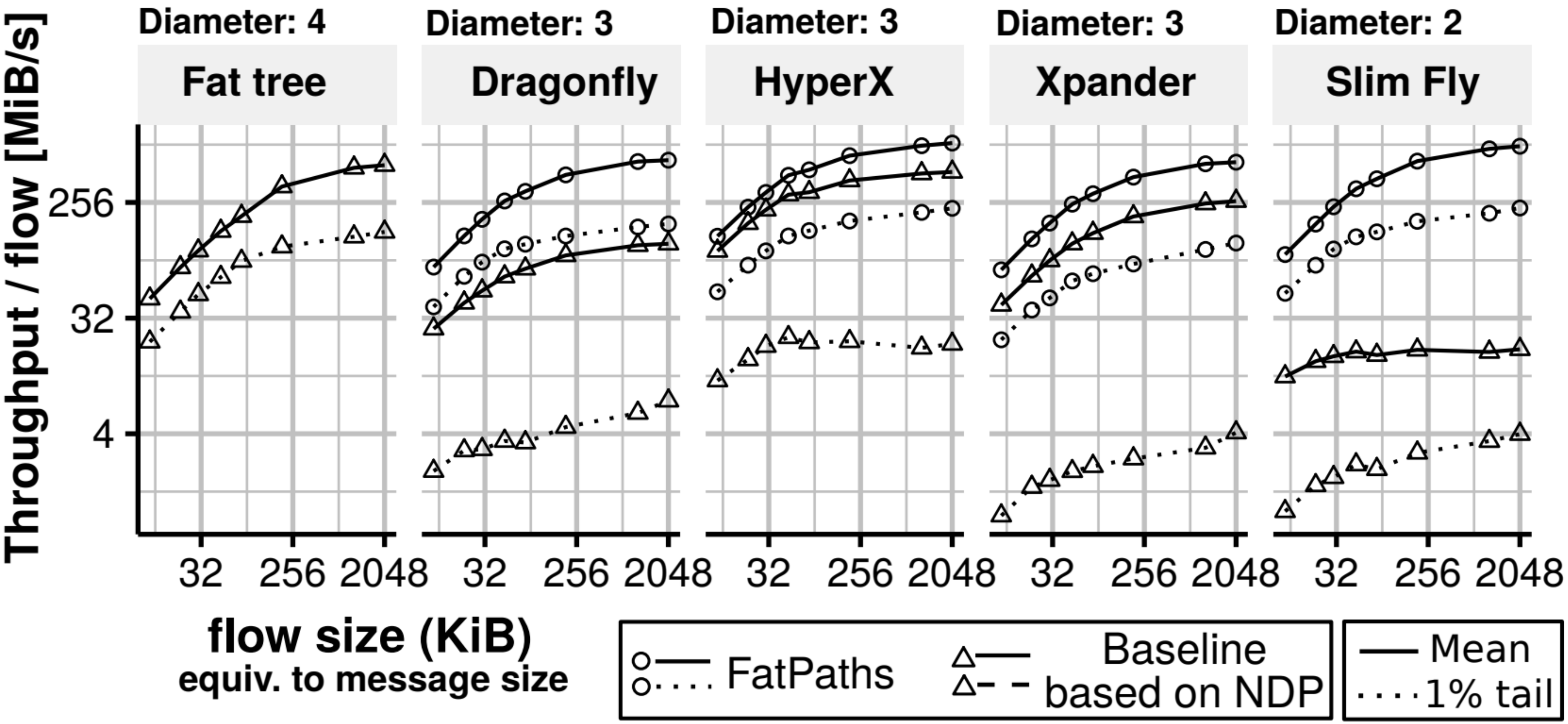

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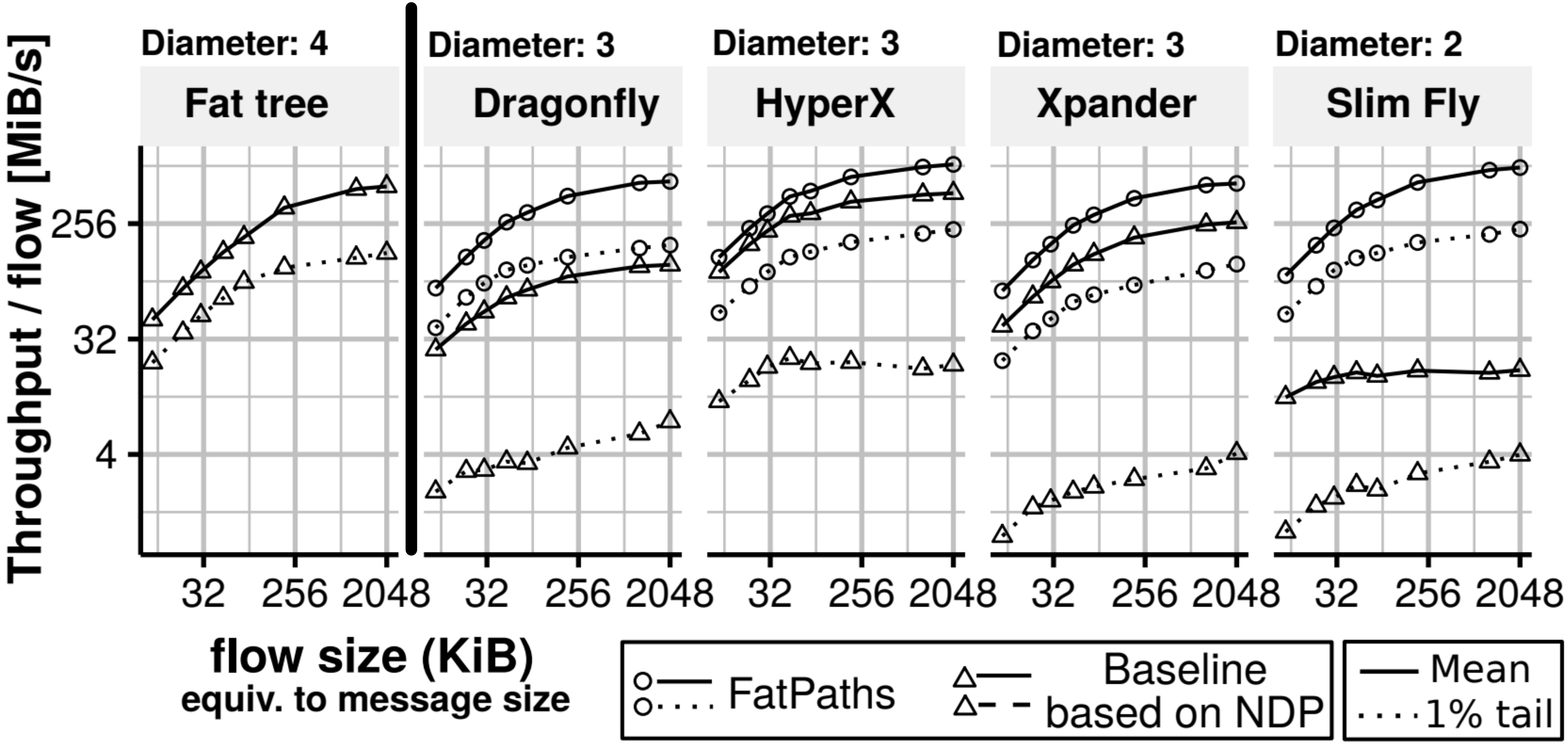

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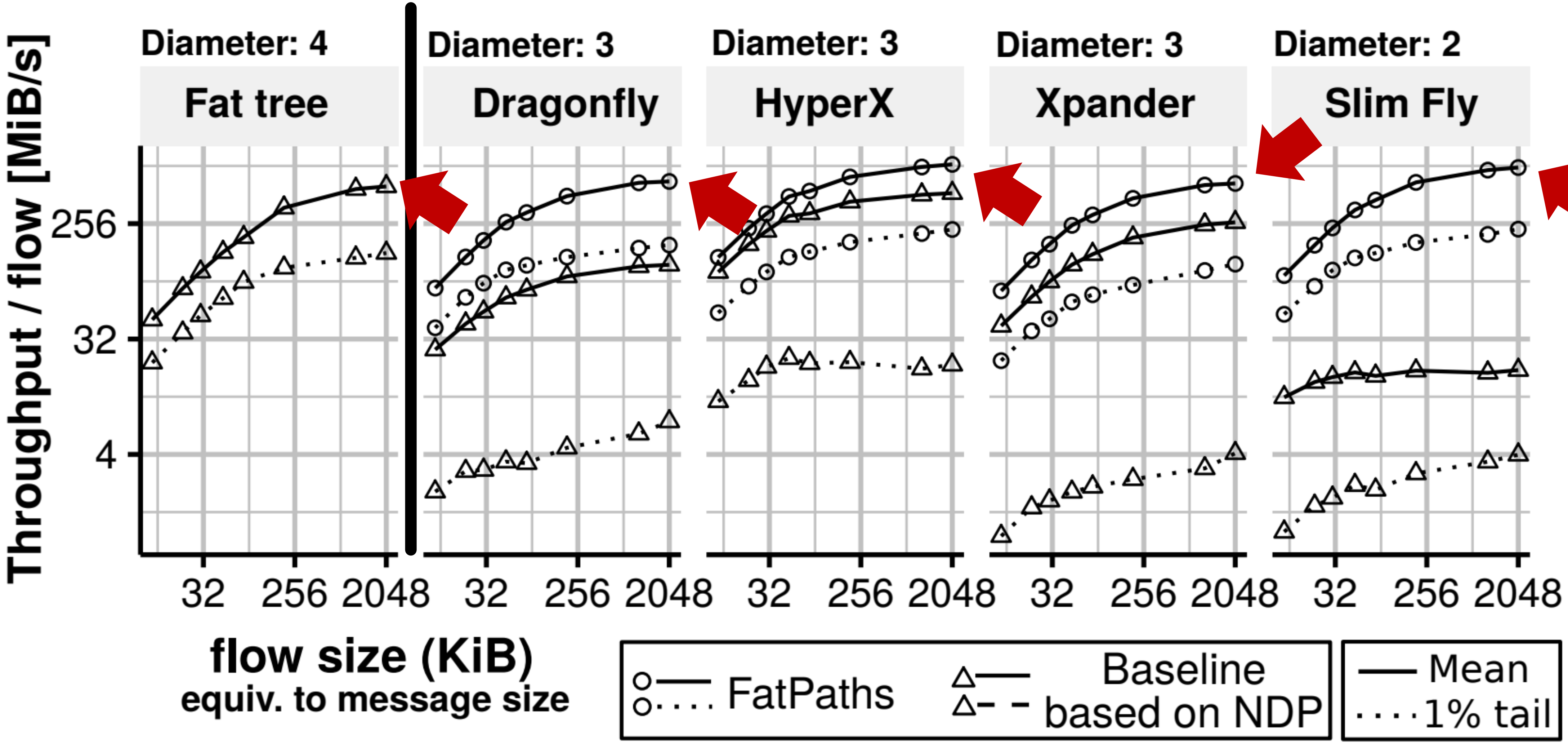

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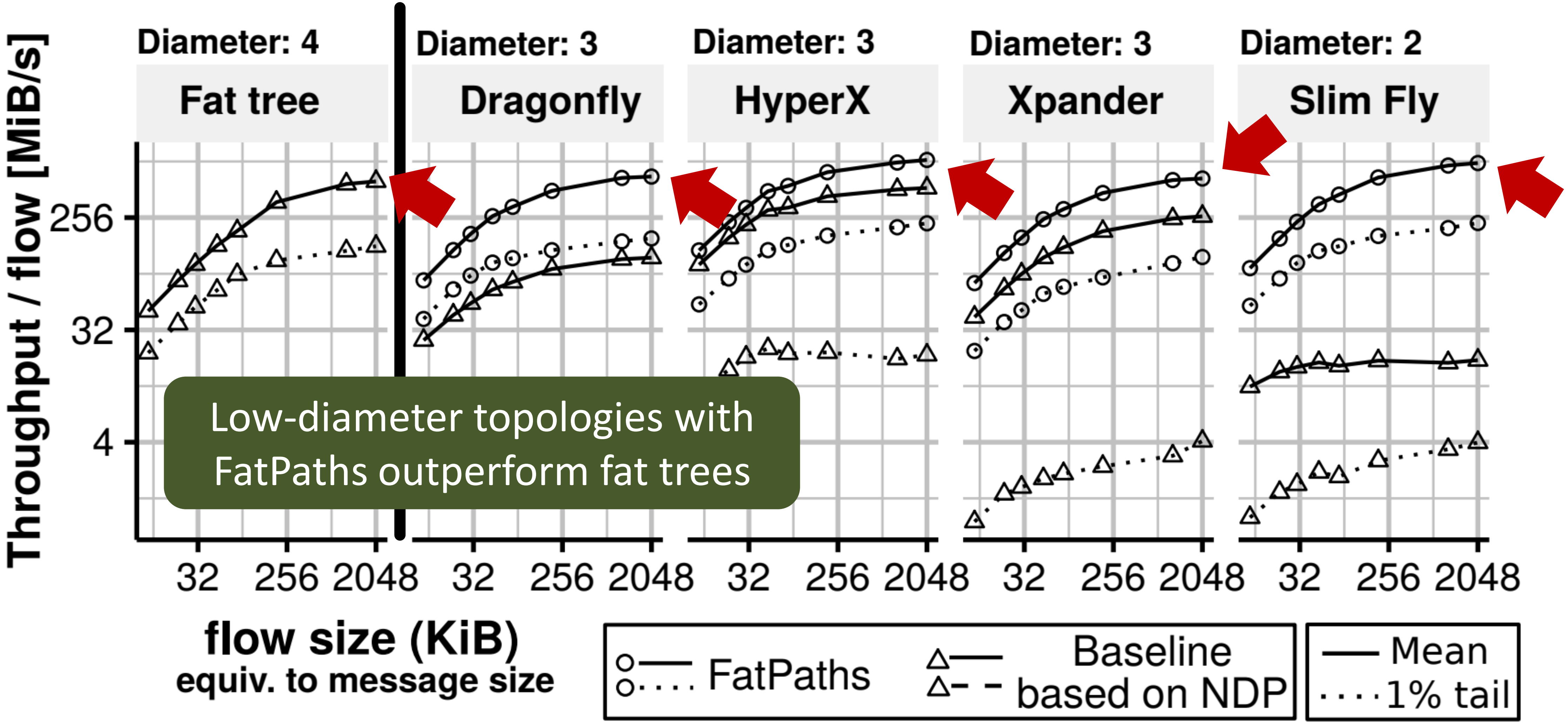

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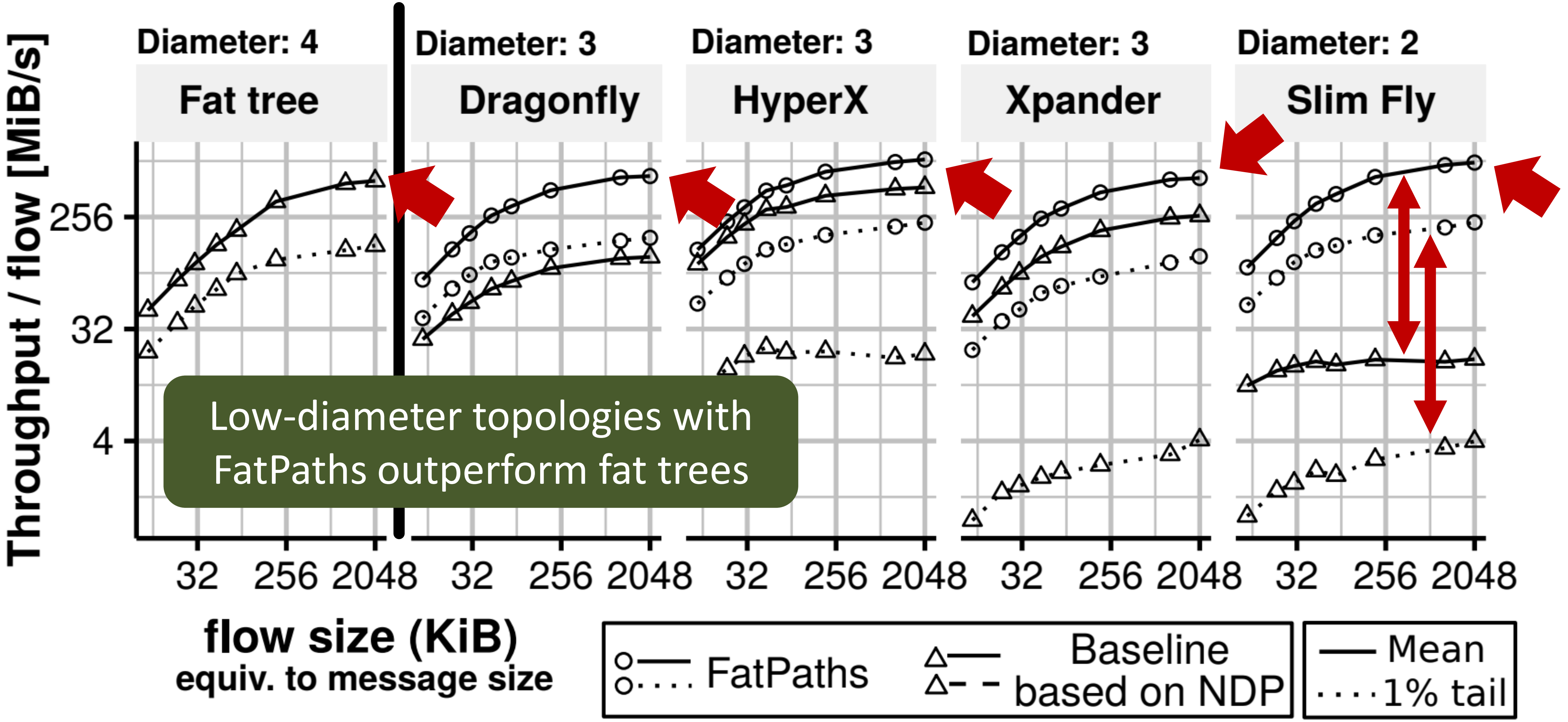

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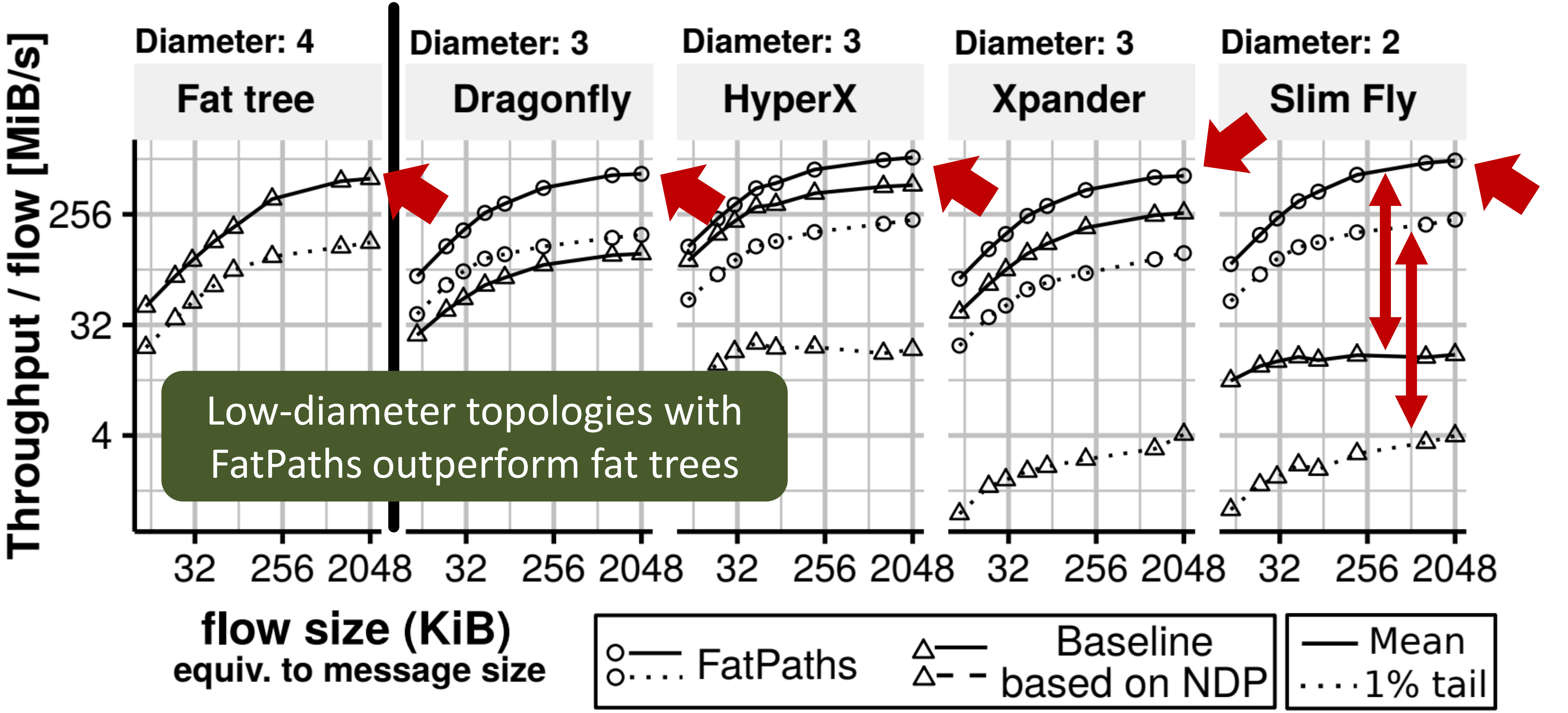

NDP: a very recent baseline for fat trees [47]

FatPaths outperforms simple NDP executed obliviously on low-diameter networks (up to 30x improvement)

EVALUATION

N ≈ 10,000; comparable cost; random uniform traffic; "full TCP" setting

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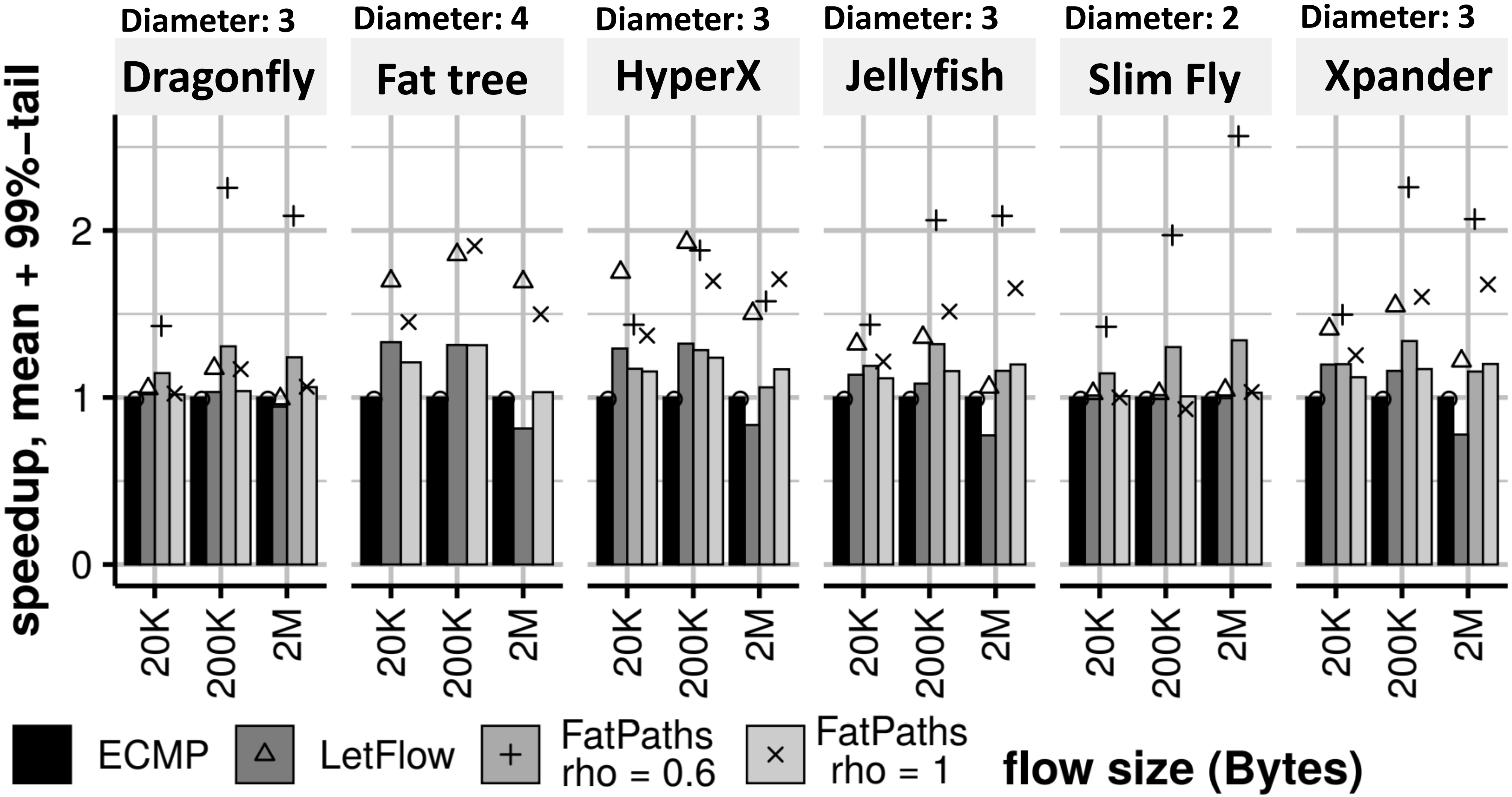

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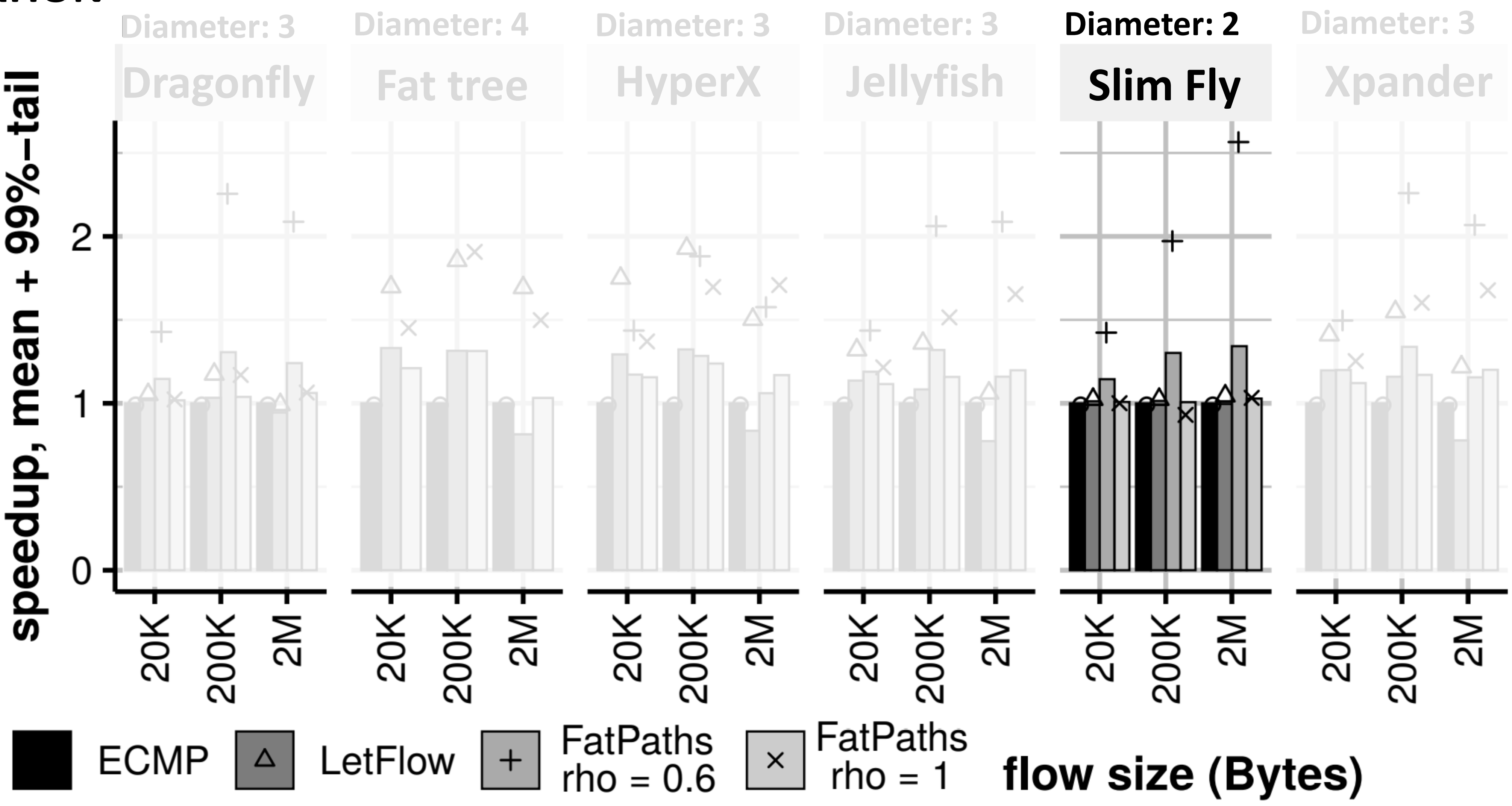

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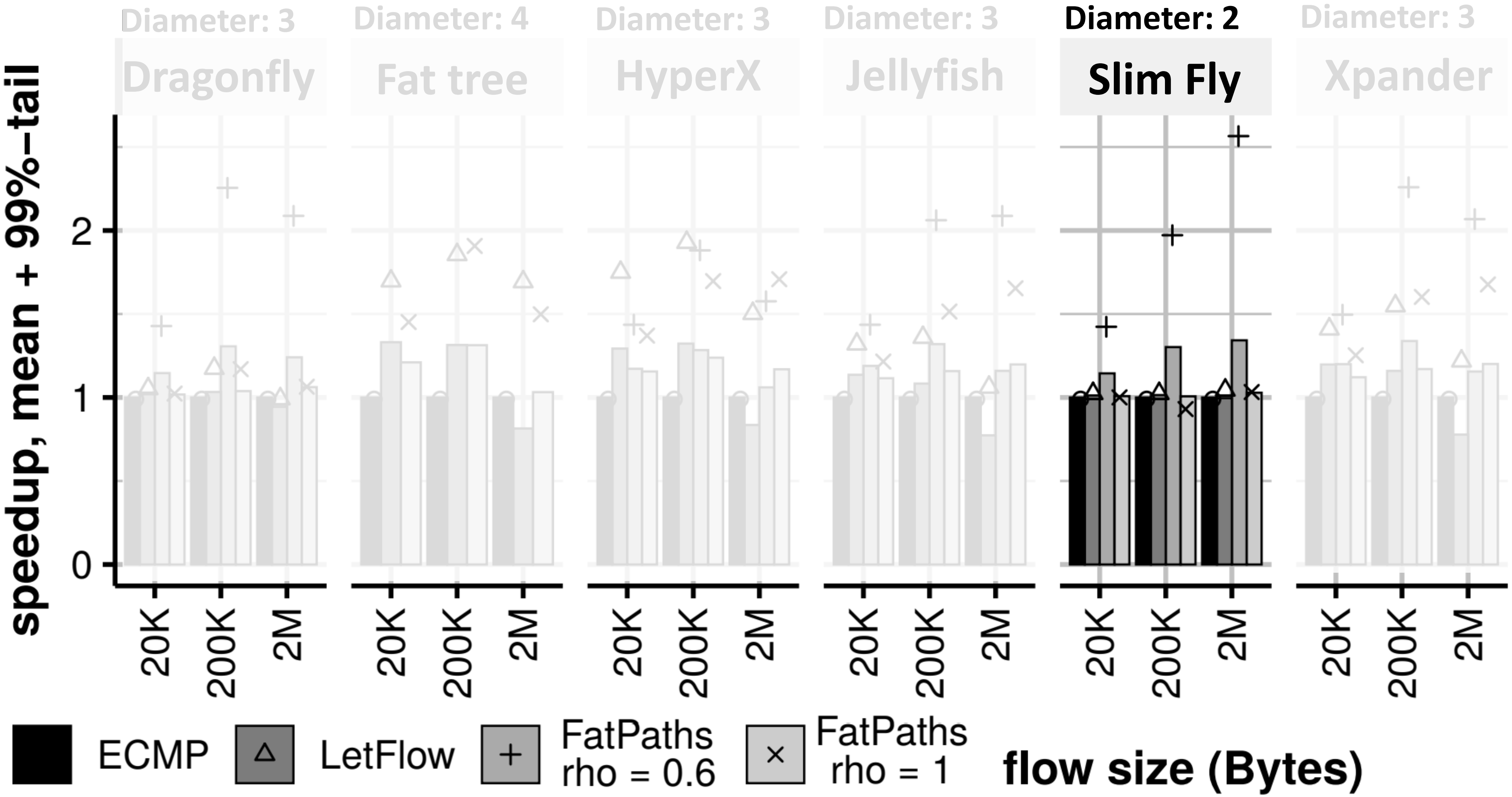

ECMP: traditional static load balancing
LetFlow: recent adaptive load balancing

Speedups are measured over ECMP
rho: fraction of links kept in a layer

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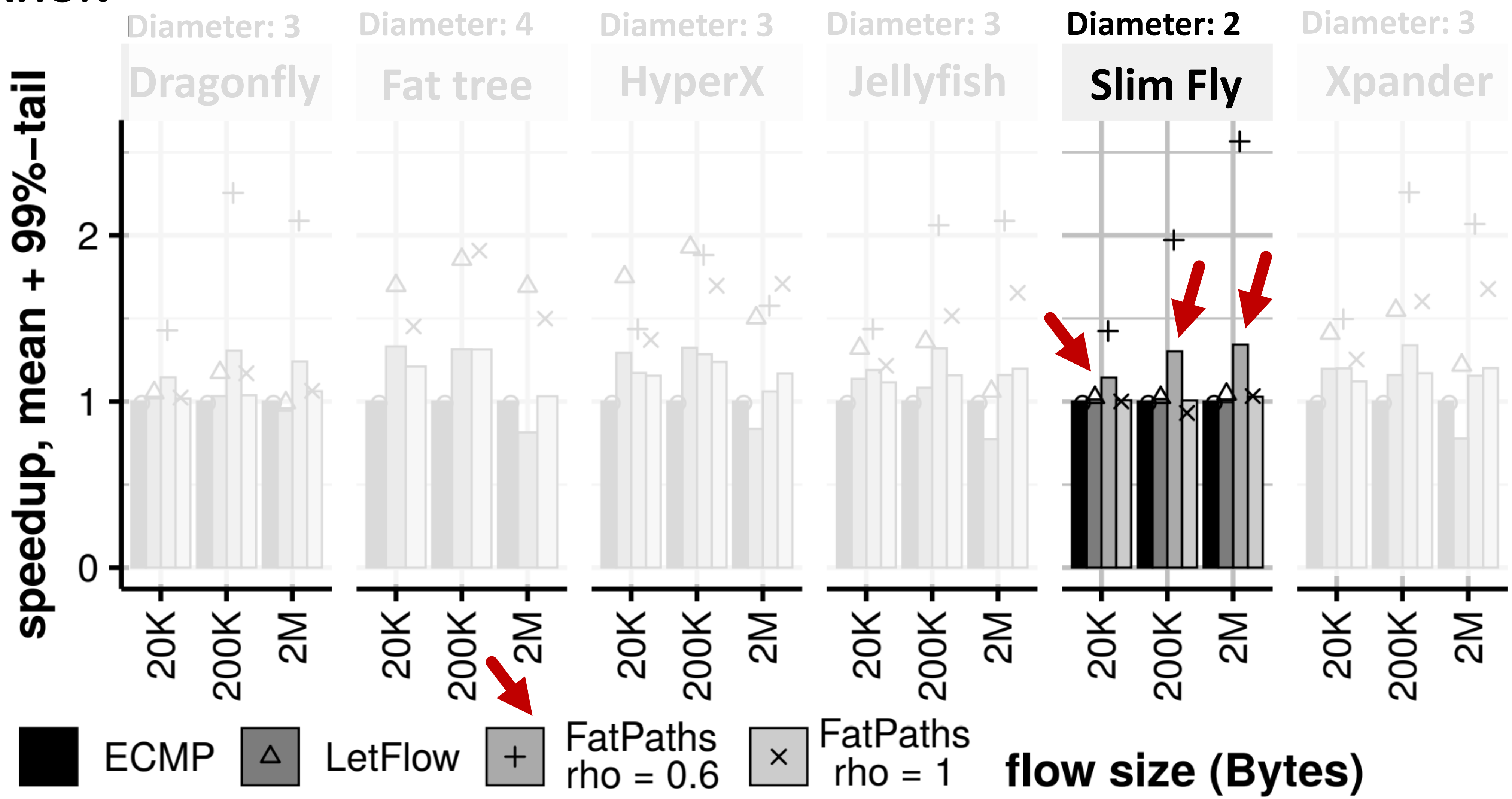

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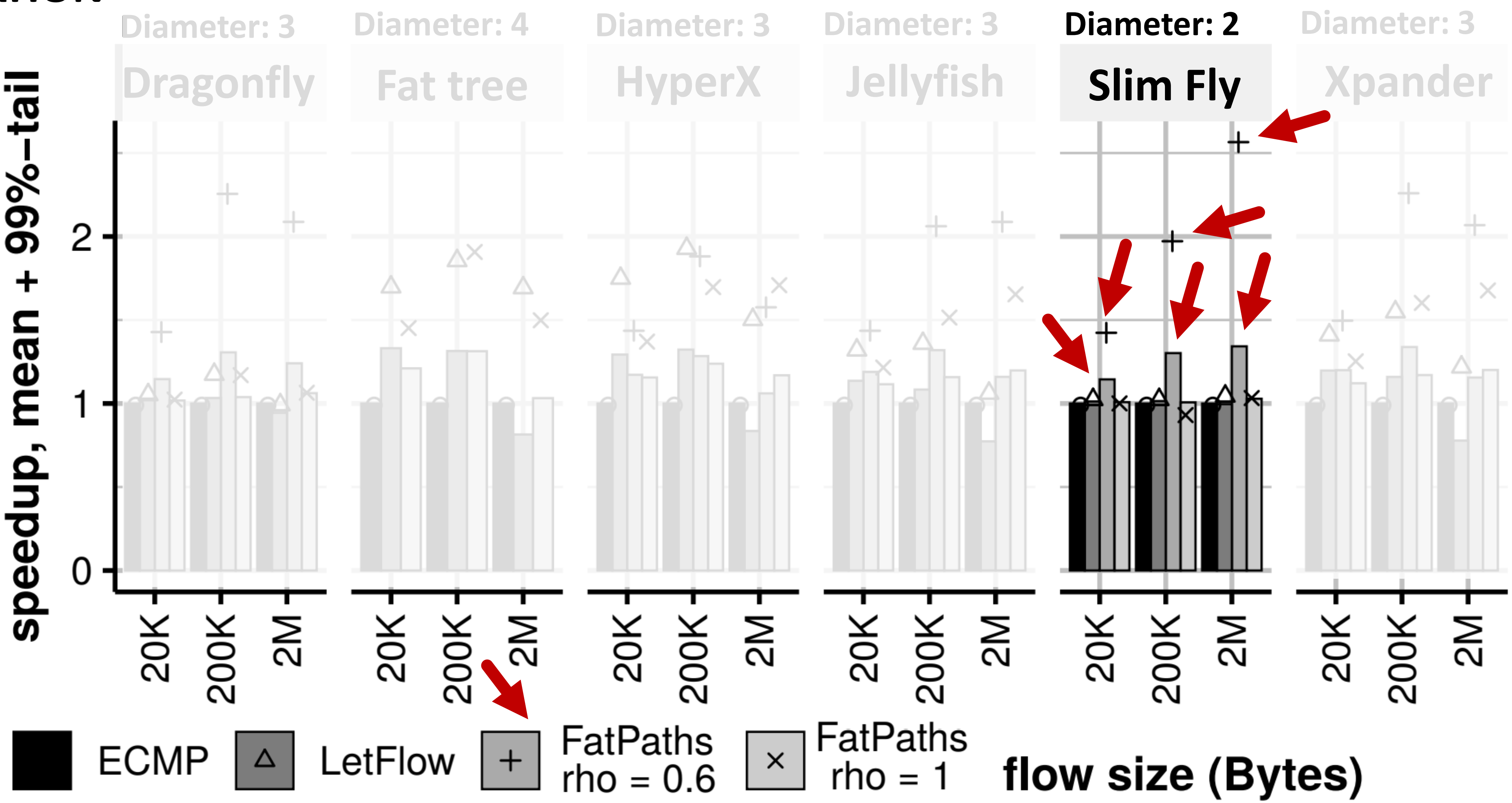

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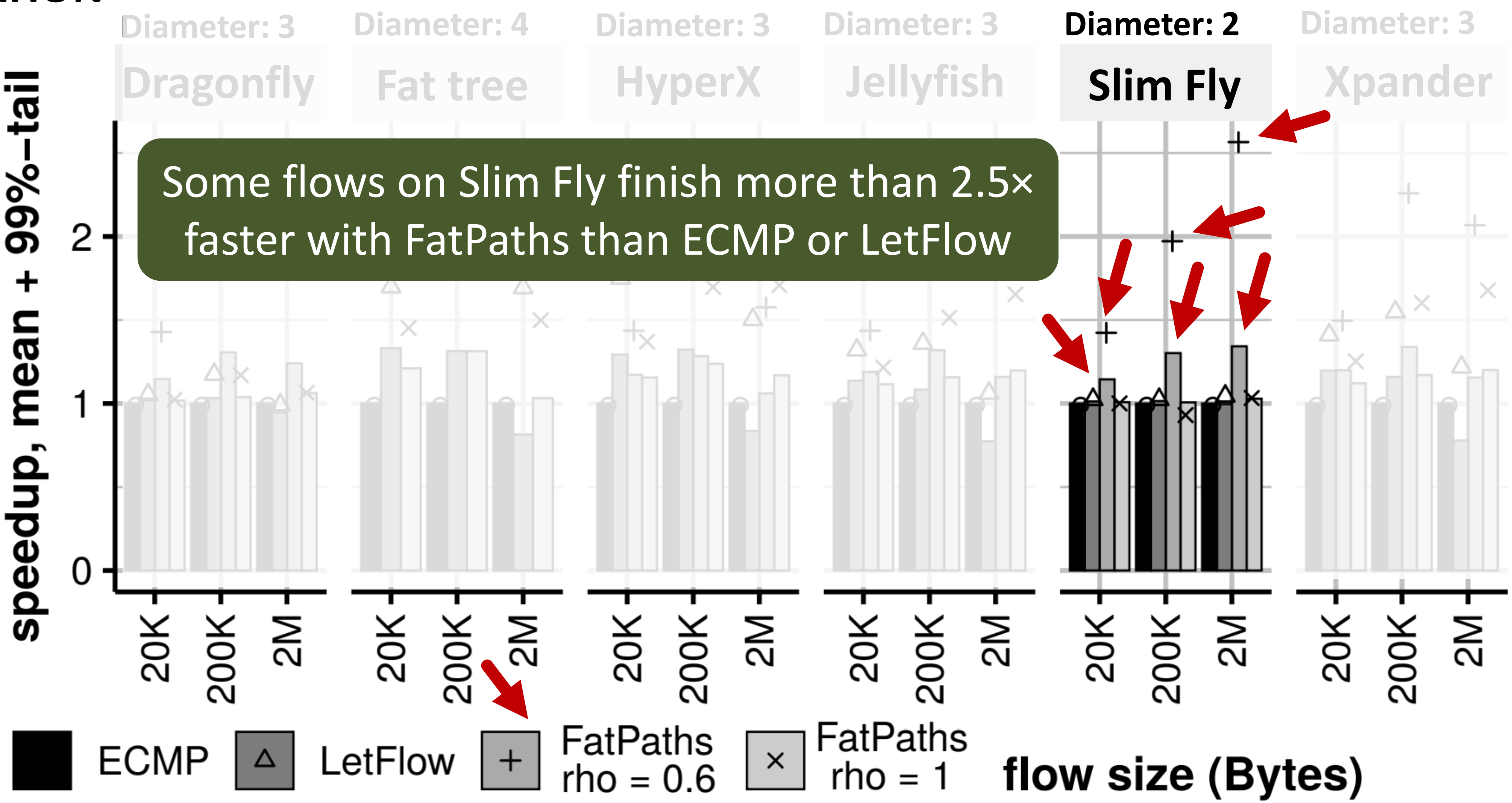

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EVALUATION

Other analyzes

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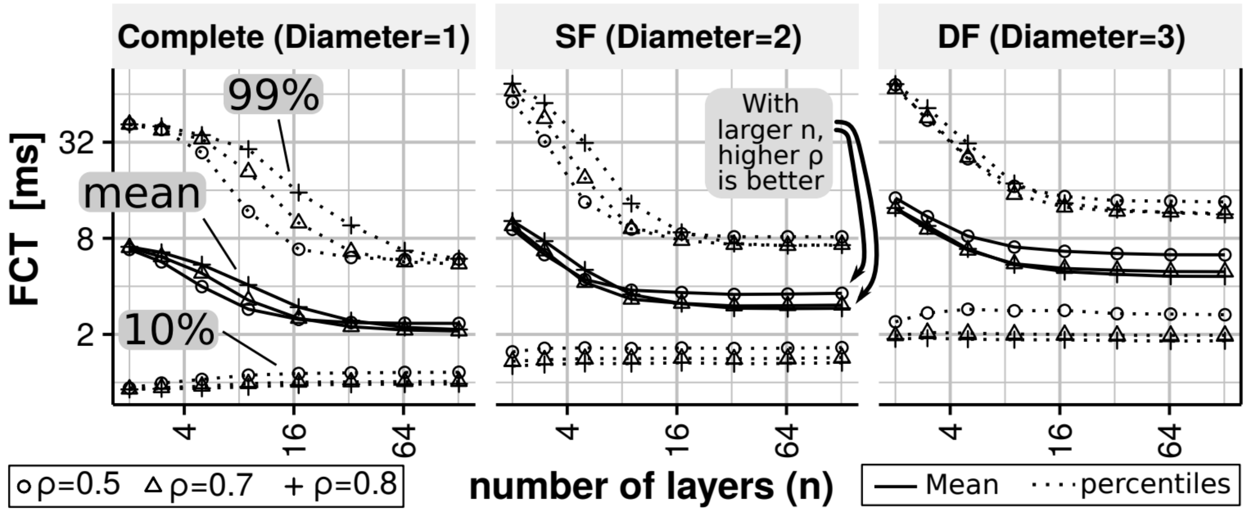
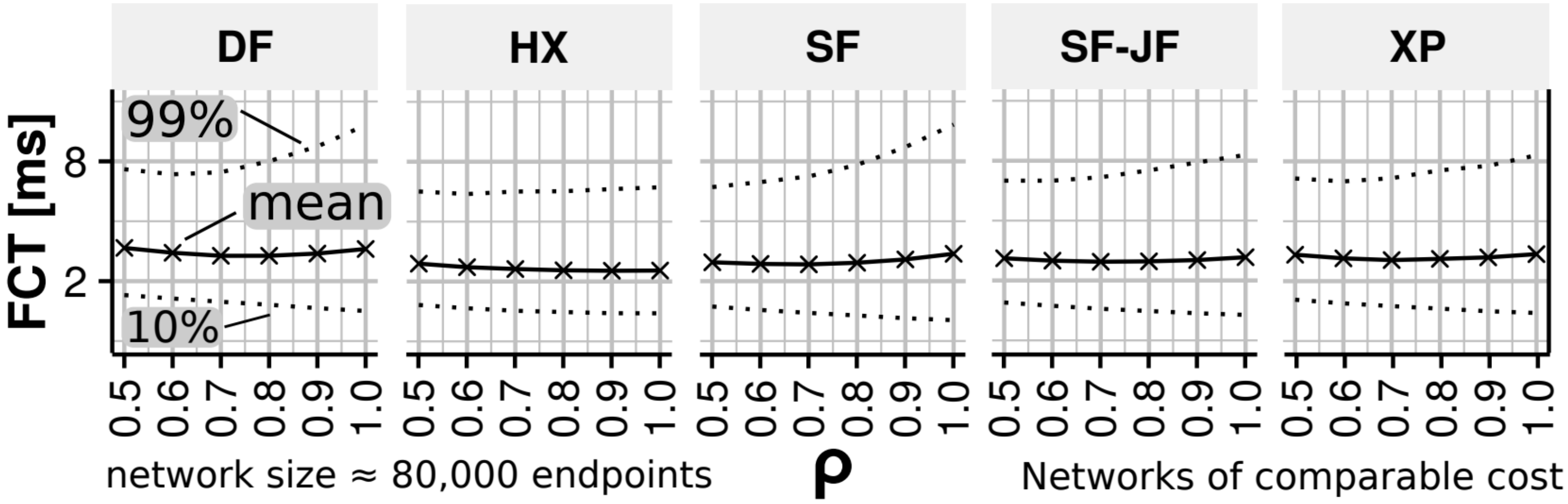


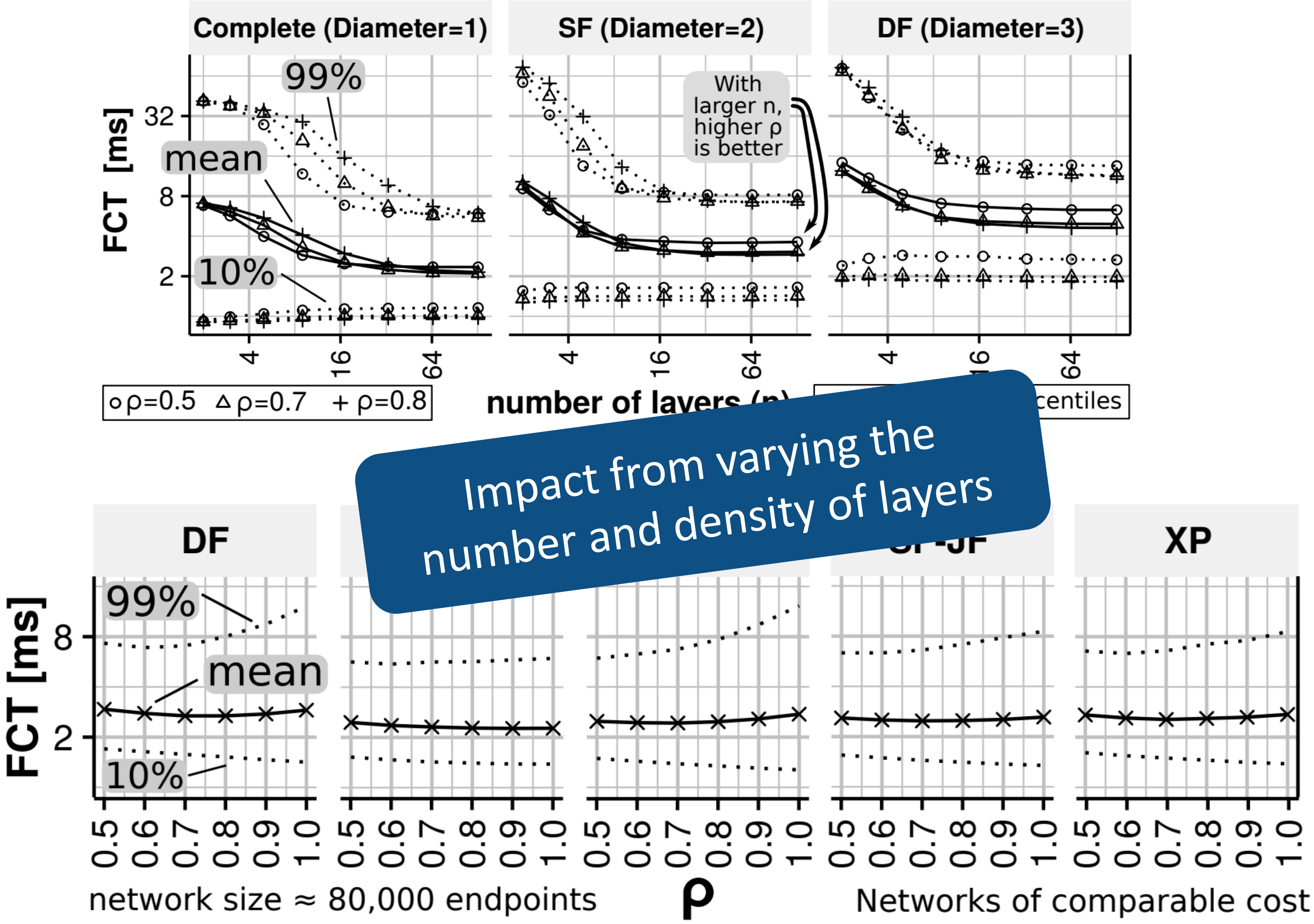


network size ≈ 80,000 endpoints

Networks of comparable cost

EVALUATION

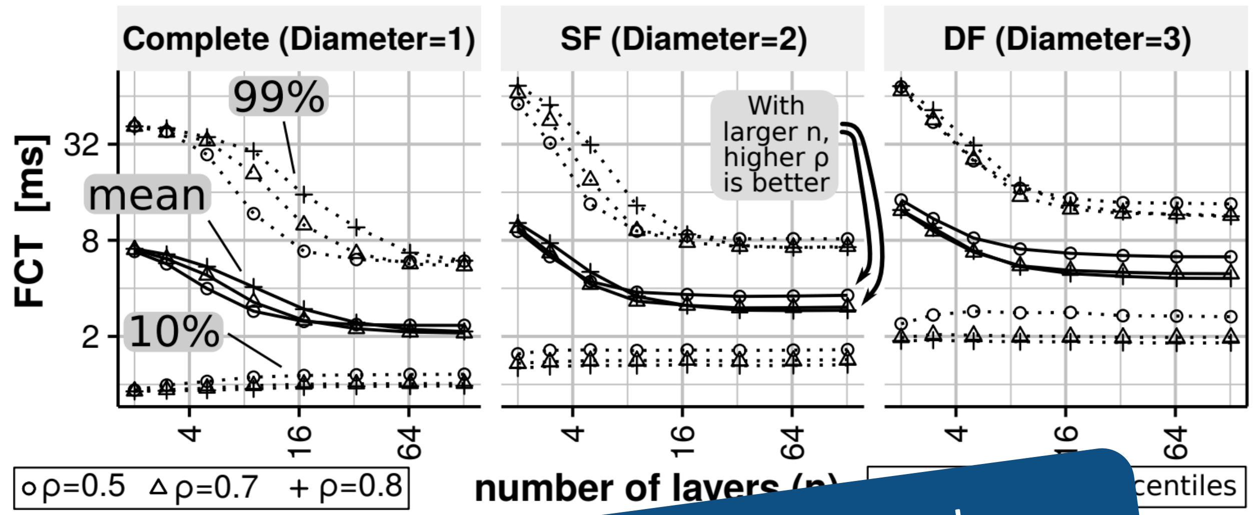
Other analyzes



Impact from varying the number and density of layers

EVALUATION

Other analyzes



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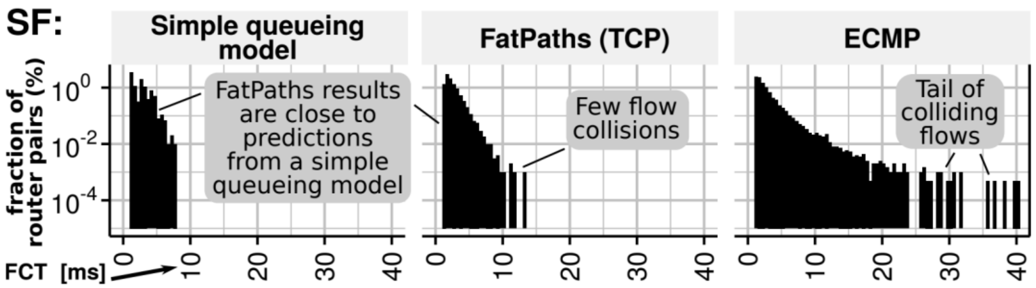

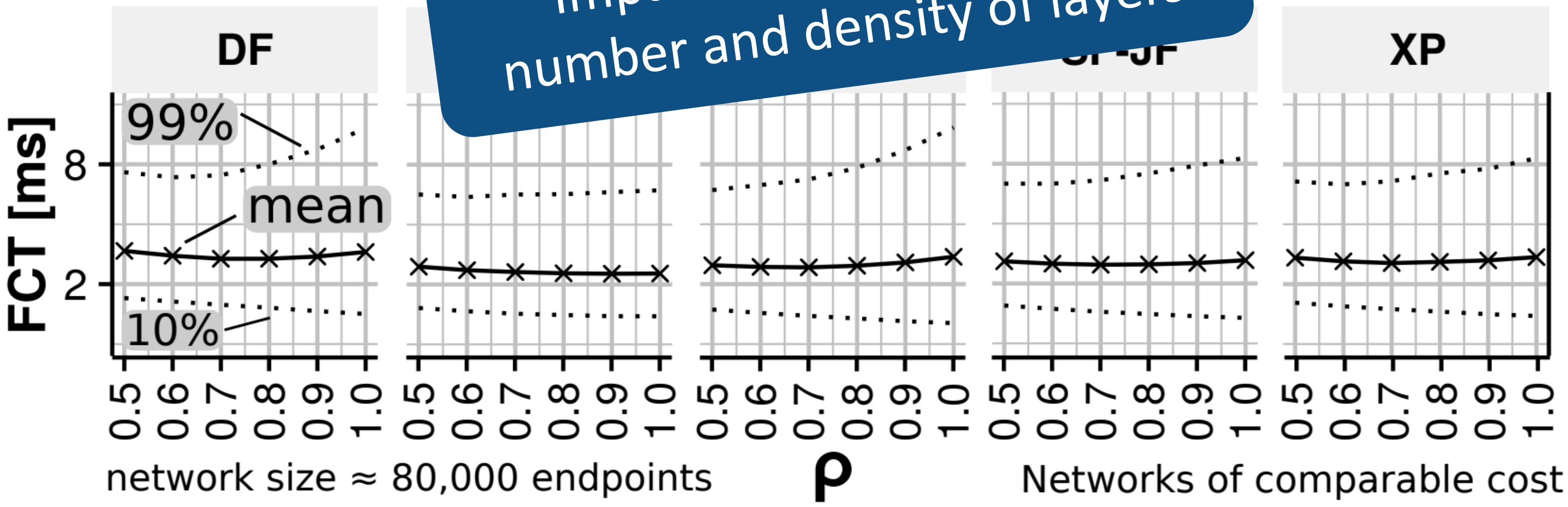

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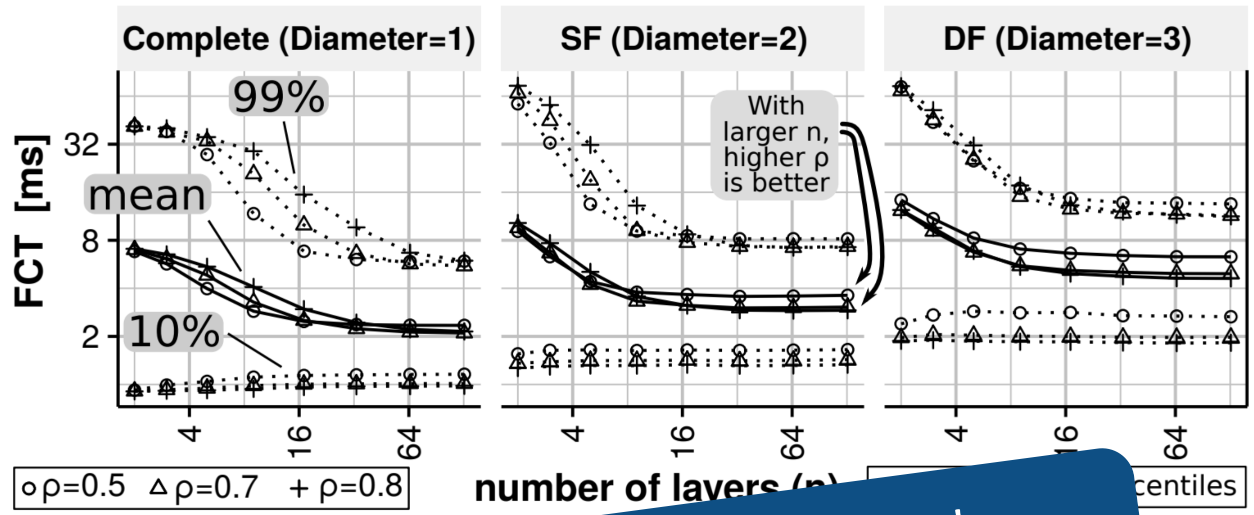
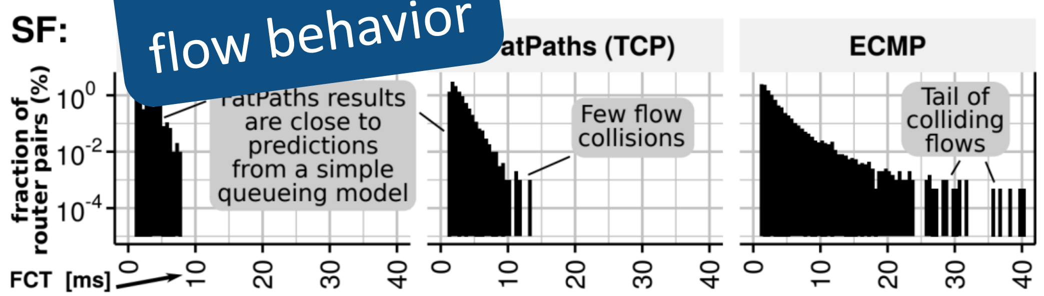
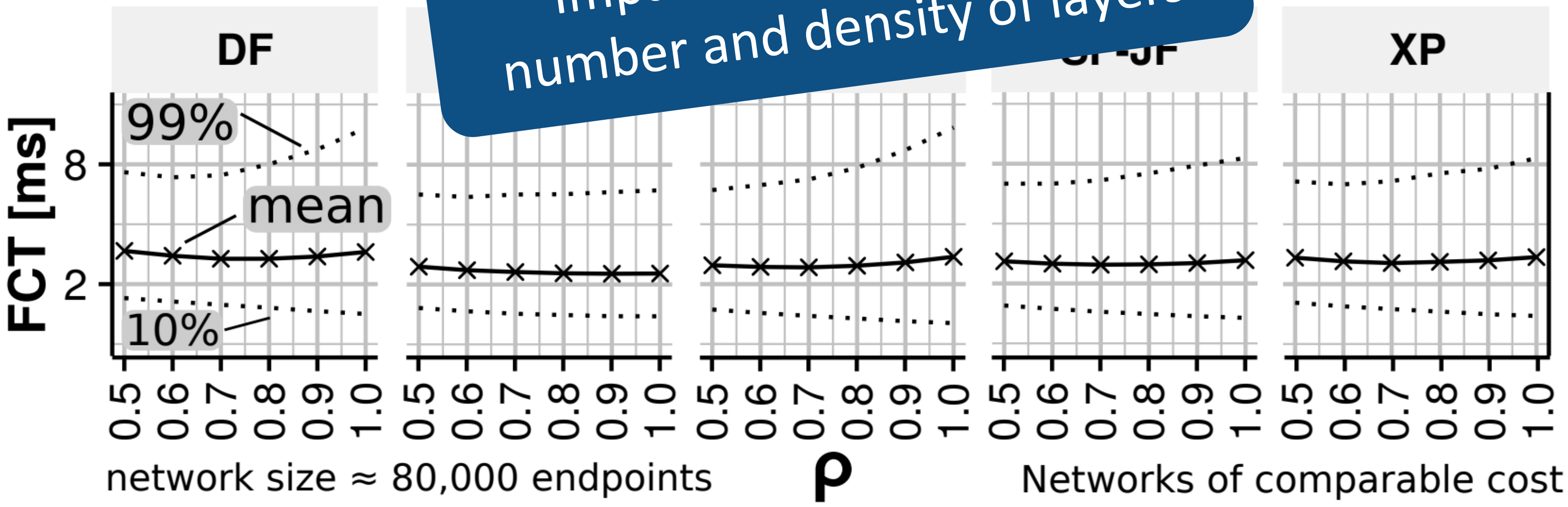




Details of flow behavior

Impact from varying the number and density of layers



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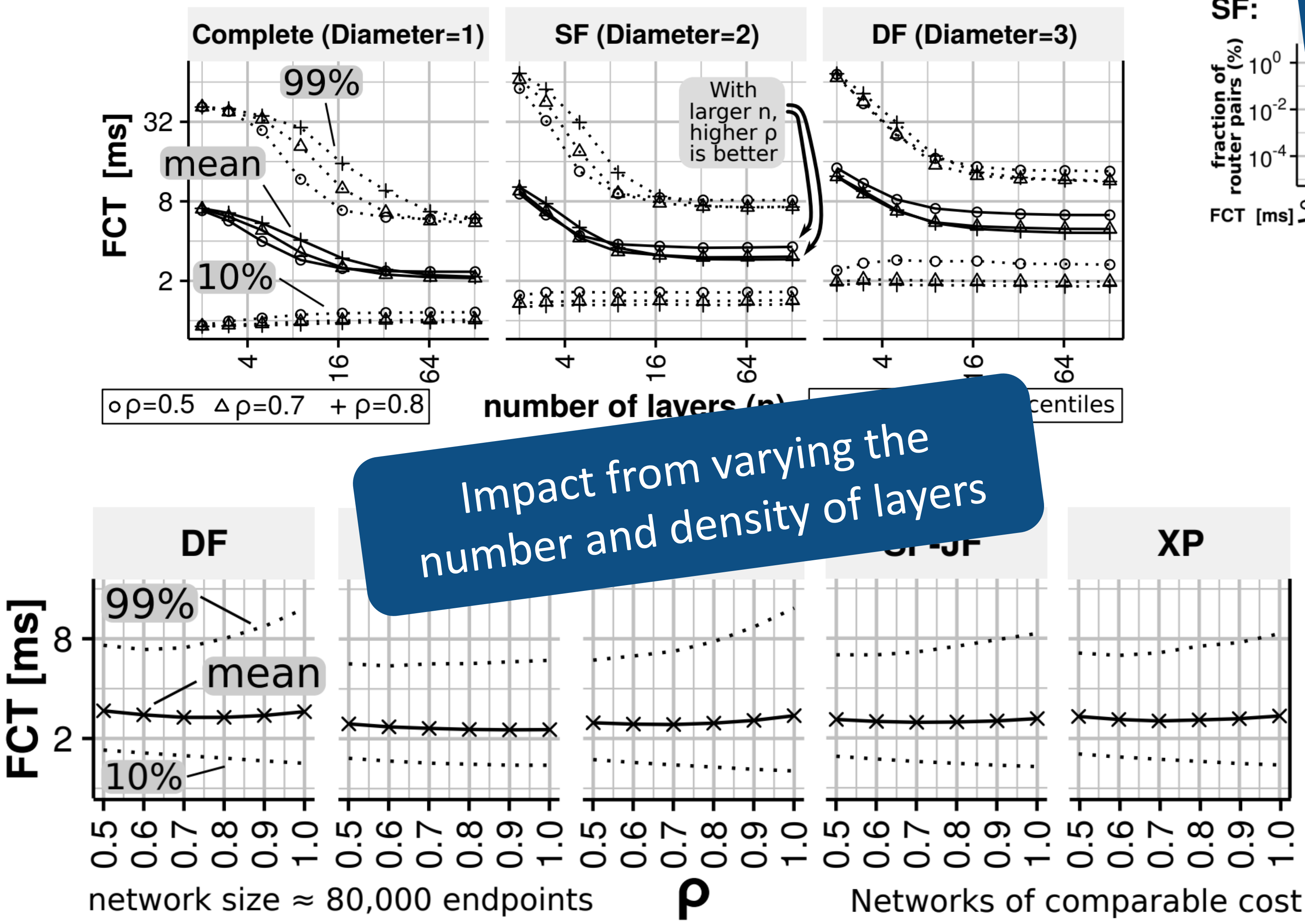

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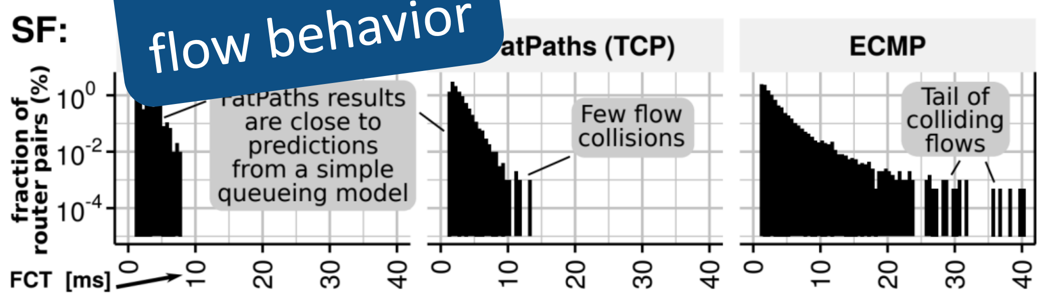

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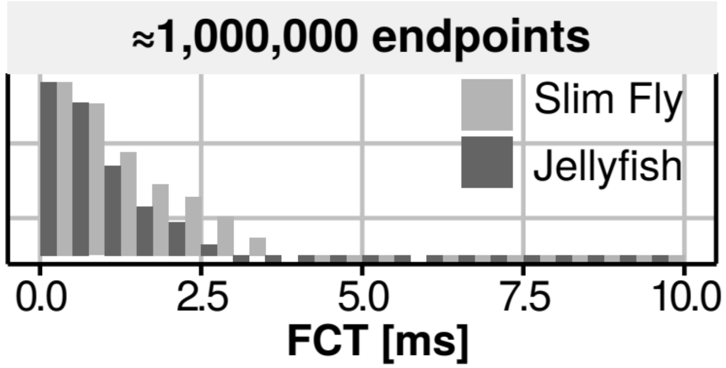
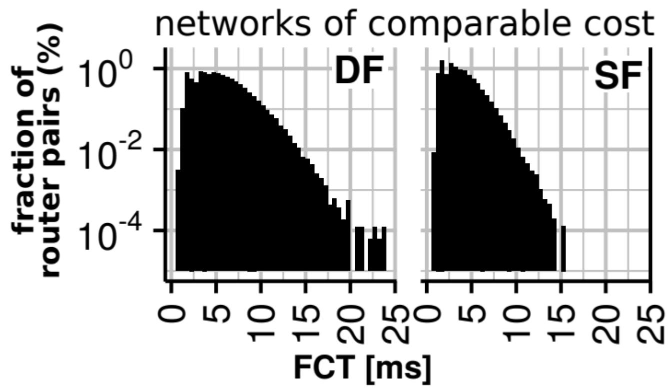
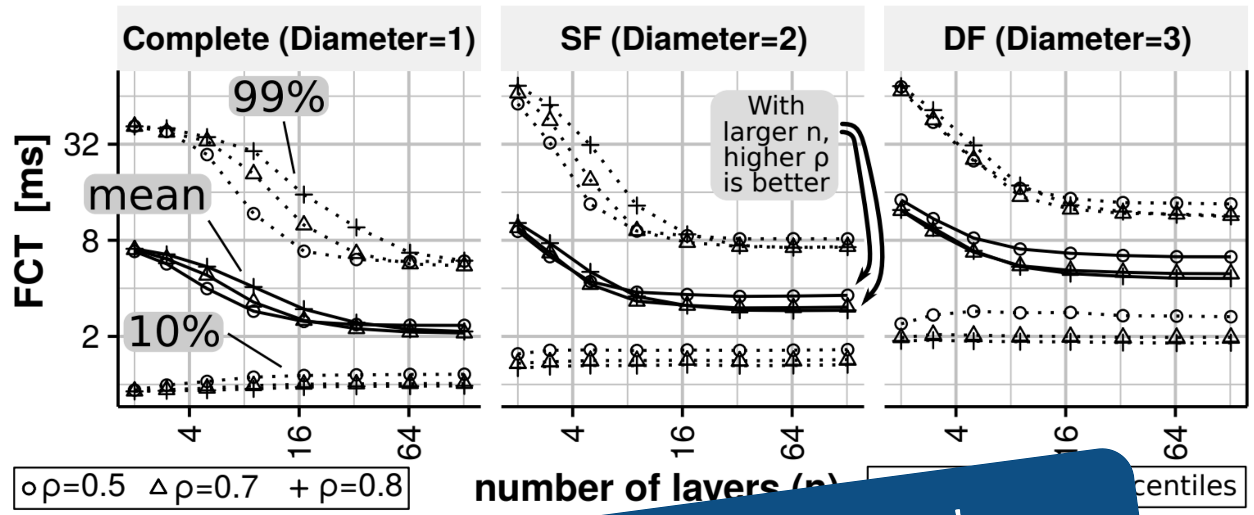




Evaluation

Other analyzes



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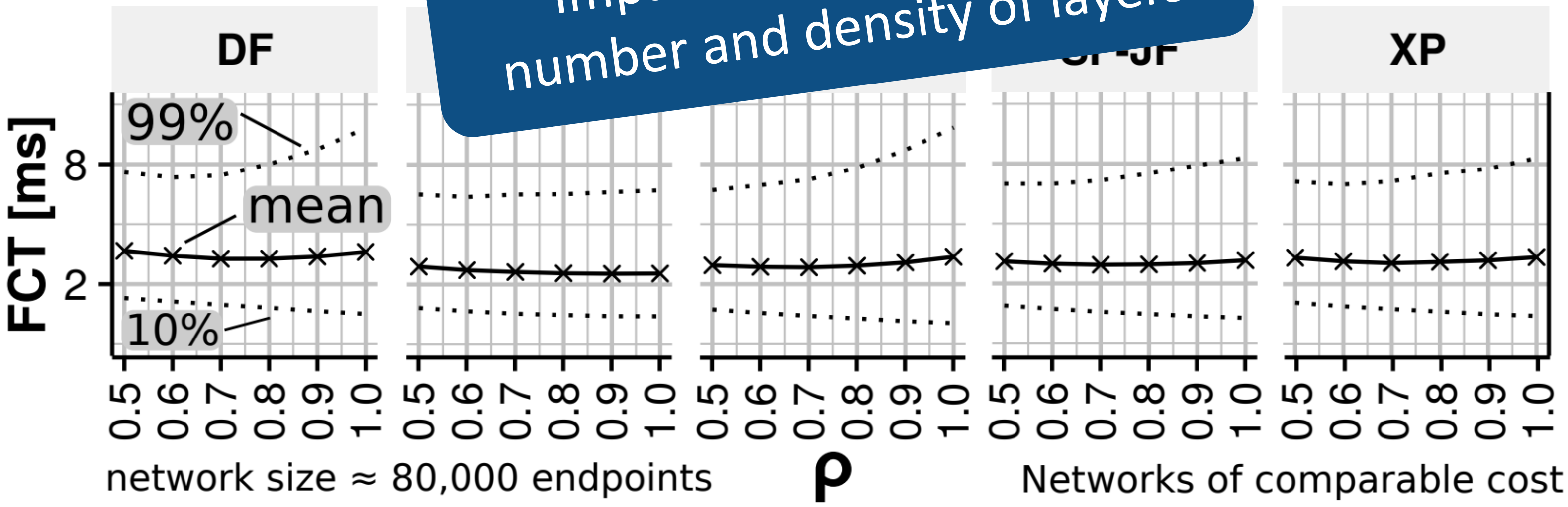

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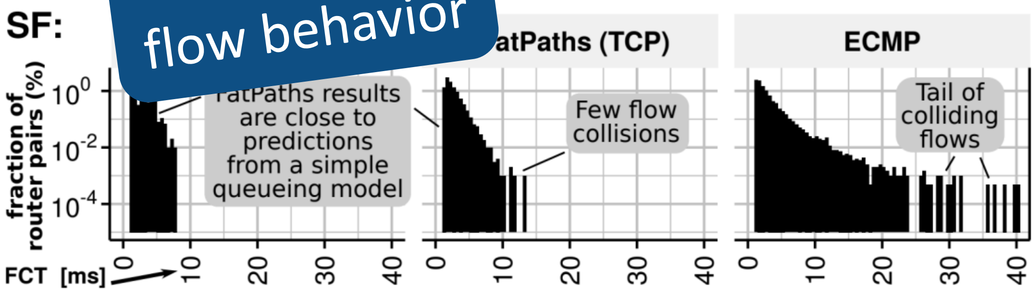
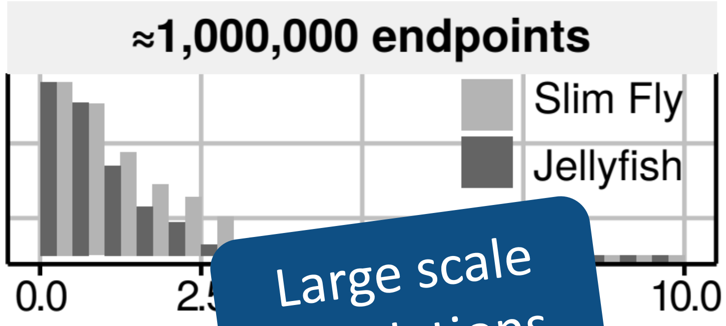
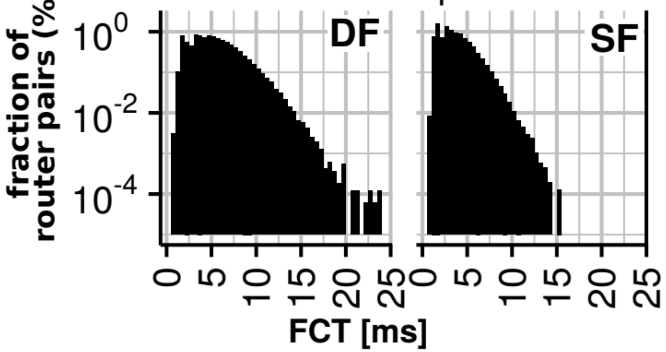
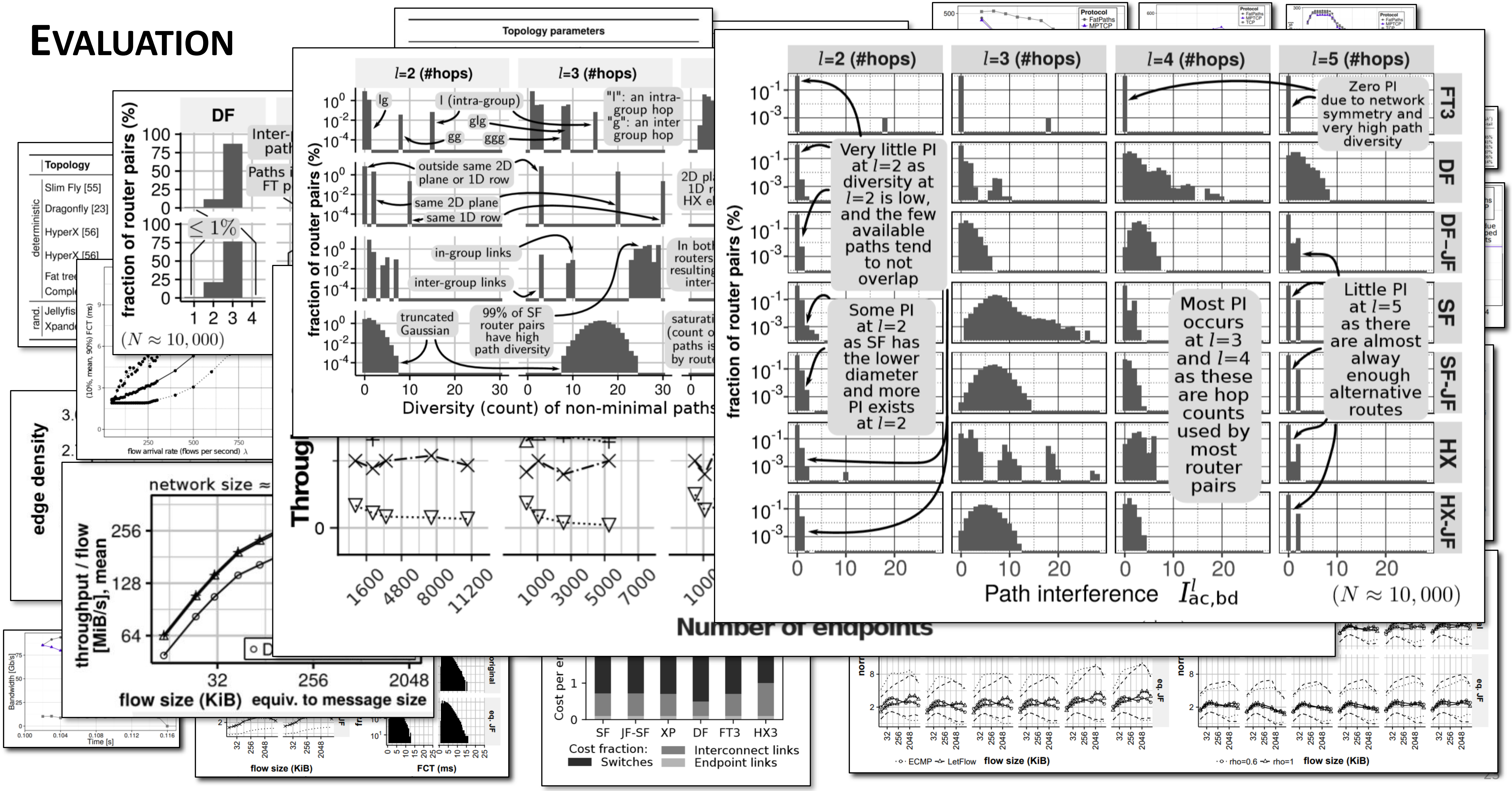




Large scale simulations



EVALUATION


l=2 (#hops)
l=3 (#hops)
l=4 (#hops)
l=5 (#hops)
FT3
DF
DF-JF
SF
SF-JF
HX
HX-JF
fraction of router pairs (%)
Zero PI due to network symmetry and very high path diversity
Very little PI at l=2 as diversity at l=2 is low, and the few available paths tend to not overlap
Some PI at l=2 as SF has the lower diameter and more PI exists at l=2
Most PI occurs at l=3 and l=4 as these are hop counts used by most router pairs
Little PI at l=5 as there are almost alway enough alternative routes
Path interference $I^l_{ac,bd}$
$(N \approx 10,000)$
Diversity (count) of non-minimal paths
truncated Gaussian
99% of SF router pairs have high path diversity
in-group links
inter-group links
outside same 2D plane or 1D row
same 2D plane
same 1D row
"l": an intra-group hop "g": an inter group hop
Topology parameters
Topology
Slim Fly [55]
Dragonfly [23]
HyperX [56]
deterministic
rand.
fraction of router pairs (%)
DF
$\leq 1\%$
$(N \approx 10,000)$
edge density
network size ≈
throughput / flow [MiB/s], mean
flow size (KiB) equiv. to message size
Number of endpoints
Cost fraction:
Switches
Interconnect links
Endpoint links
flow size (KiB)
FCT (ms)
flow arrival rate (flows per second) λ
ECMP
LetFlow
rho=0.6
rho=1

Evaluation

$$-\sum_{v \in V} \sum_{l=1,\ldots,n} f_{is_ivl} \cdot \delta_{v,\sigma_l(s_i,t_i)} + T(s_i,t_i) \cdot \mathcal{T} \leq 0, \quad i = 1, 2, \ldots, k \tag{5}$$

$$\sum_{i=1,\ldots k} \sum_{l=1,\ldots,n} f_{iuvl} \cdot \delta_{v,\sigma_l(u,t_i)} \leq c(u,v), \quad \forall (u,v) \in E \tag{6}$$

$$\sum_{v \in V} f_{iuvl} \cdot \delta_{v,\sigma_l(u,t_i)} - \sum_{v \in V} f_{ivul} \cdot \delta_{u,\sigma_l(v,t_i)} = 0, \quad i = 1, \ldots, k, \quad l = 1, \ldots, n, \forall u \in V \setminus \{s_i, t_i\} \tag{7}$$

$$\sum_{v \in V} \sum_{l=1,\ldots,n} f_{is_ivl} \cdot \delta_{v,\sigma_l(s_i,t_i)} \leq \mathcal{T}_{upperbound} \cdot T(s_i,t_i), \quad i = 1, \ldots, k \tag{8}$$

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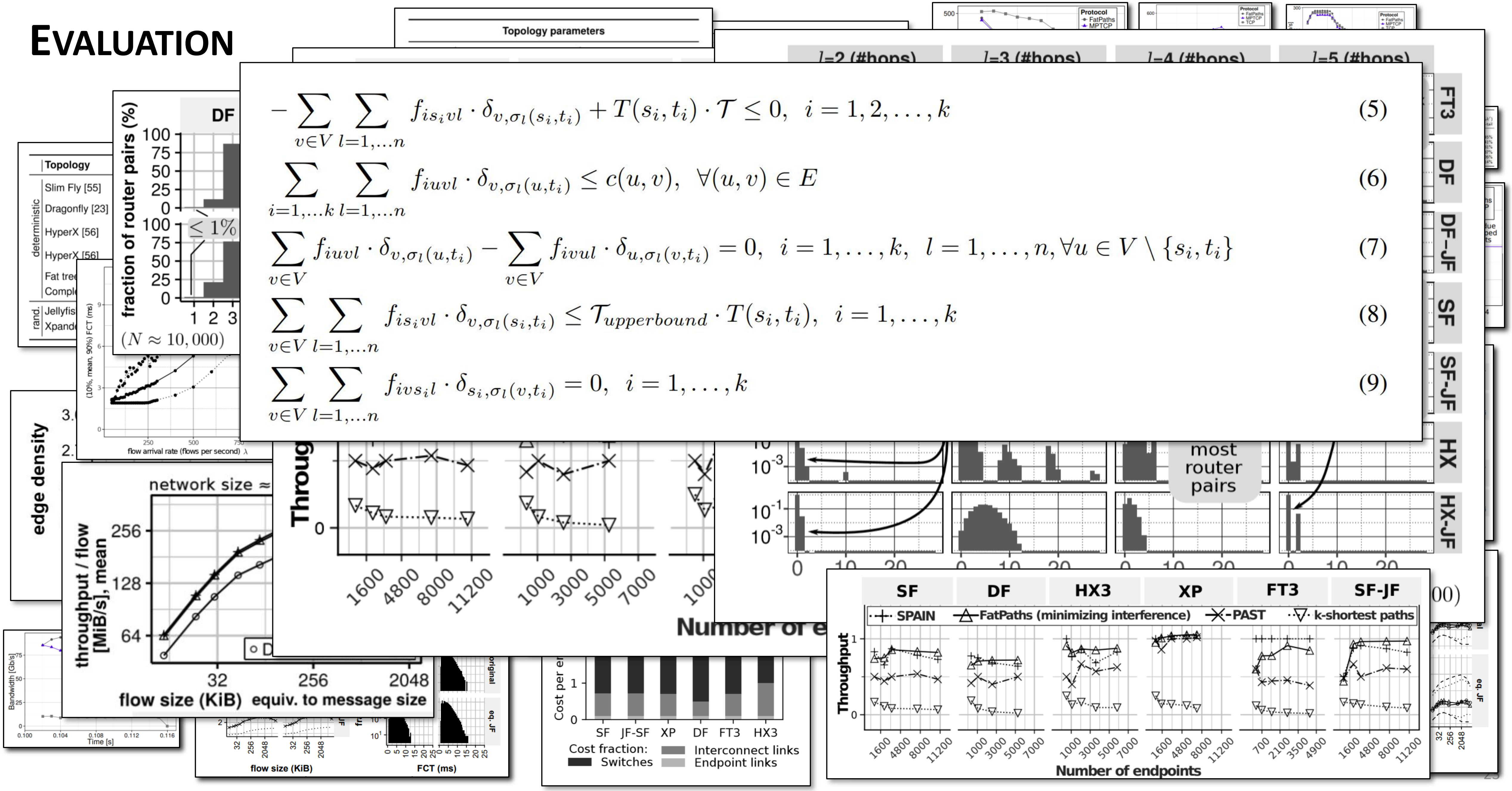
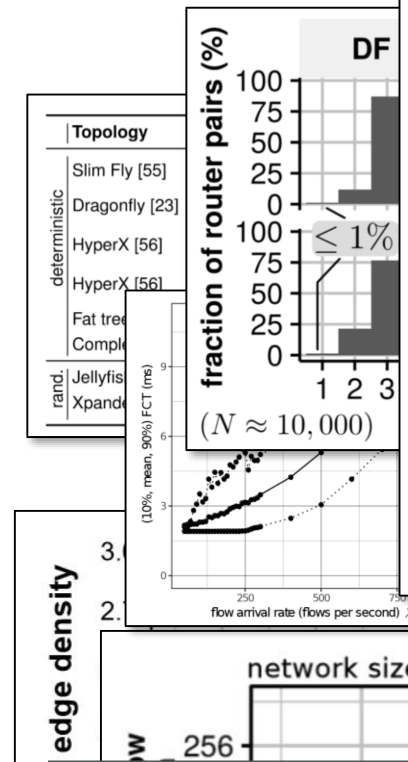


Evaluation



$$-\sum_{v\in V}\sum_{l=1,\dots,n} f_{is_ivl}\cdot\delta_{v,\sigma_l(s_i,t_i)} + T(s_i,t_i)\cdot\mathcal{T}\le 0,\ \ i=1,2,\dots,k \tag{5}$$

$$\sum_{i=1,\dots k}\sum_{l=1,\dots,n} f_{iuvl}\cdot\delta_{v,\sigma_l(u,t_i)}\le c(u,v),\ \ \forall(u,v)\in E \tag{6}$$

$$\sum_{v\in V} f_{iuvl}\cdot\delta_{v,\sigma_l(u,t_i)} - \sum_{v\in V} f_{ivul}\cdot\delta_{u,\sigma_l(v,t_i)} = 0,\ \ i=1,\dots,k,\ \ l=1,\dots,n,\forall u\in V\setminus\{s_i,t_i\} \tag{7}$$

$$\sum_{v\in V}\sum_{l=1,\dots,n} f_{is_ivl}\cdot\delta_{v,\sigma_l(s_i,t_i)}\le \mathcal{T}_{upperbound}\cdot T(s_i,t_i),\ \ i=1,\dots,k \tag{8}$$

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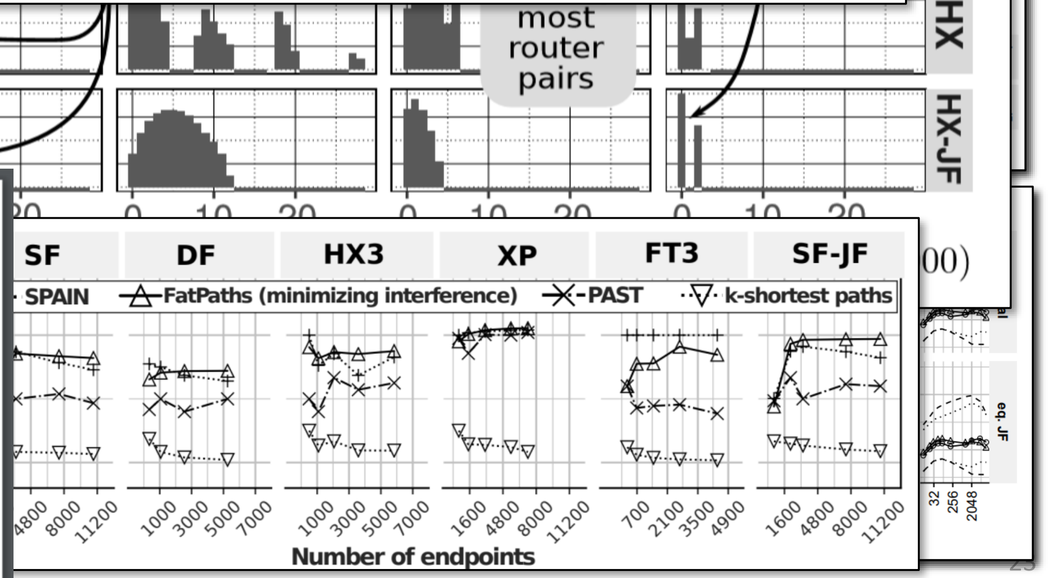
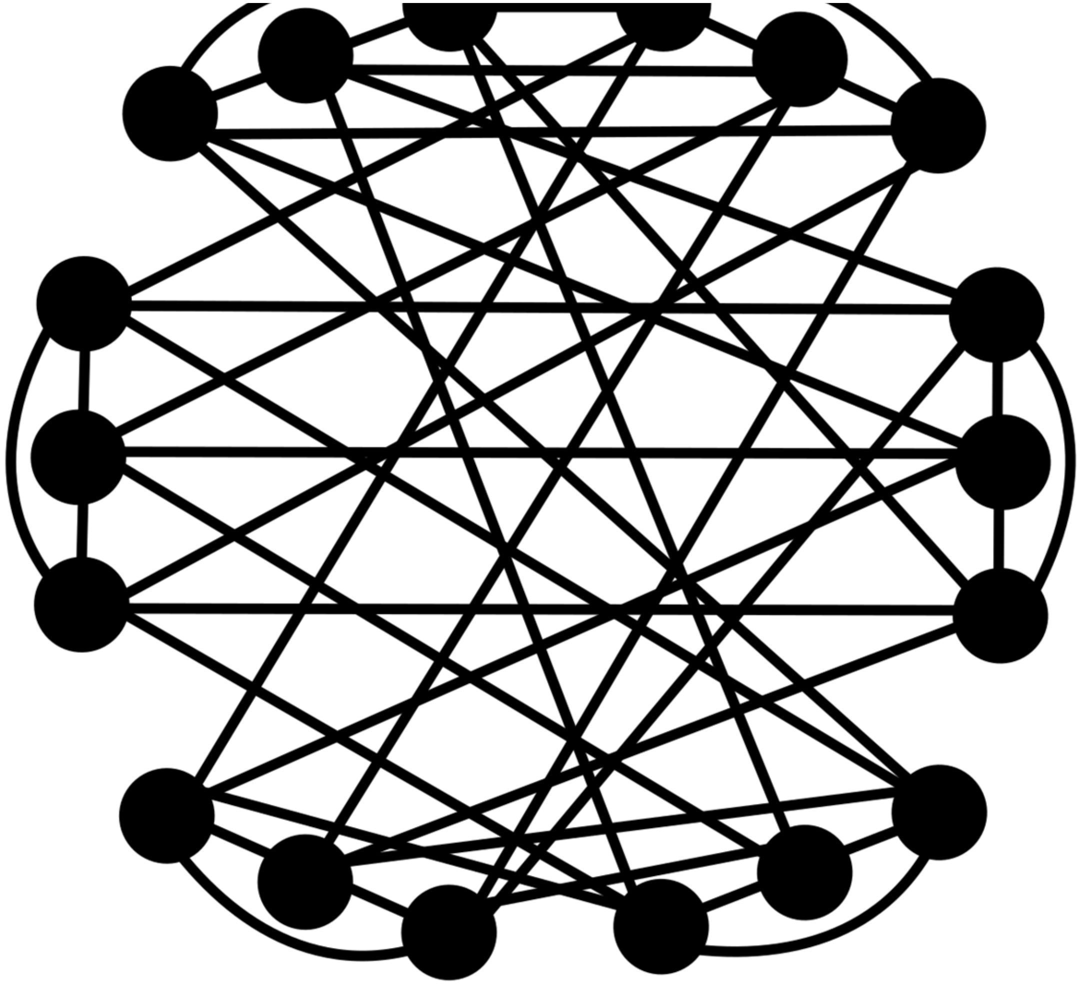
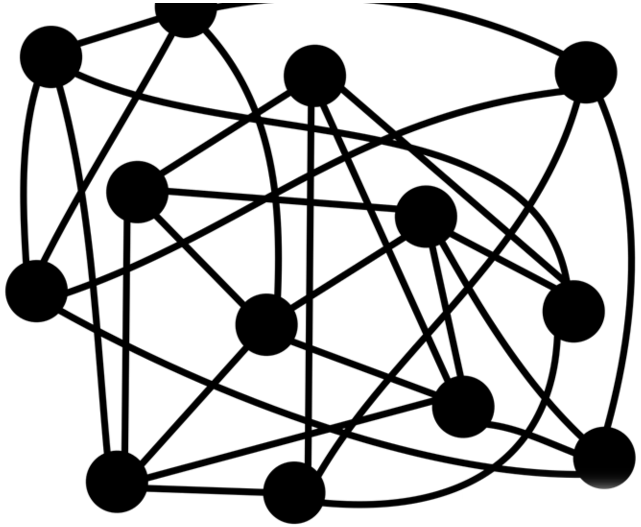


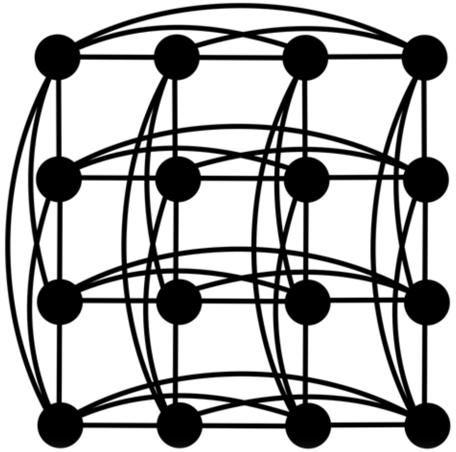
1

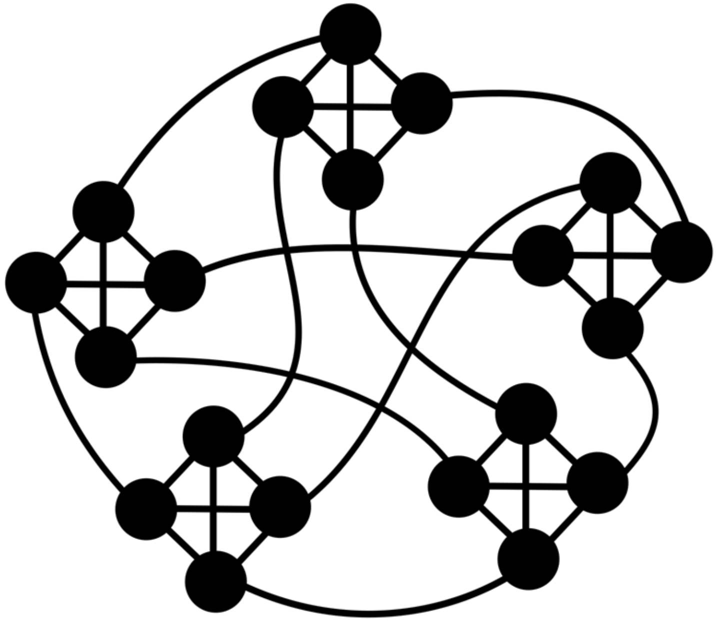
High-Performance Routing with Multipathing and Path Diversity in Supercomputers and Data Centers

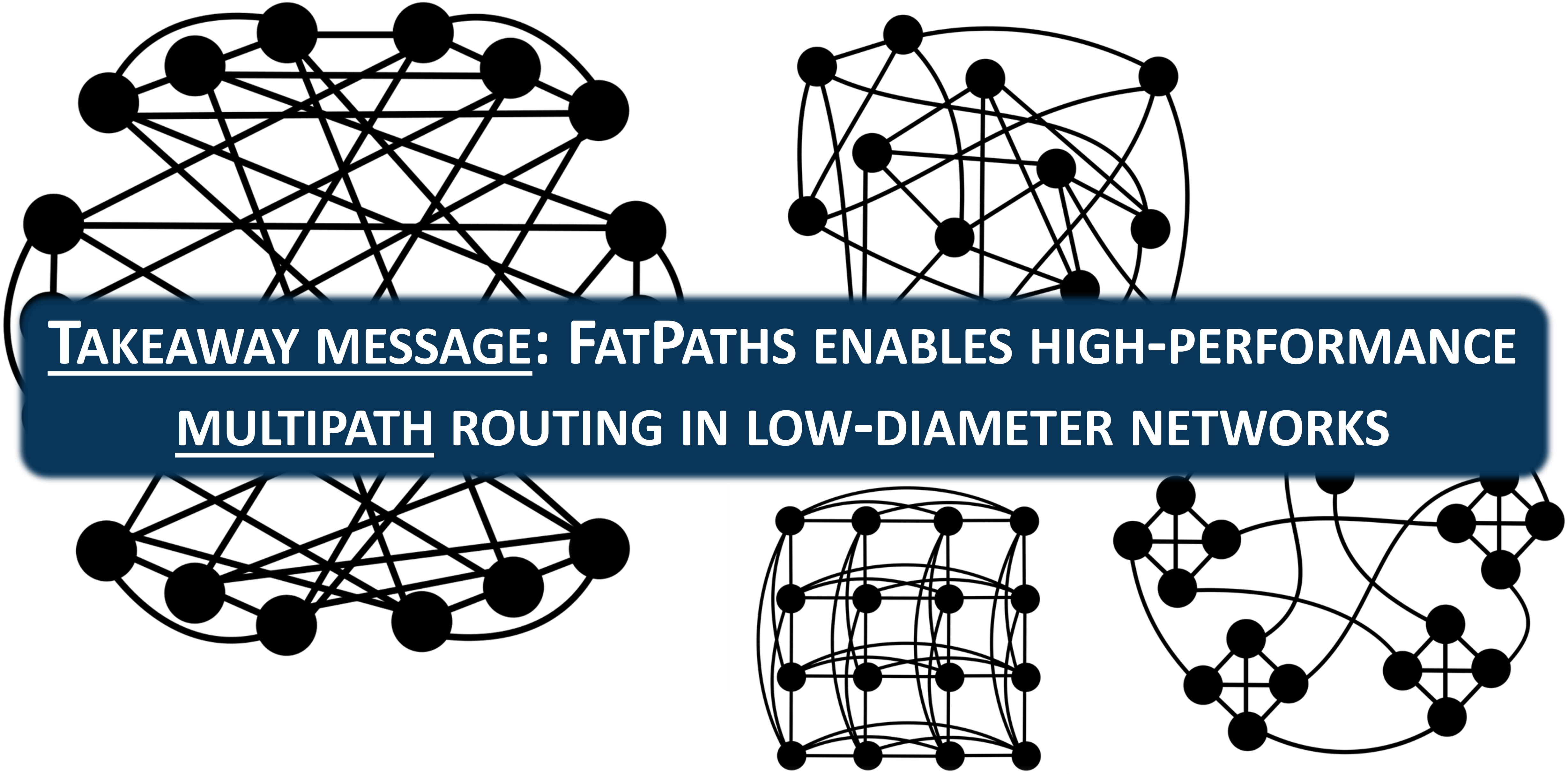
Maciej Besta[1], Jens Domke[2], Marcel Schneider[1], Marek Konieczny[3], Salvatore Di Girolamo[1], Timo Schneider[1], Ankit Singla[1], Torsten Hoefler[1]
[1]Department of Computer Science, ETH Zurich; [2]RIKEN Center for Computational Science (R-CCS)
[3]Department of Computer Science, Electronics and Telecommunications; AGH-UST





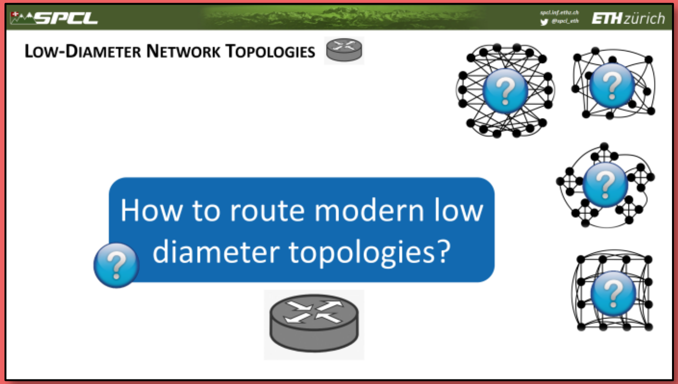


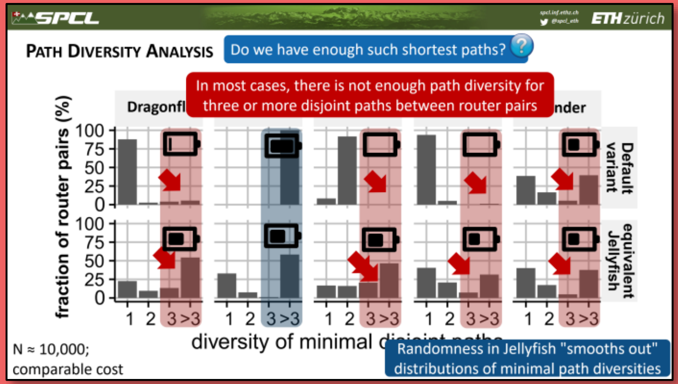


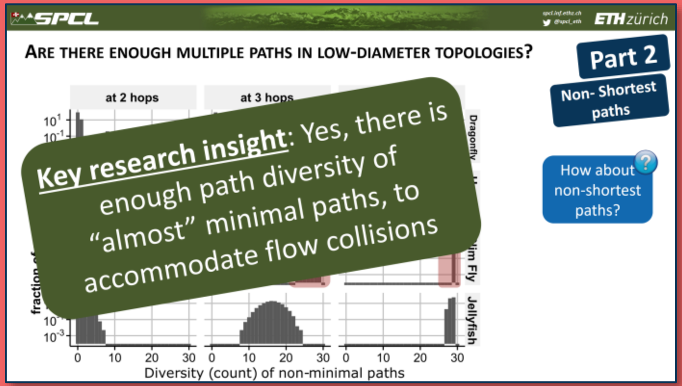


TAKEAWAY MESSAGE: FATPATHS ENABLES HIGH-PERFORMANCE MULTIPATH ROUTING IN LOW-DIAMETER NETWORKS

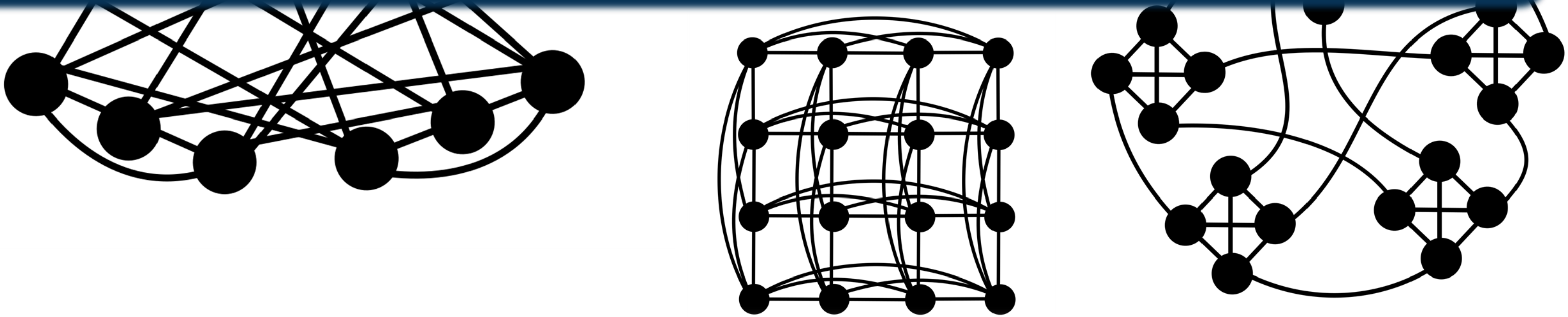
Potential for multipath routing in modern low-diameter networks







Takeaway message: FatPaths enables high-performance multipath routing in low-diameter networks



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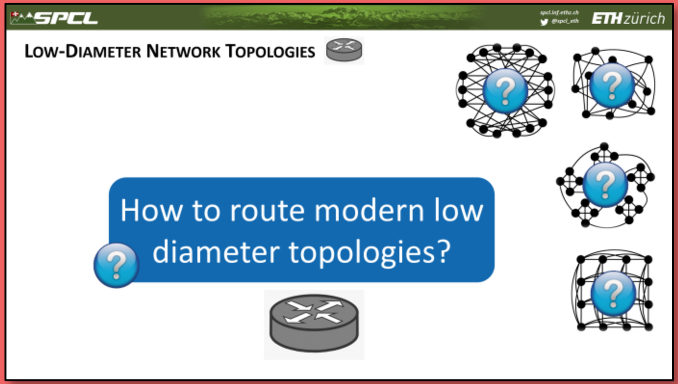
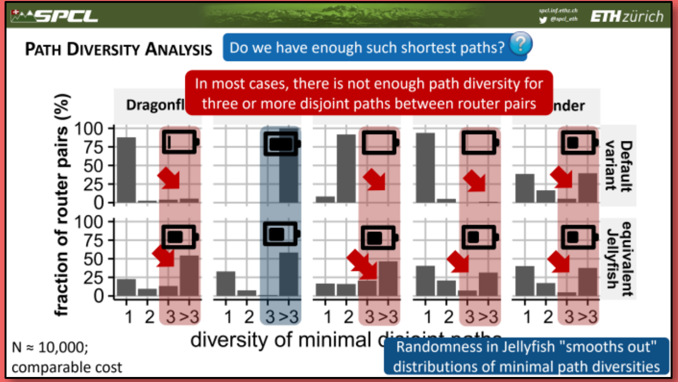
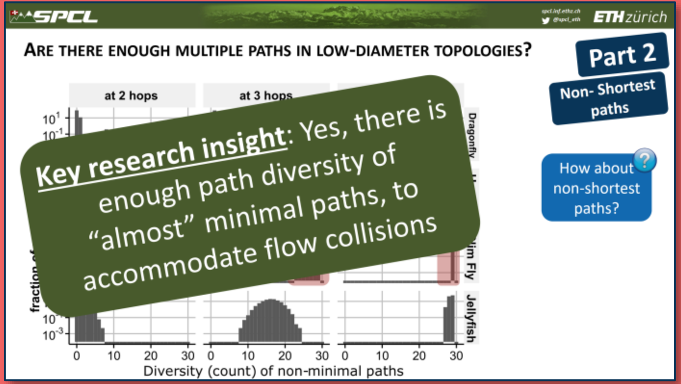
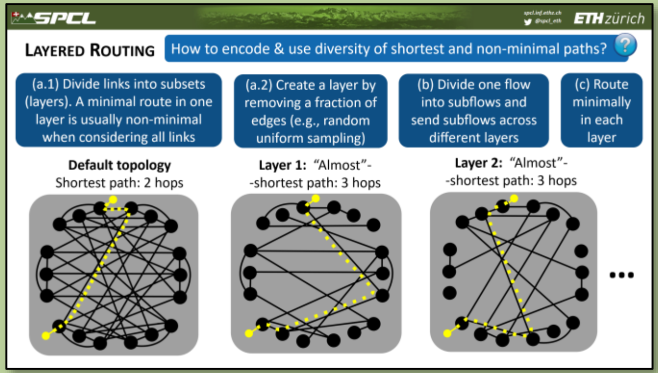


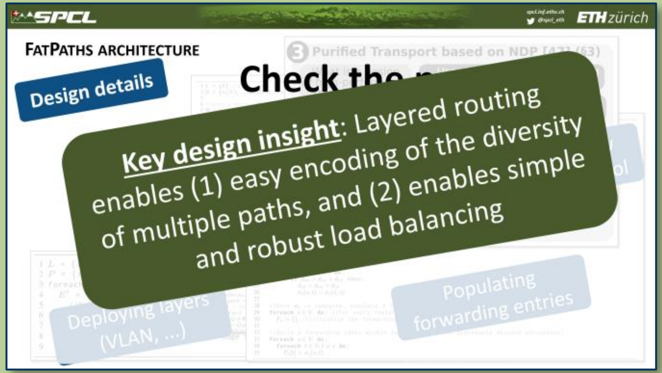




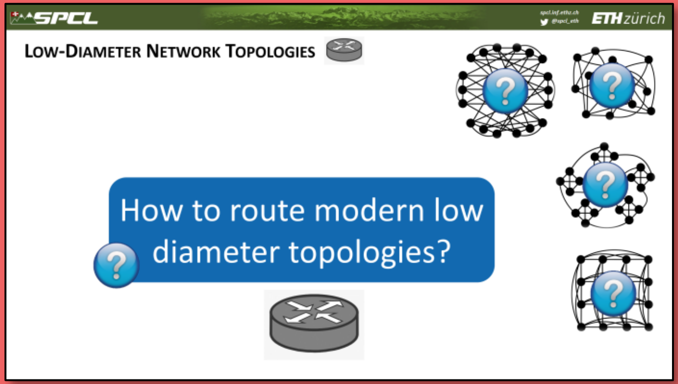
Takeaway message: FatPaths enables high-performance multipath routing in low-diameter networks

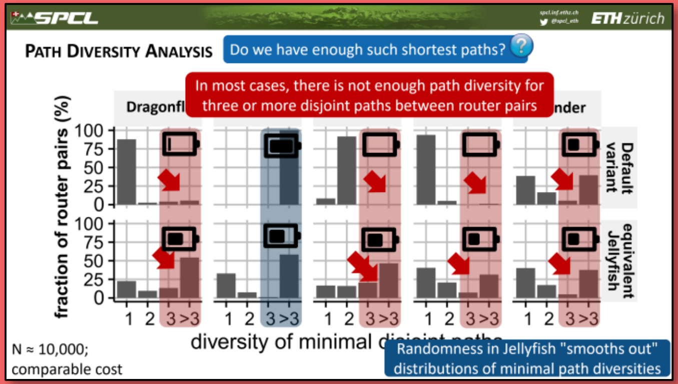
High-performance routing protocol & architecture

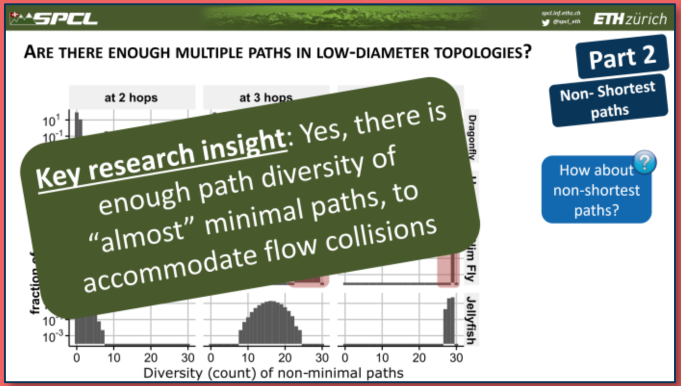




Potential for multipath routing in modern low-diameter networks

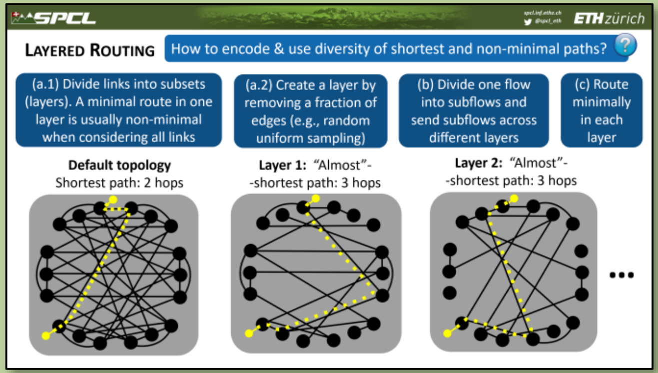


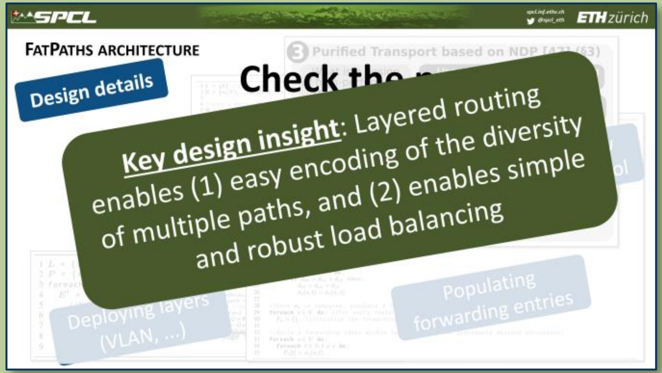




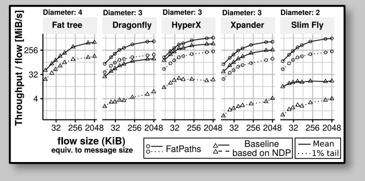
Takeaway message: FatPaths enables high-performance multipath routing in low-diameter networks

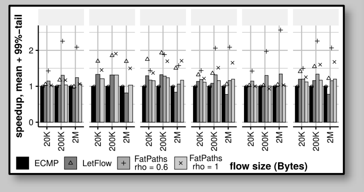
High-performance routing protocol & architecture

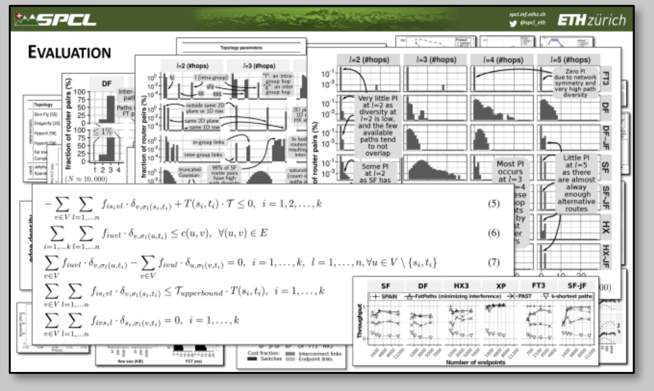




Rich evaluation & theoretical analysis

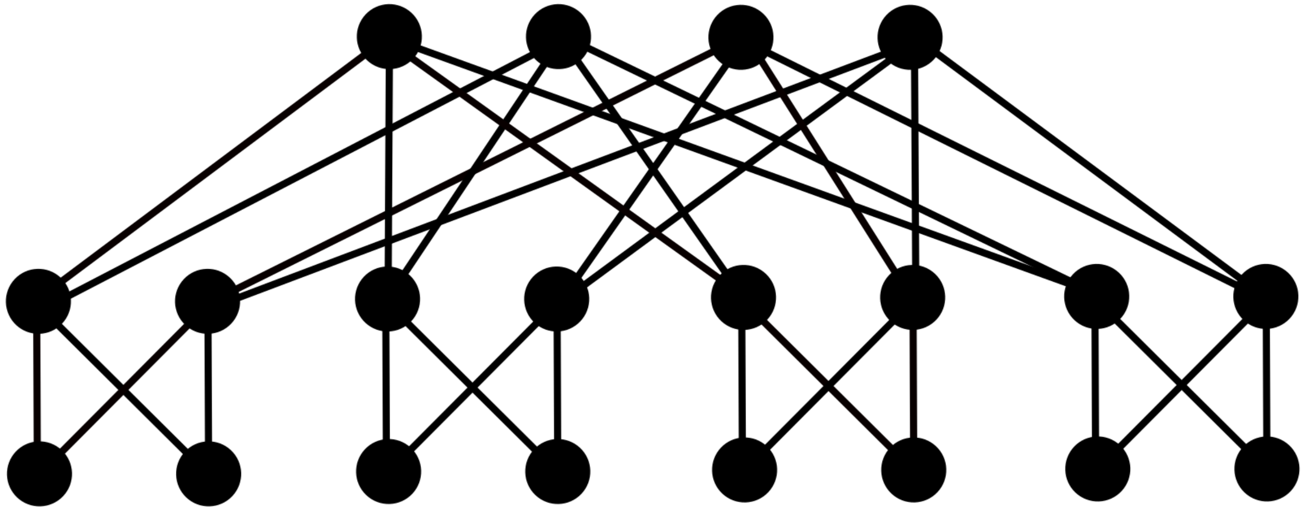






Backup Slides and Slides' Variants

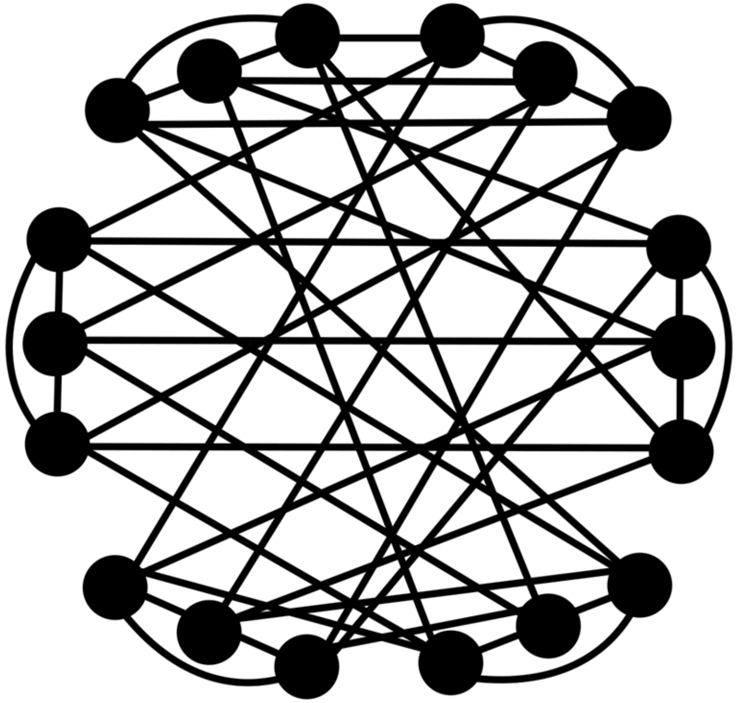
Low-Diameter Network Topologies vs Fat Trees



3-level Fat tree

Diameter = 4

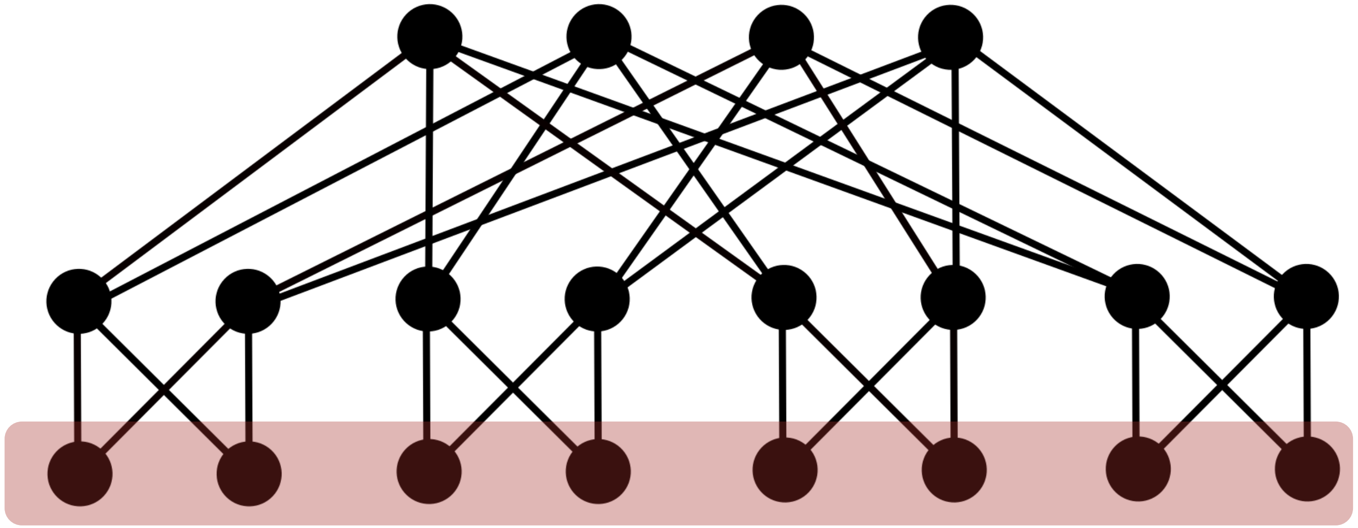
Example Slim Fly (based on the Hoffman-Singleton Graph [1])



Diameter = 2

[1] Hoffman, Alan J.; Singleton, Robert R. (1960), *Moore graphs with diameter 2 and 3*, IBM Journal of Research and Development

Low-Diameter Network Topologies vs Fat Trees



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Diameter = 4
Only edge (leaf) routers attach to endpoints

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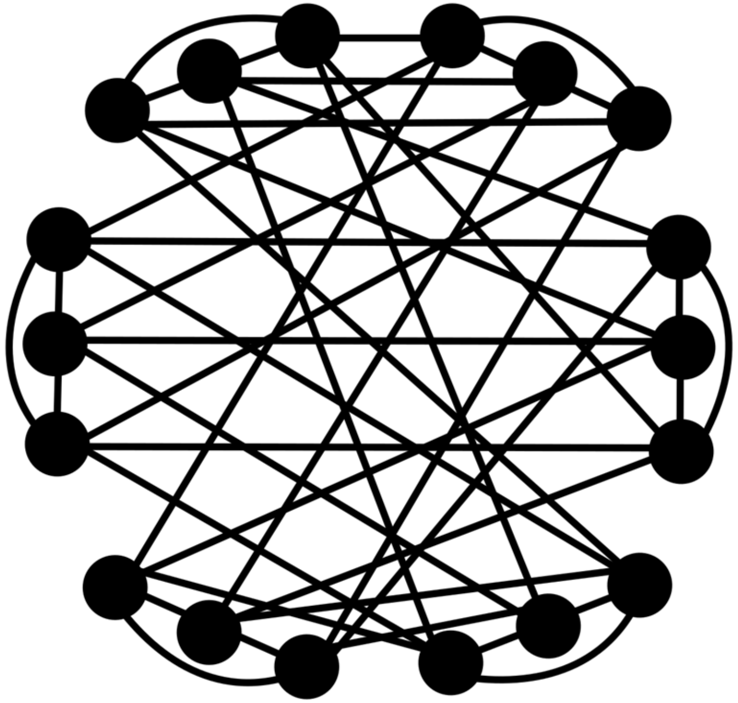

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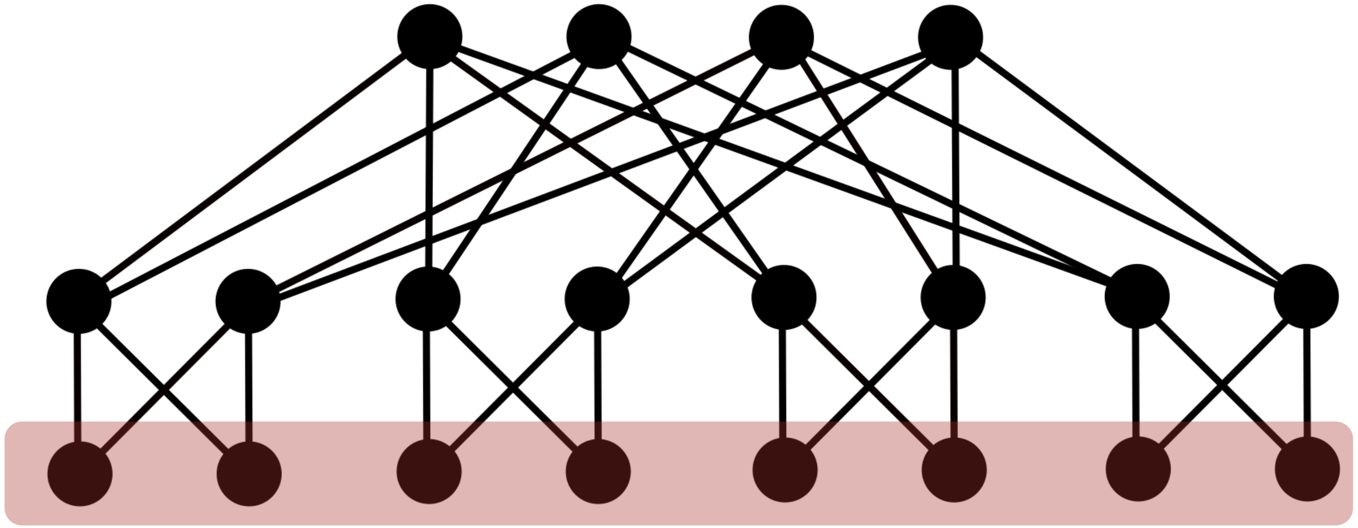

3-level Fat tree

Diameter = 4

Only edge (leaf) routers attach to endpoints

All routers attach to endpoints

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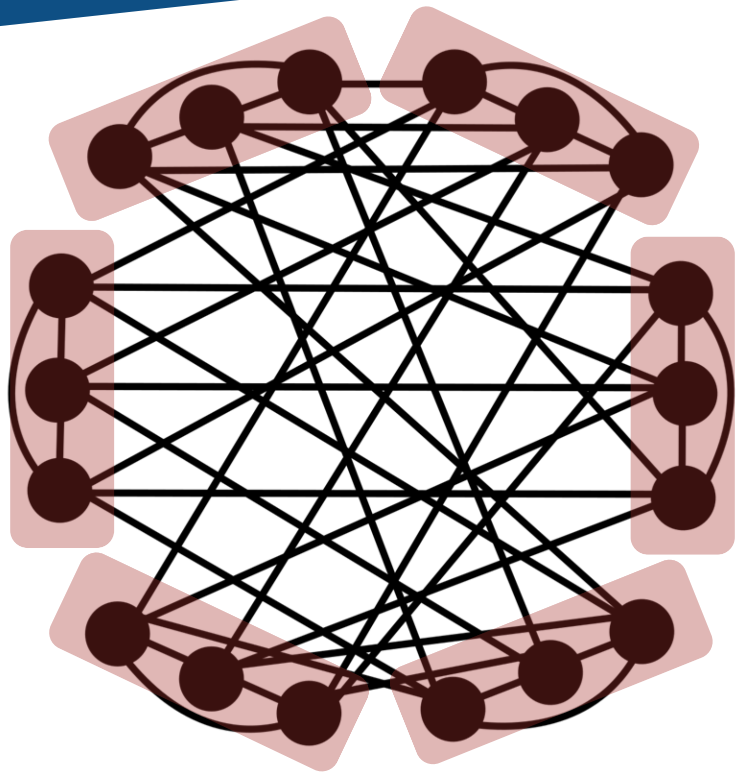

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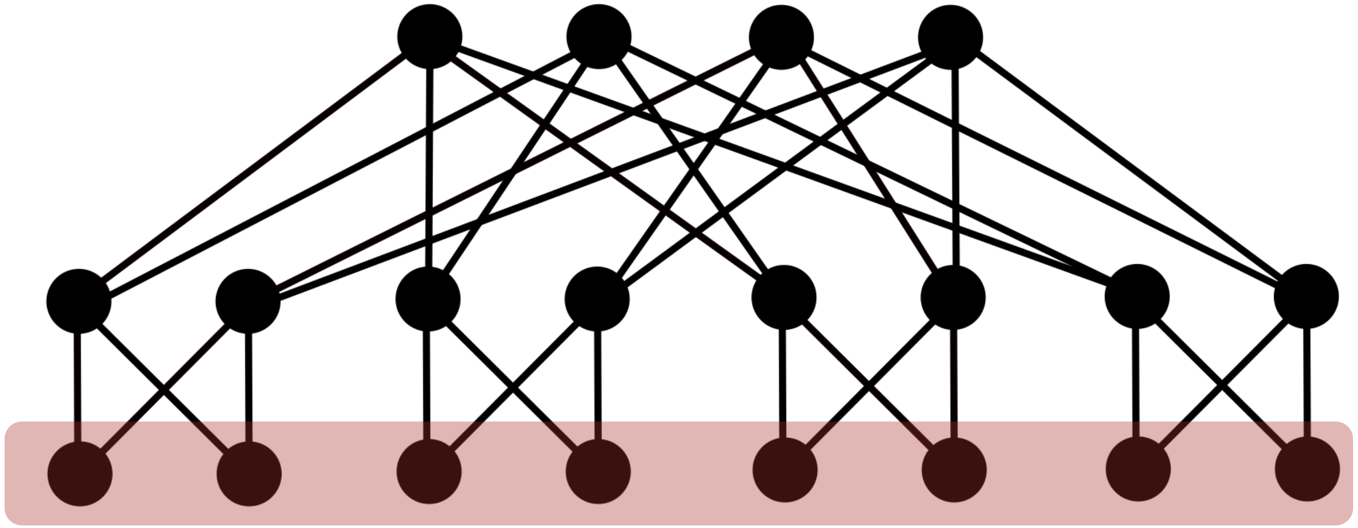

3-level Fat tree

Diameter = 4

Only edge (leaf) routers attach to endpoints

Lower concentration

All routers attach to endpoints

Higher concentration

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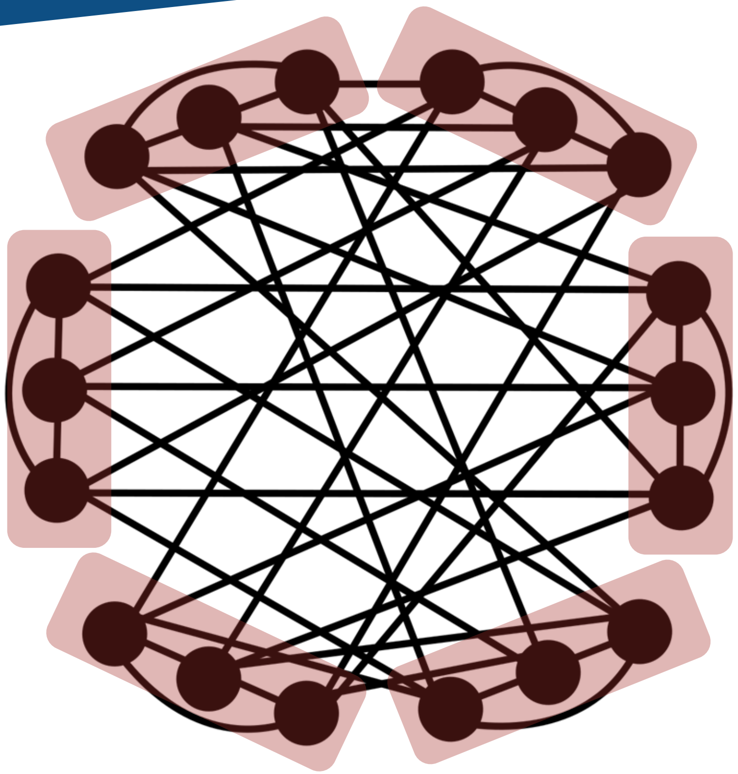

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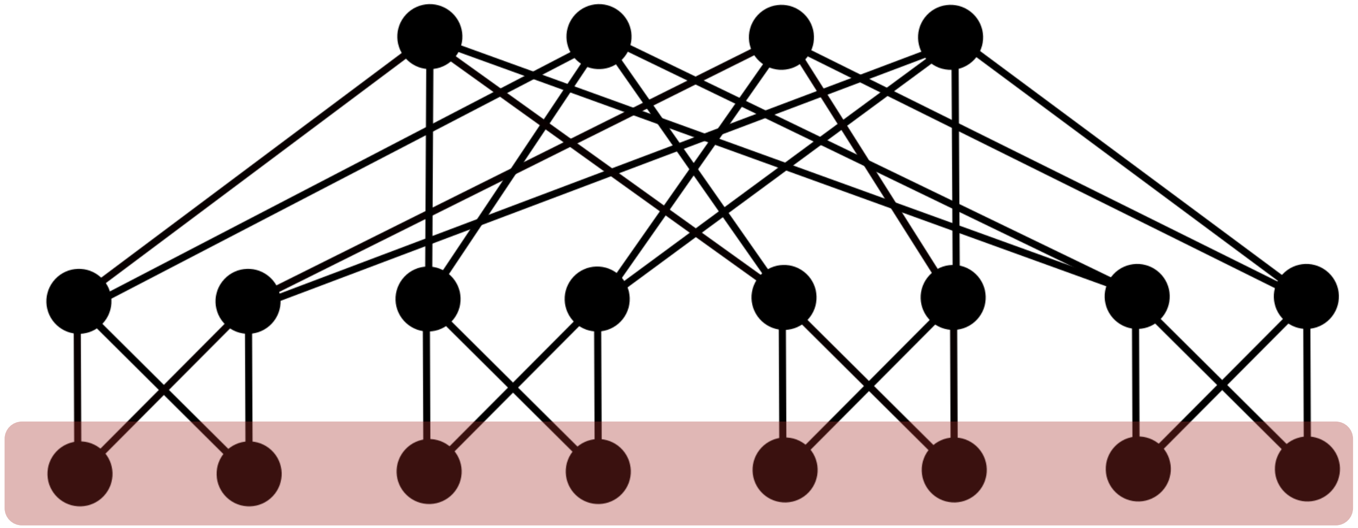

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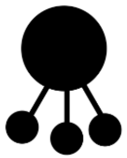
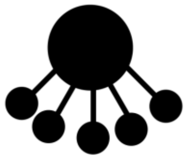




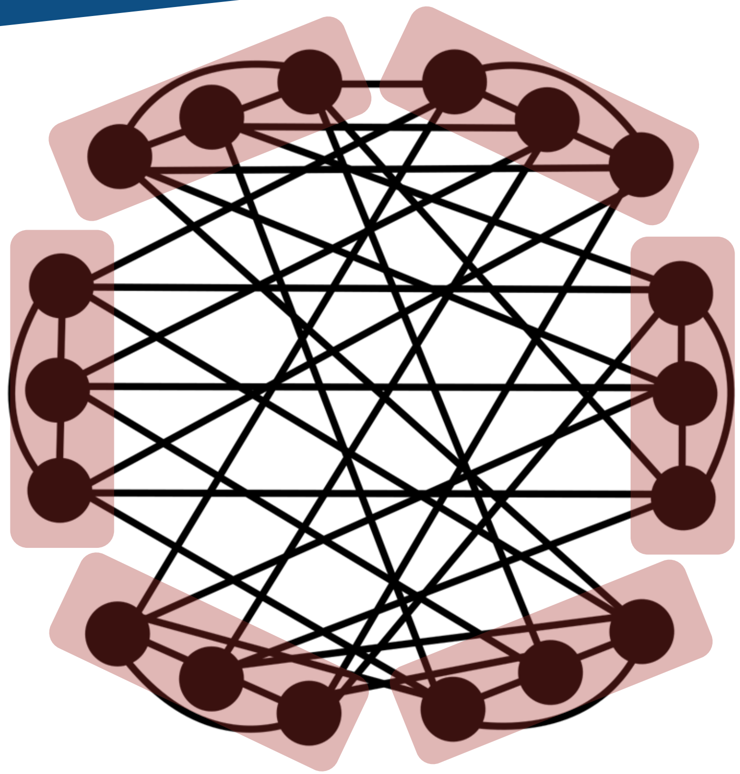
Higher concentration

All routers attach to endpoints

> ≈50% fewer routers

> ≈30% fewer cables

Example Slim Fly (based on the Hoffman-Singleton Graph [1])



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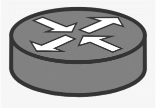
MULTIPATH ROUTING: MOTIVATION



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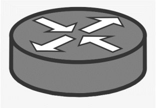

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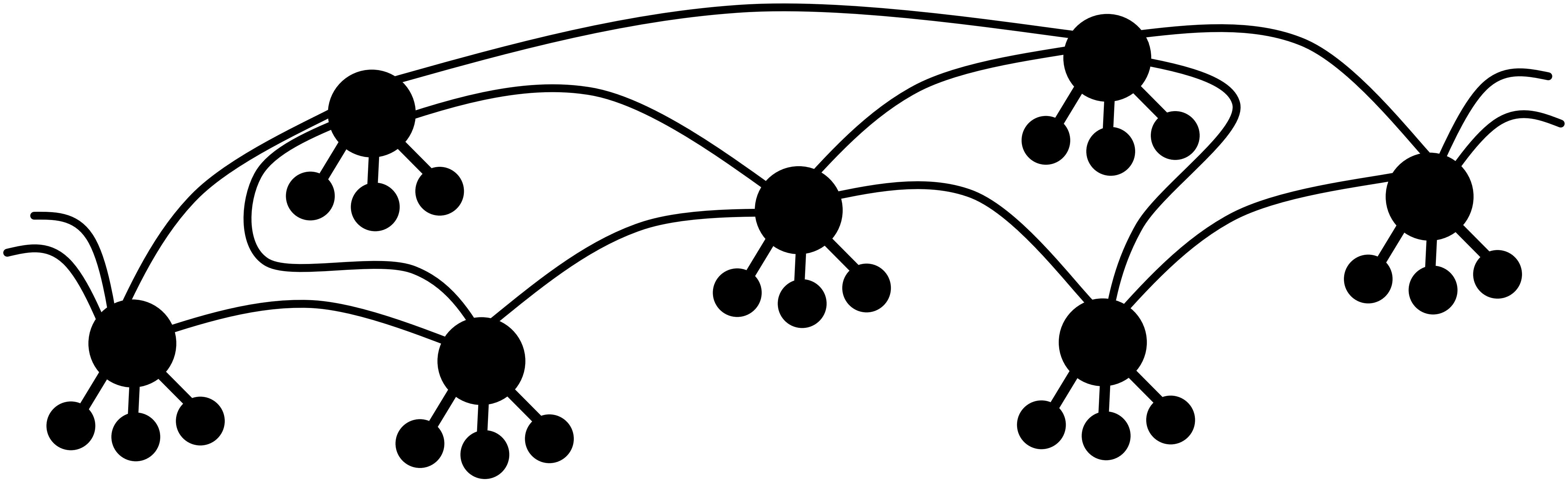

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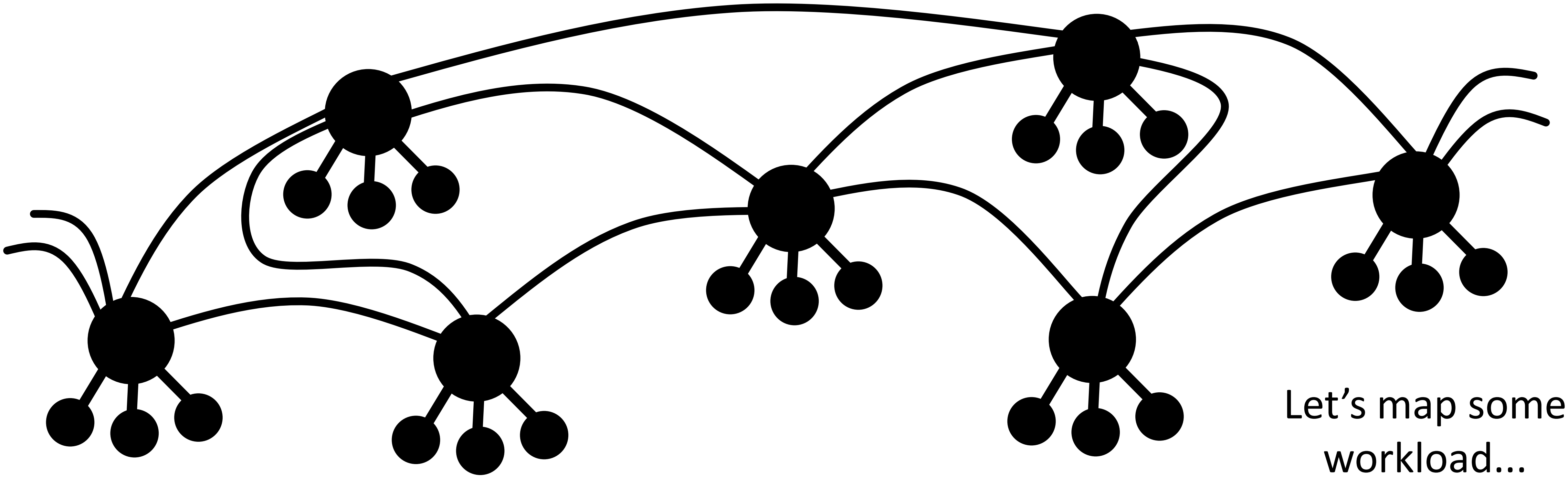

Let’s map some workload...

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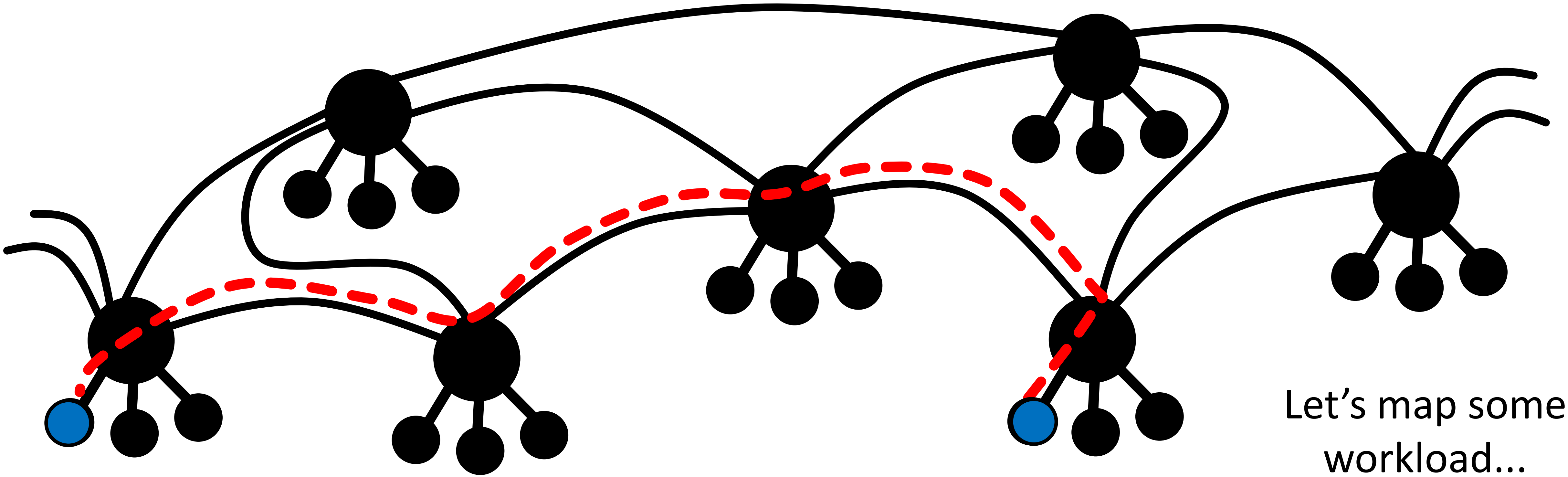

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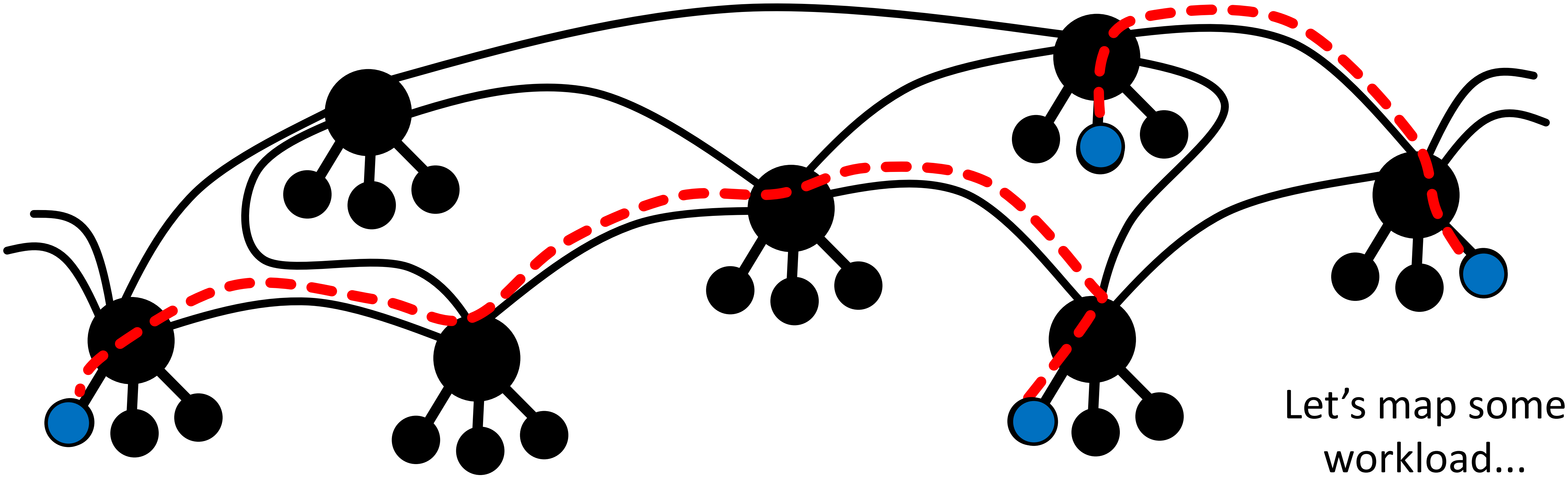

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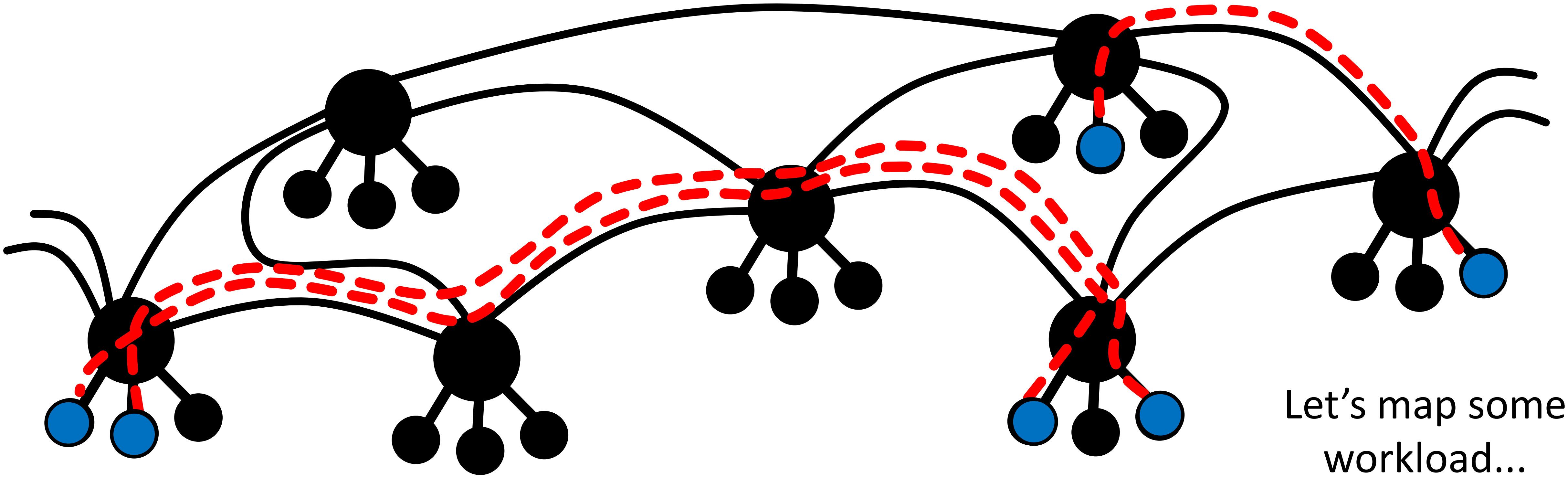

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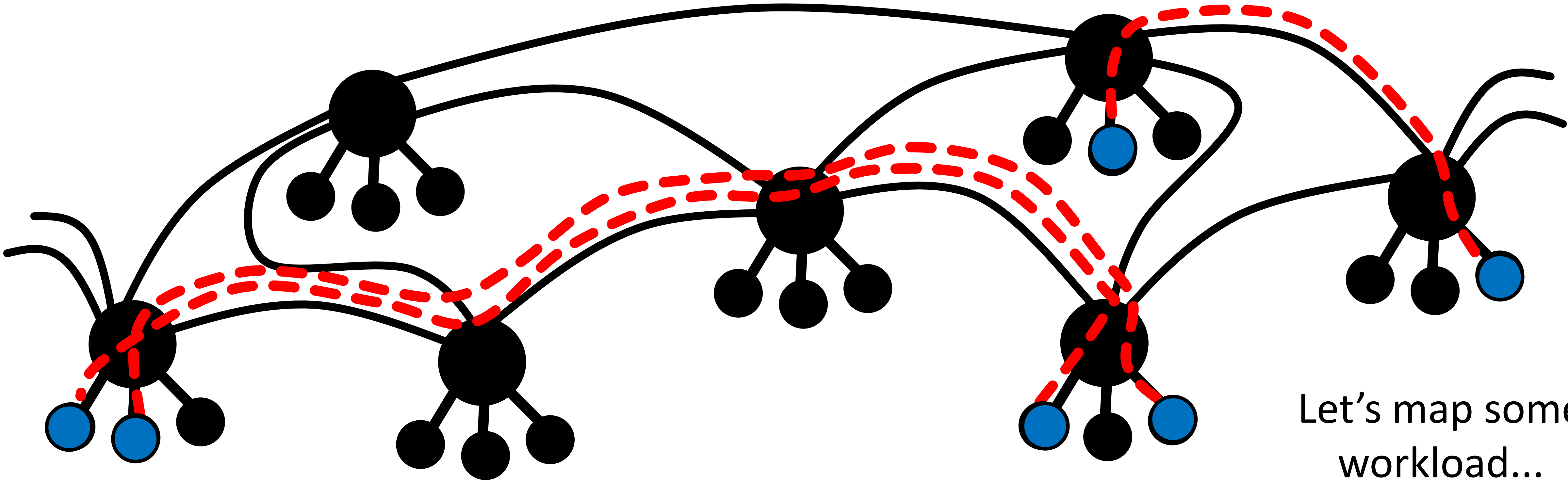
Flows collide!



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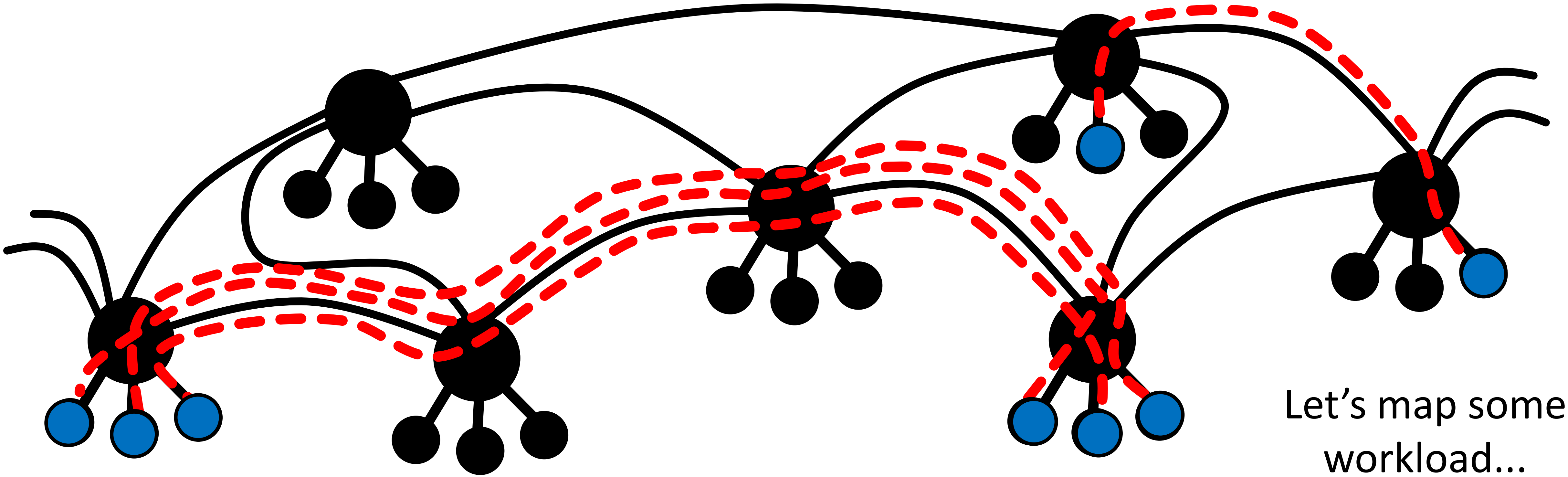

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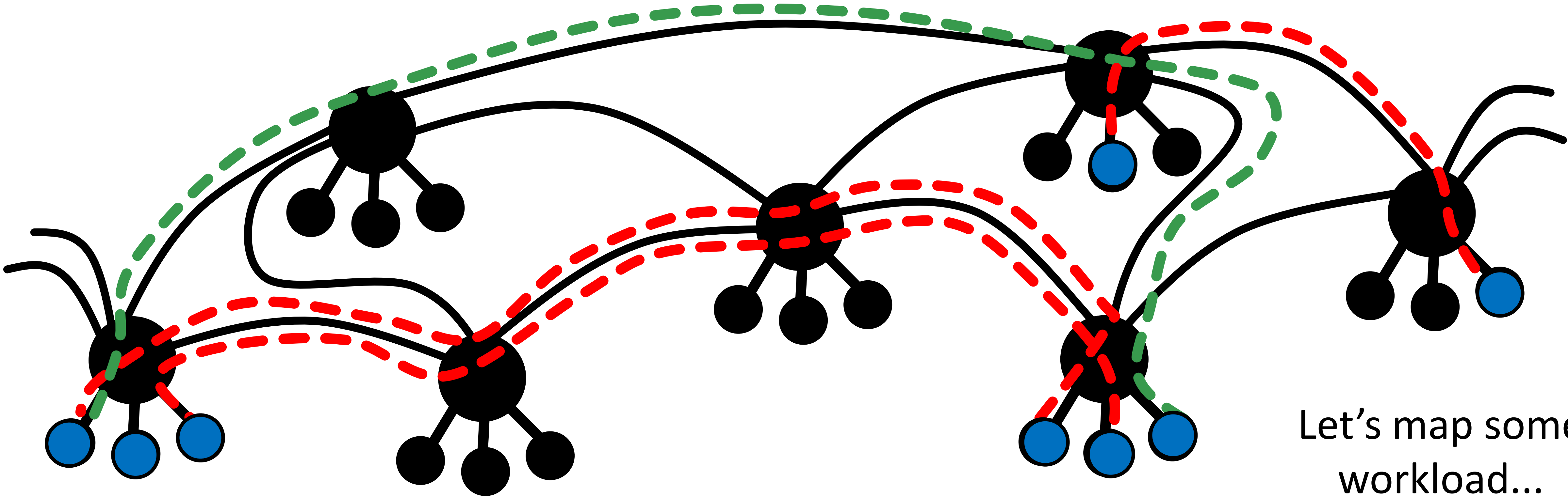

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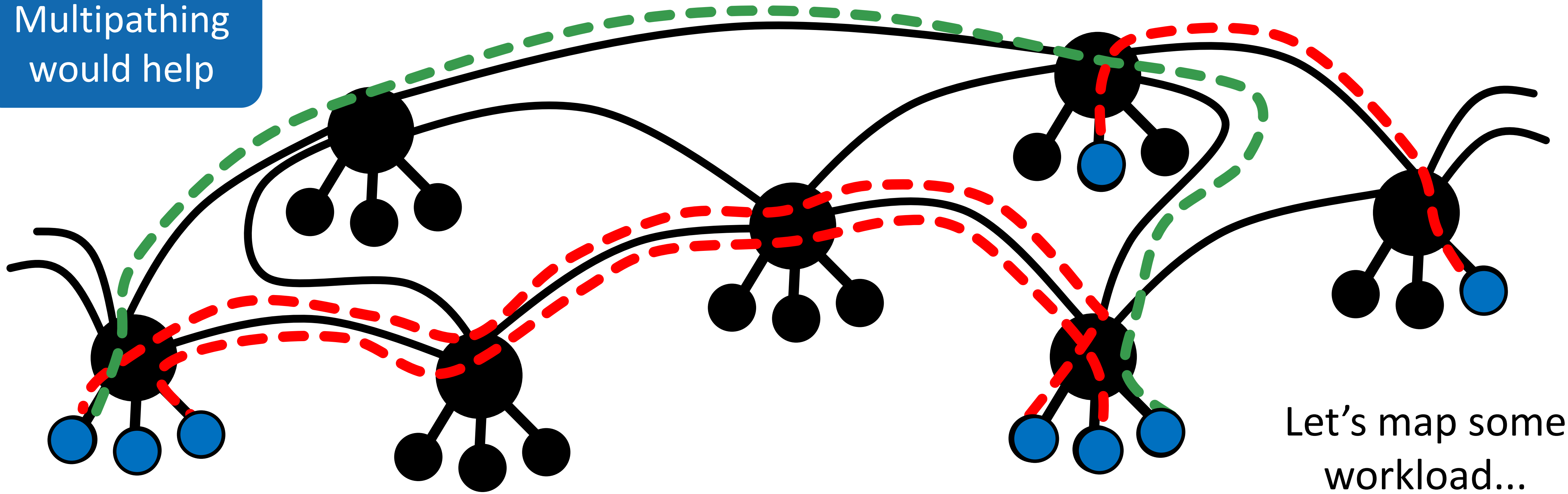
MULTIPATH ROUTING: MOTIVATION

What are the problems that we want to tackle with multipathing?

Multipathing would help

Flows collide!



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Multipath Routing: Motivation

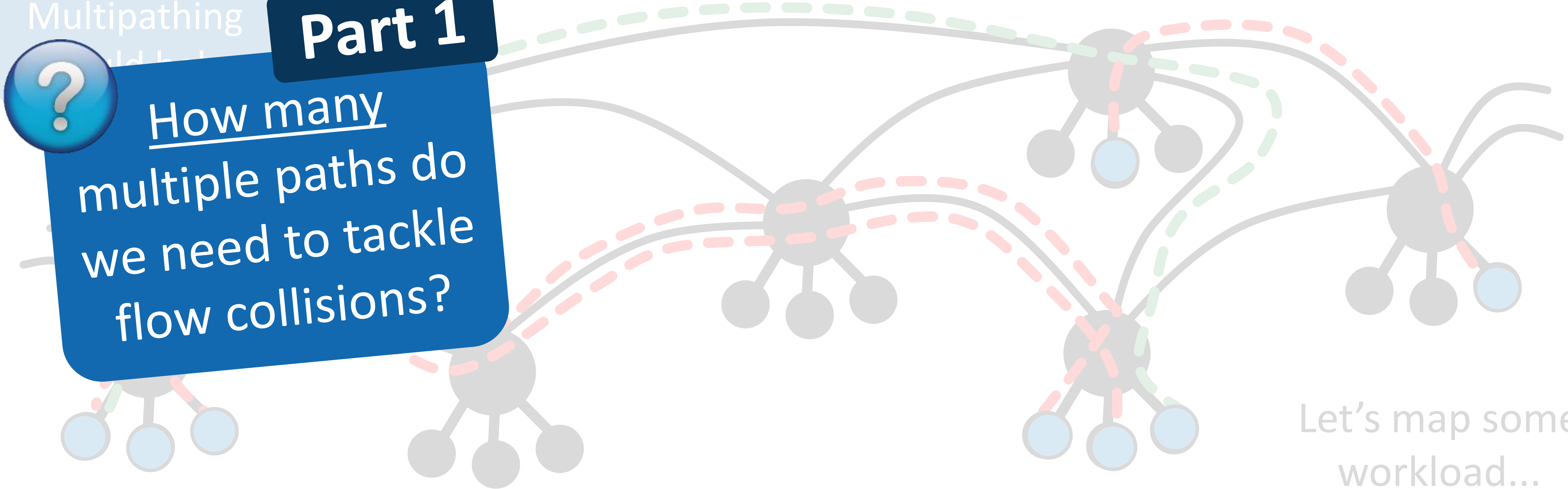
What are the problems that we want to tackle with multipathing?

Multipathing

Part 1

How many multiple paths do we need to tackle flow collisions?

Flows collide!



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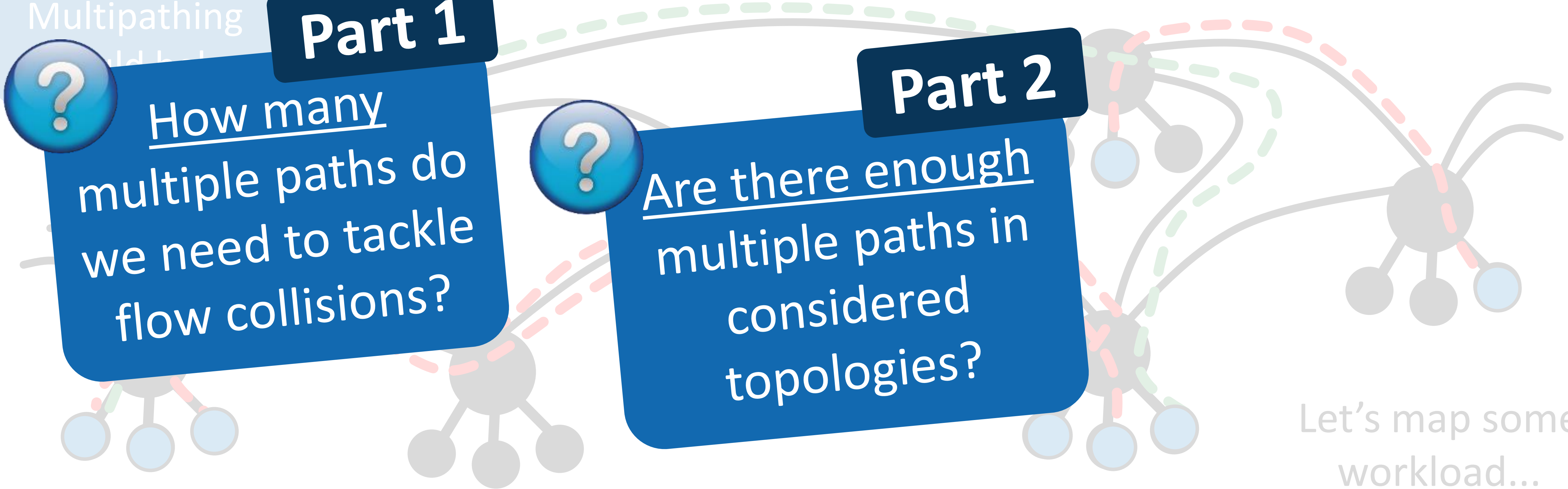


Part 1

How many multiple paths do we need to tackle flow collisions?

Part 2

Are there enough multiple paths in considered topologies?

Let's map some workload...

MULTIPATH ROUTING: MOTIVATION

What are the problems that we want to tackle with multipathing?

Flows collide!

Multipathing

Part 1

How many multiple paths do we need to tackle flow collisions?

Part 2

Are there enough multiple paths in considered topologies?

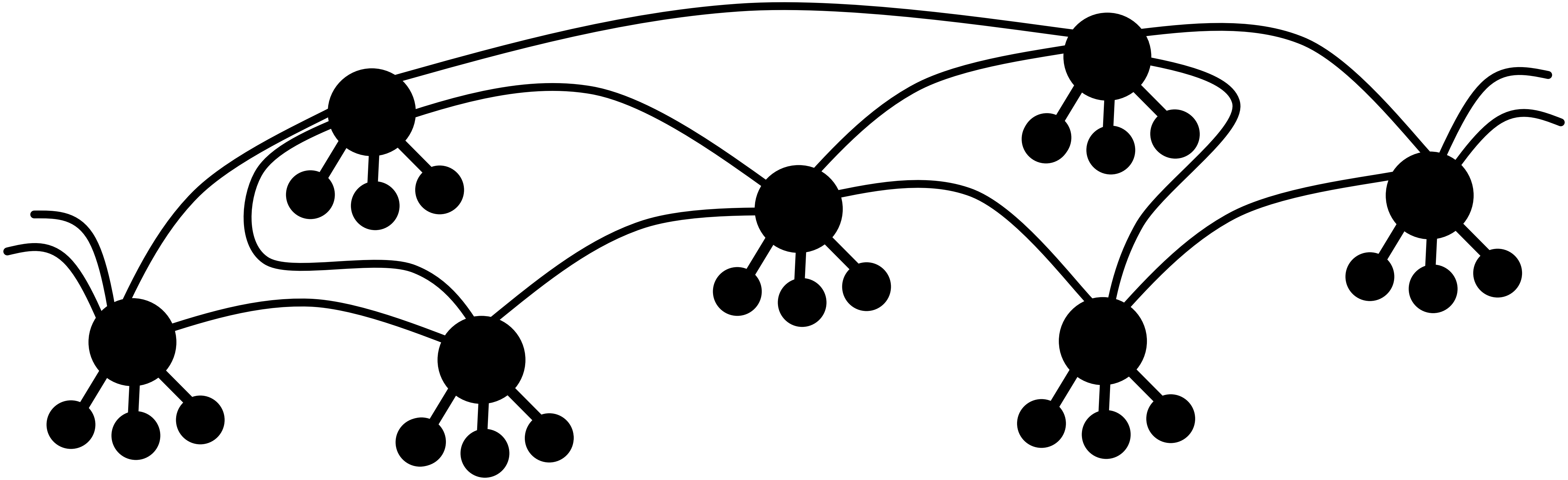
Part 3

How to use such multiple paths in considered topologies?

workload...

How many multiple paths do we need to tackle flow collisions?

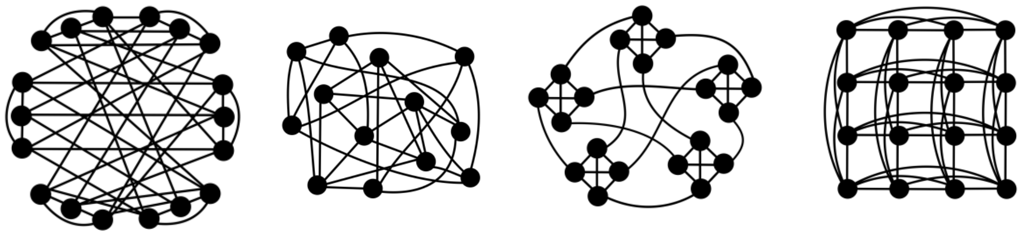
Part 1

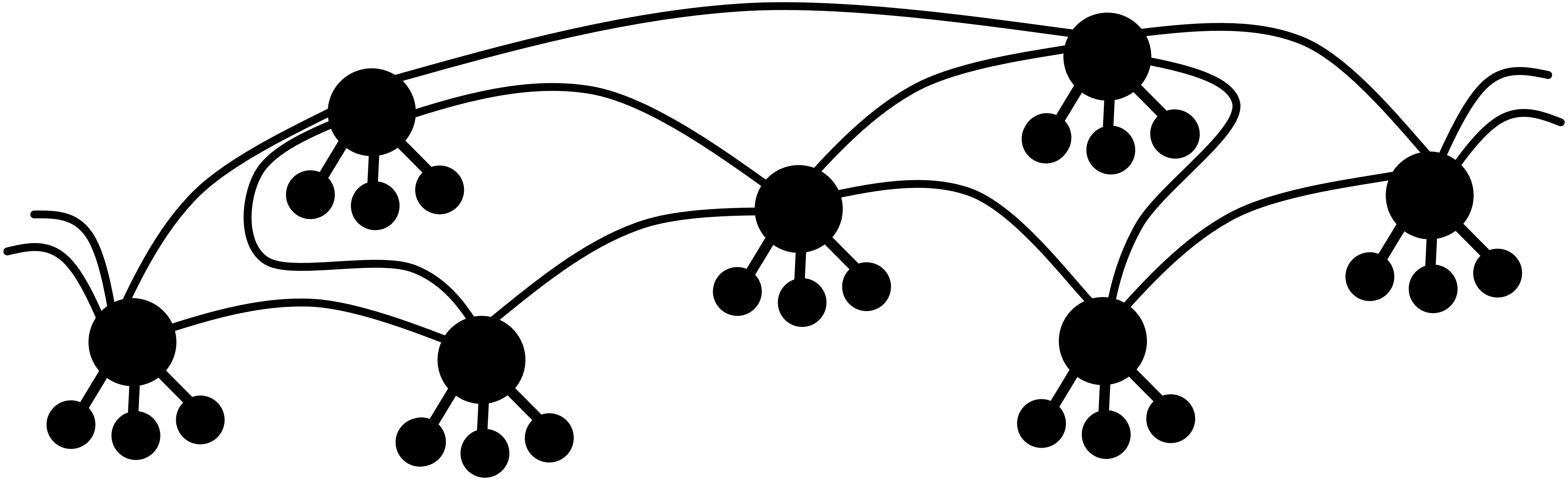


How many multiple paths do we need to tackle flow collisions?

Part 1

...For different topologies





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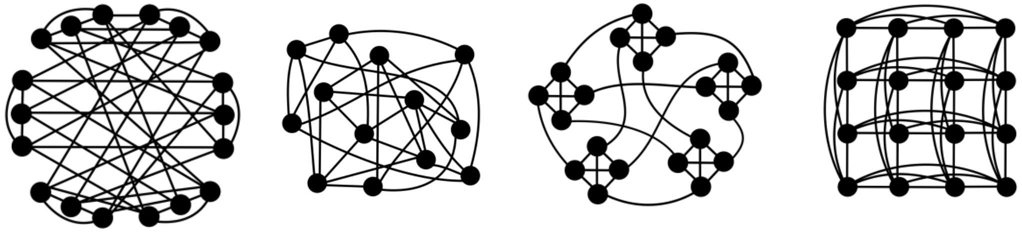


...For different workloads

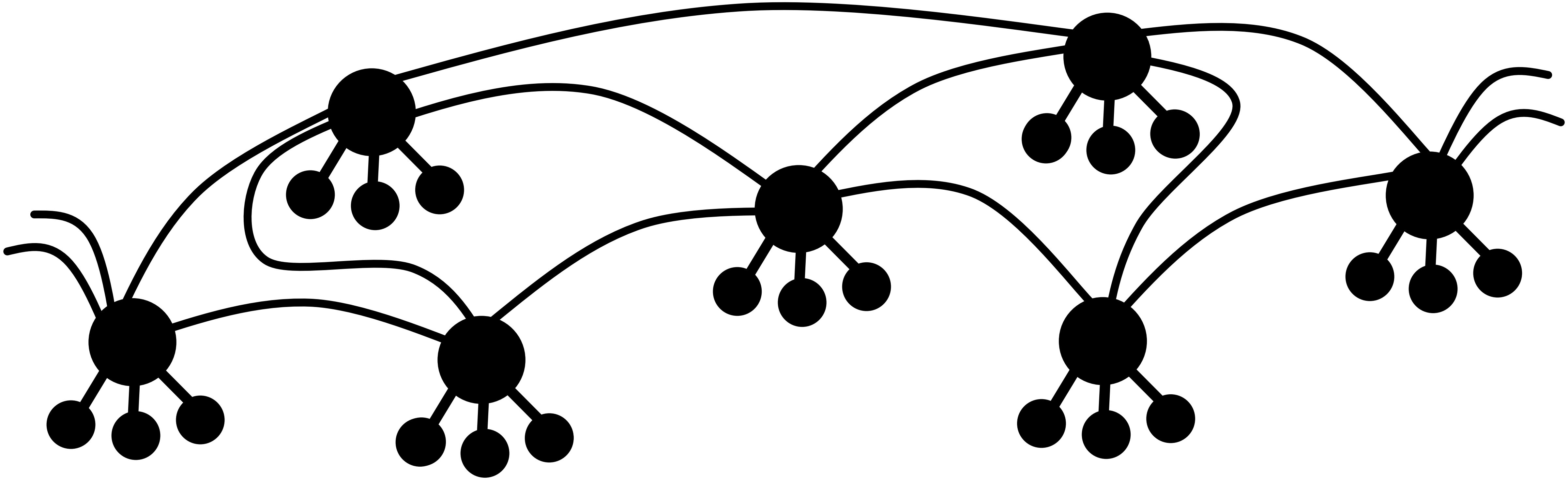
Random uniform

Off-diagonal

Stencil

Shuffle

...



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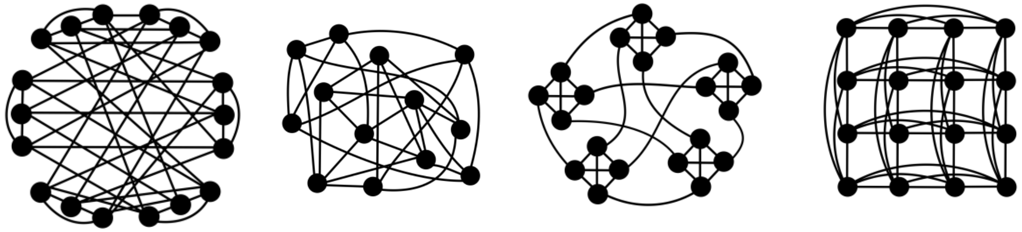

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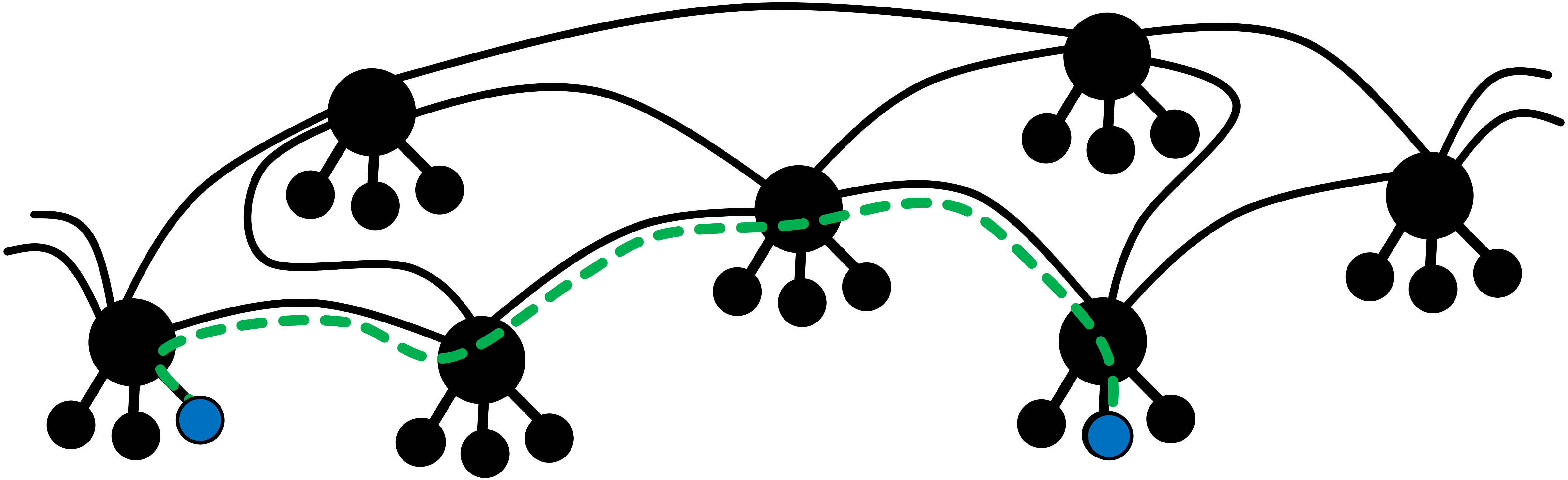
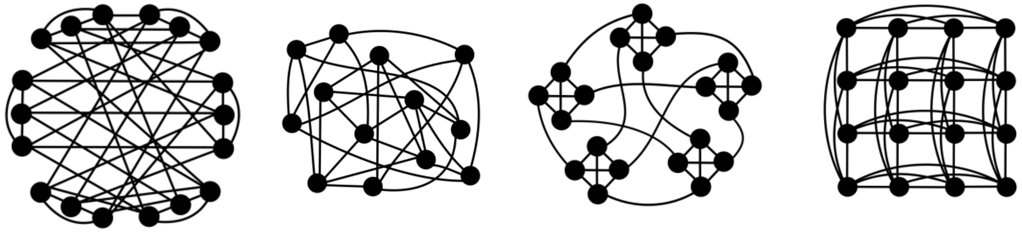


HOW MANY MULTIPLE PATHS DO WE NEED TO TACKLE FLOW COLLISIONS?

Part 1

...For different topologies



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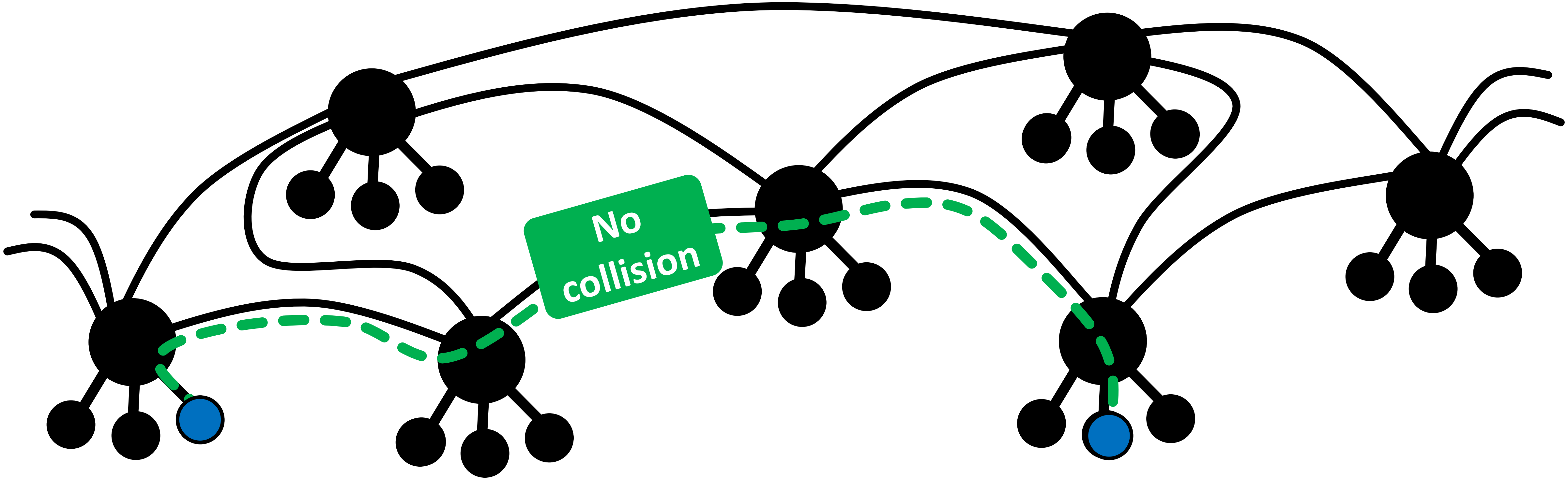

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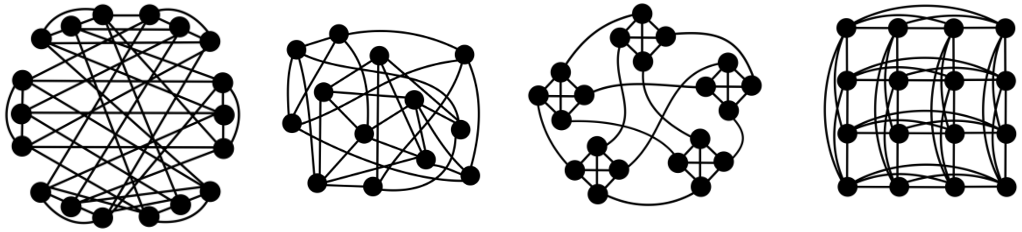

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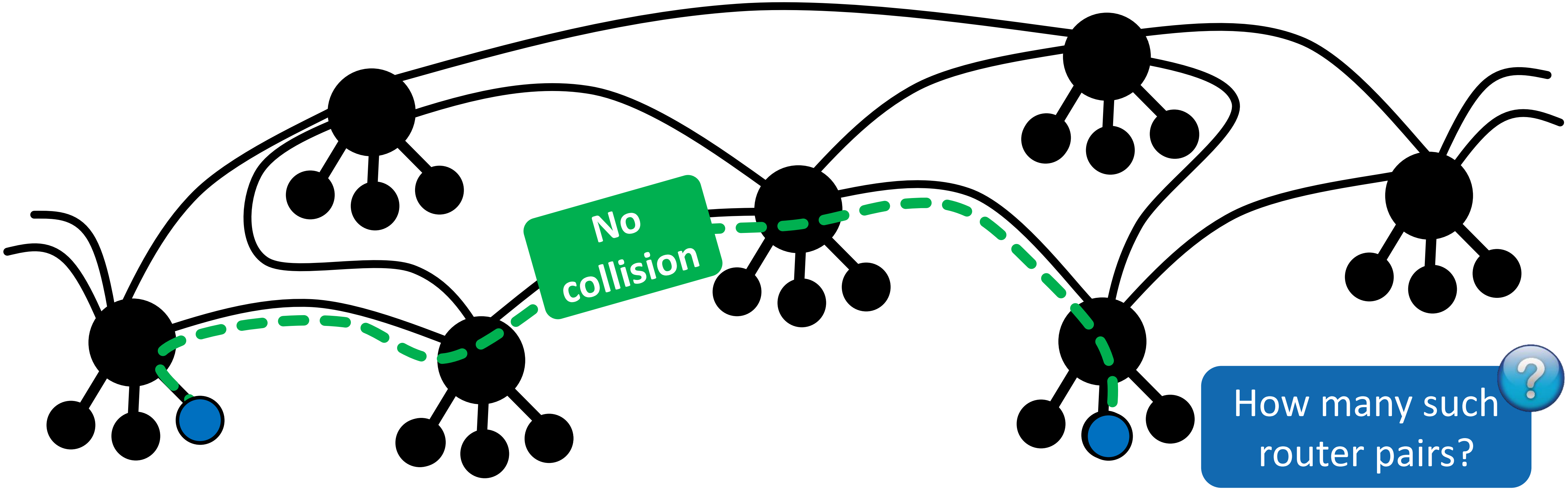

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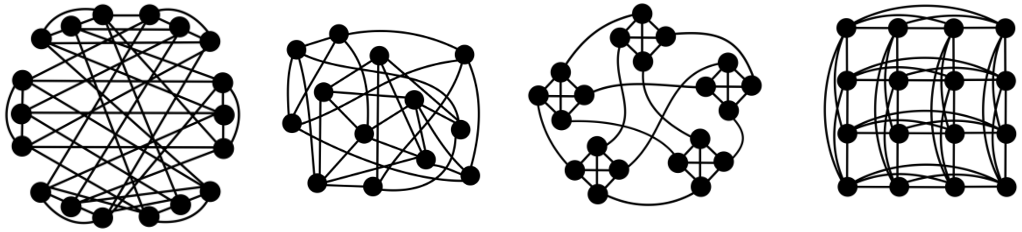

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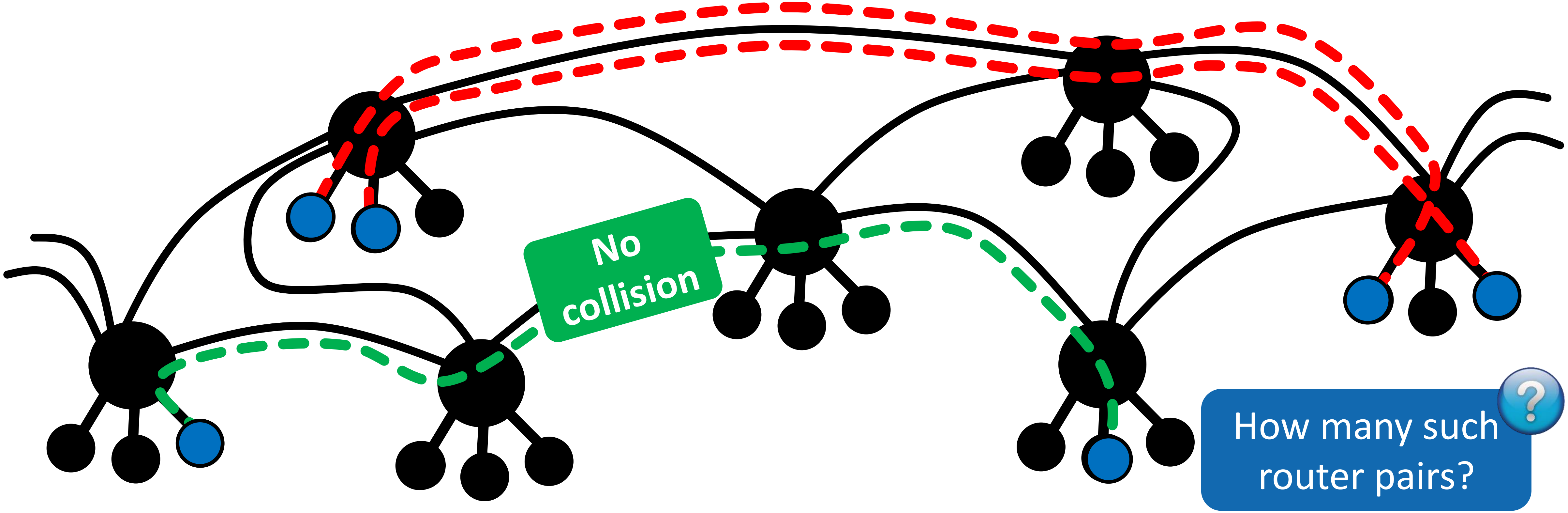

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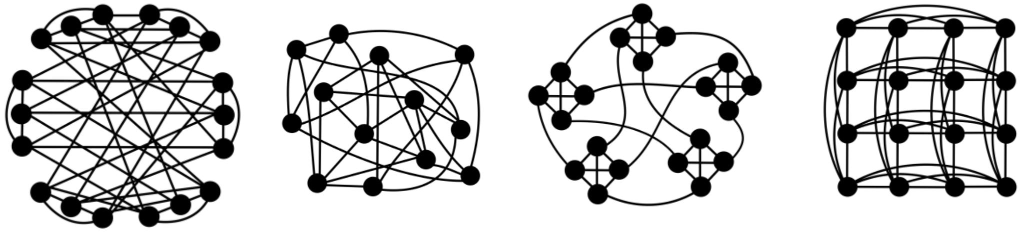

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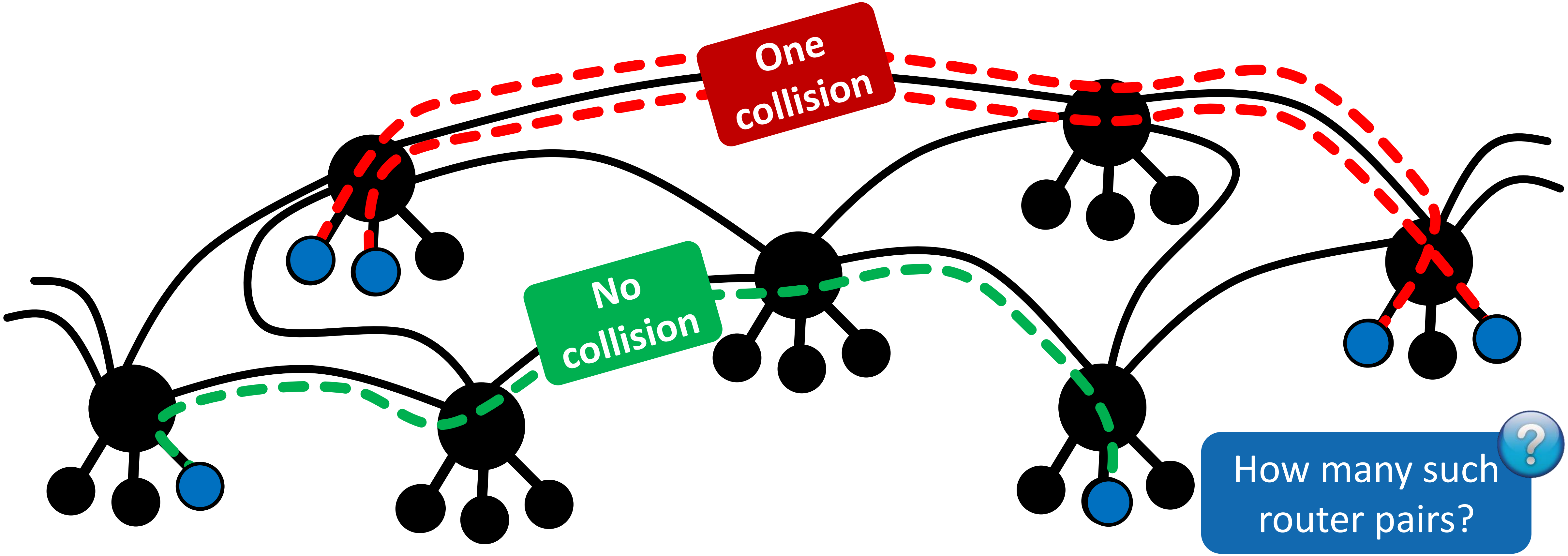
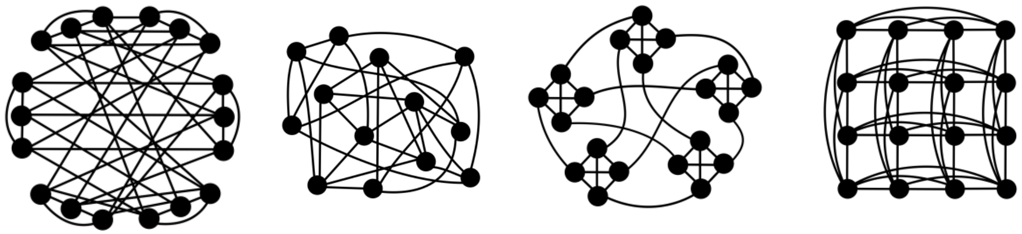


How many such router pairs?

How many multiple paths do we need to tackle flow collisions?

Part 1

...For different topologies



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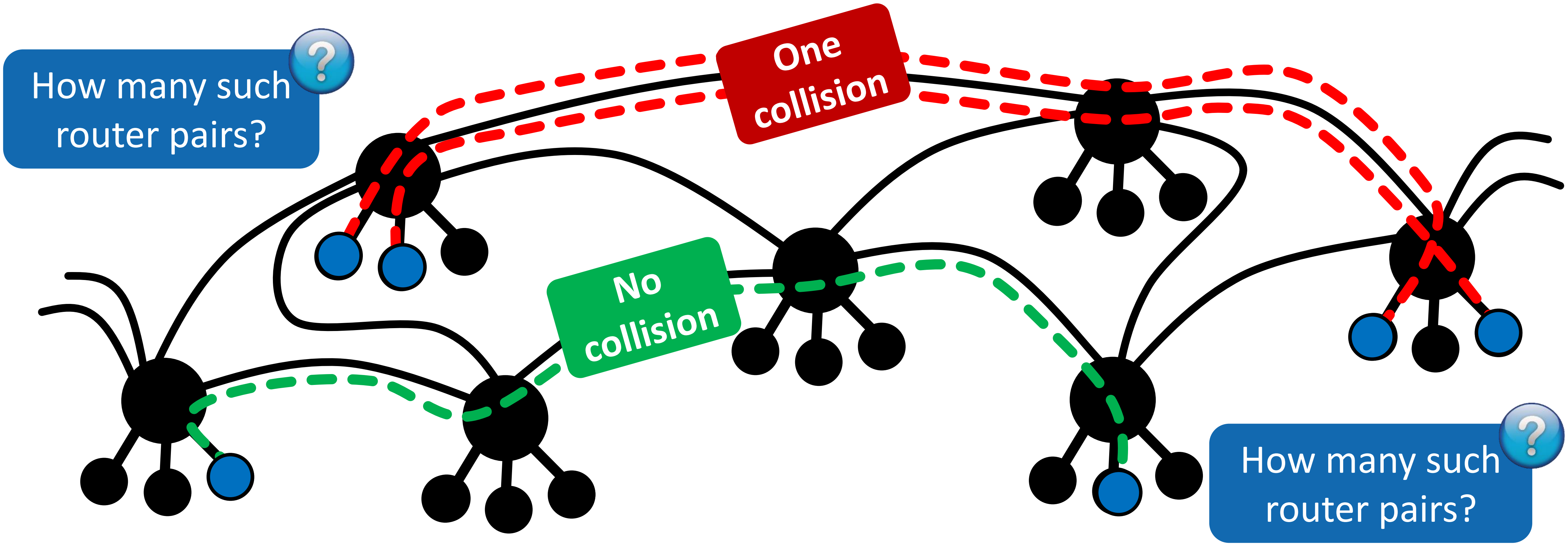

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Part 1

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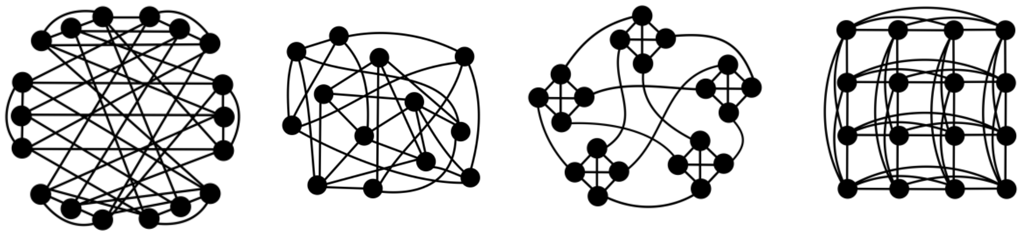

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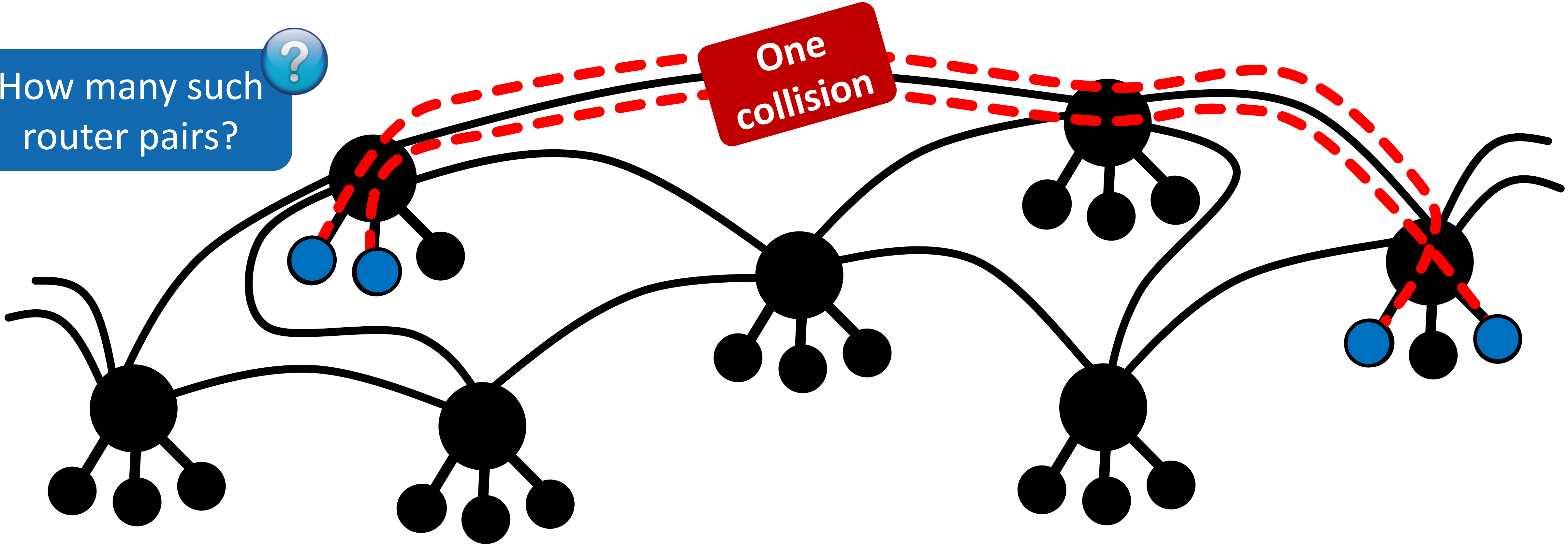

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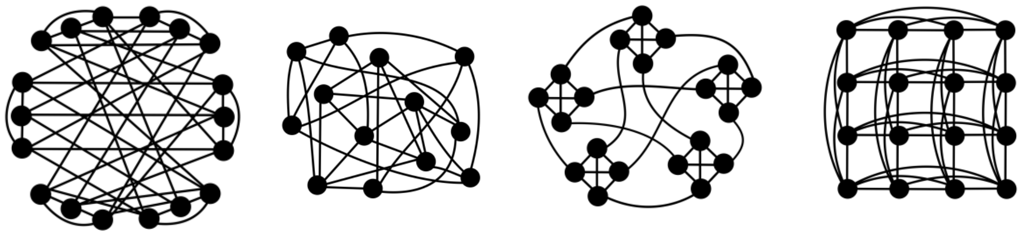

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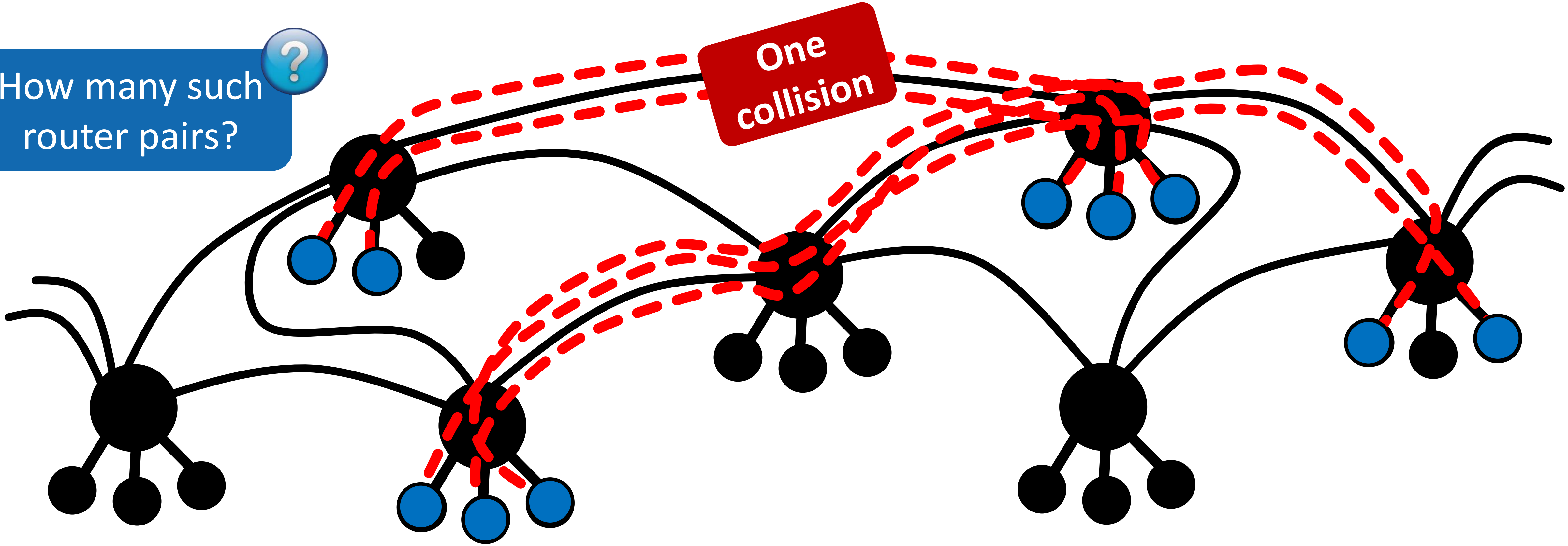

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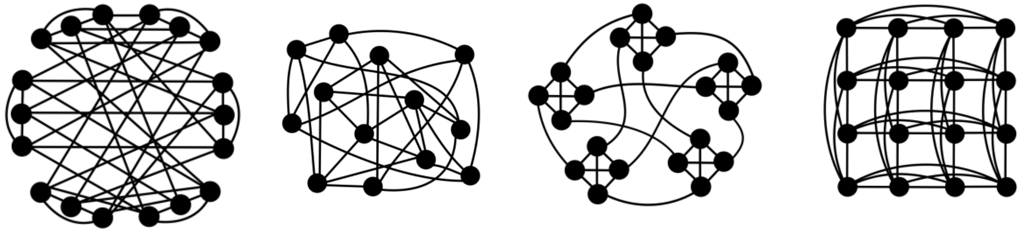

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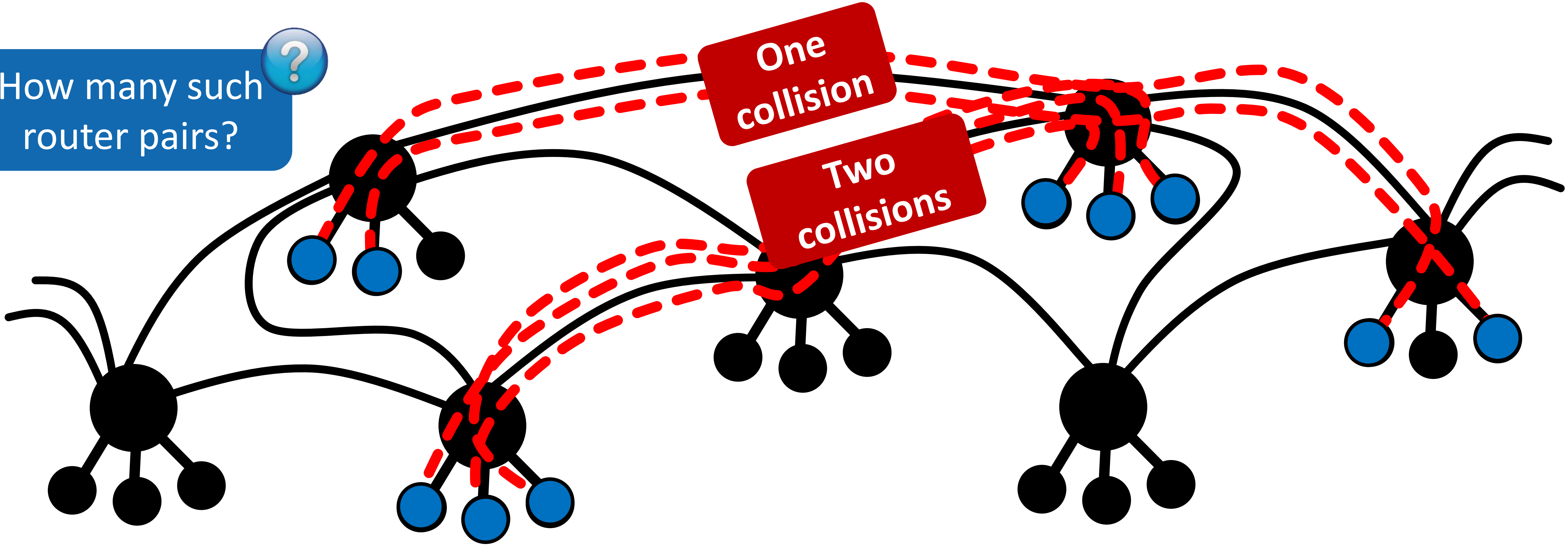

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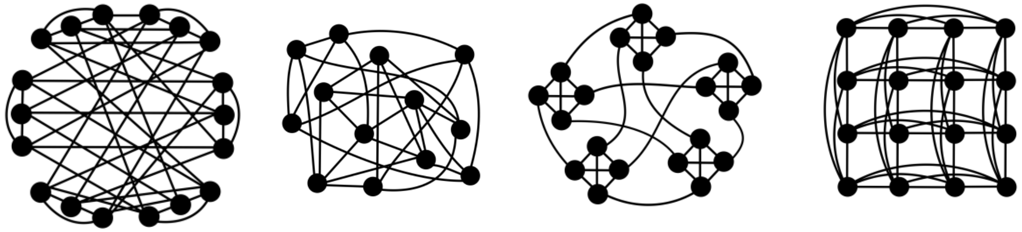

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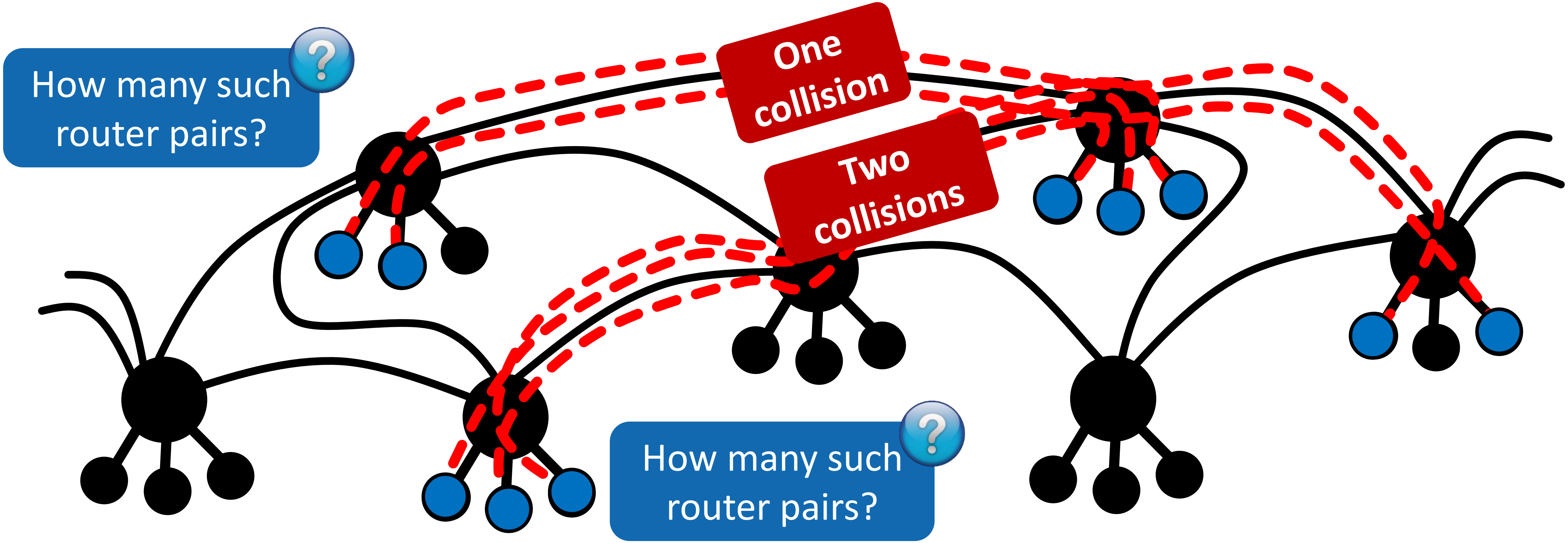

PATH DIVERSITY ANALYSIS

Do we have enough such shortest paths?

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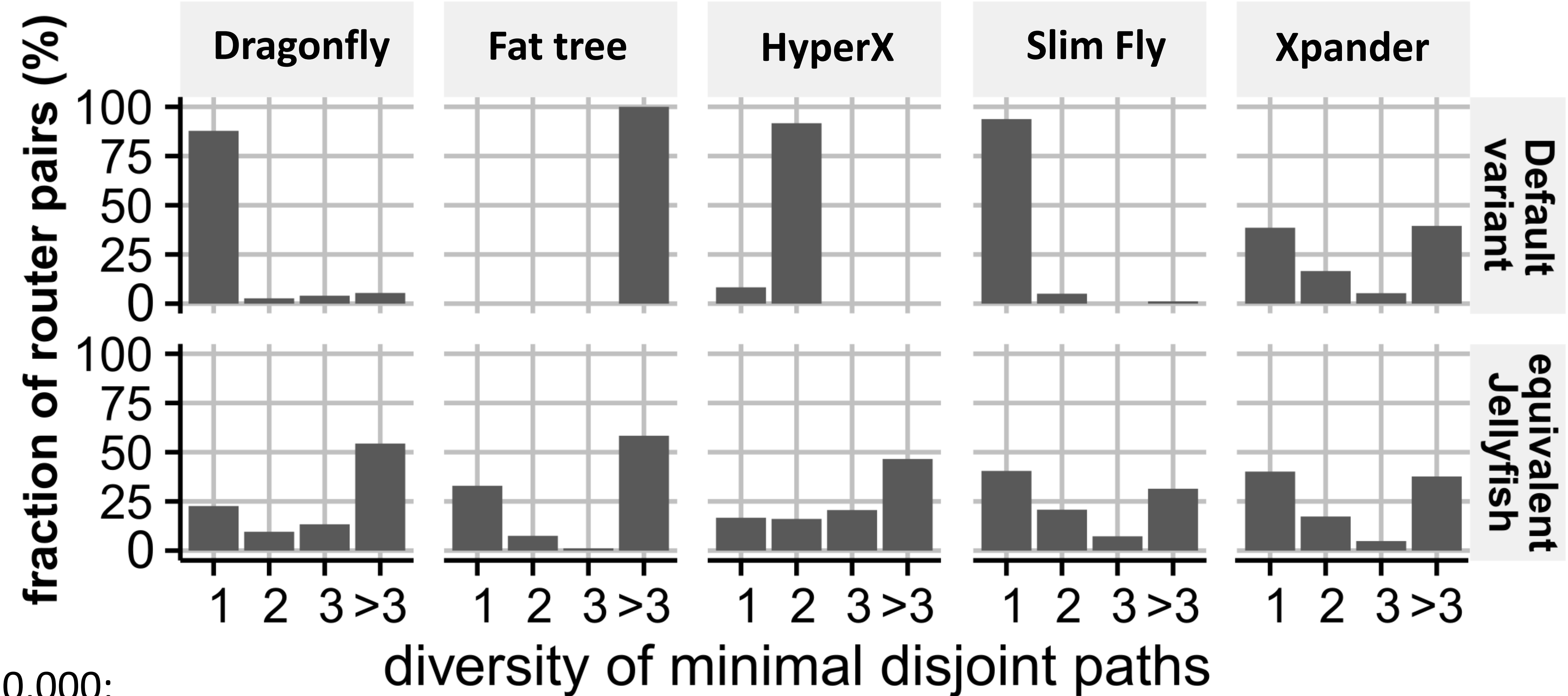

N ≈ 10,000;
comparable cost

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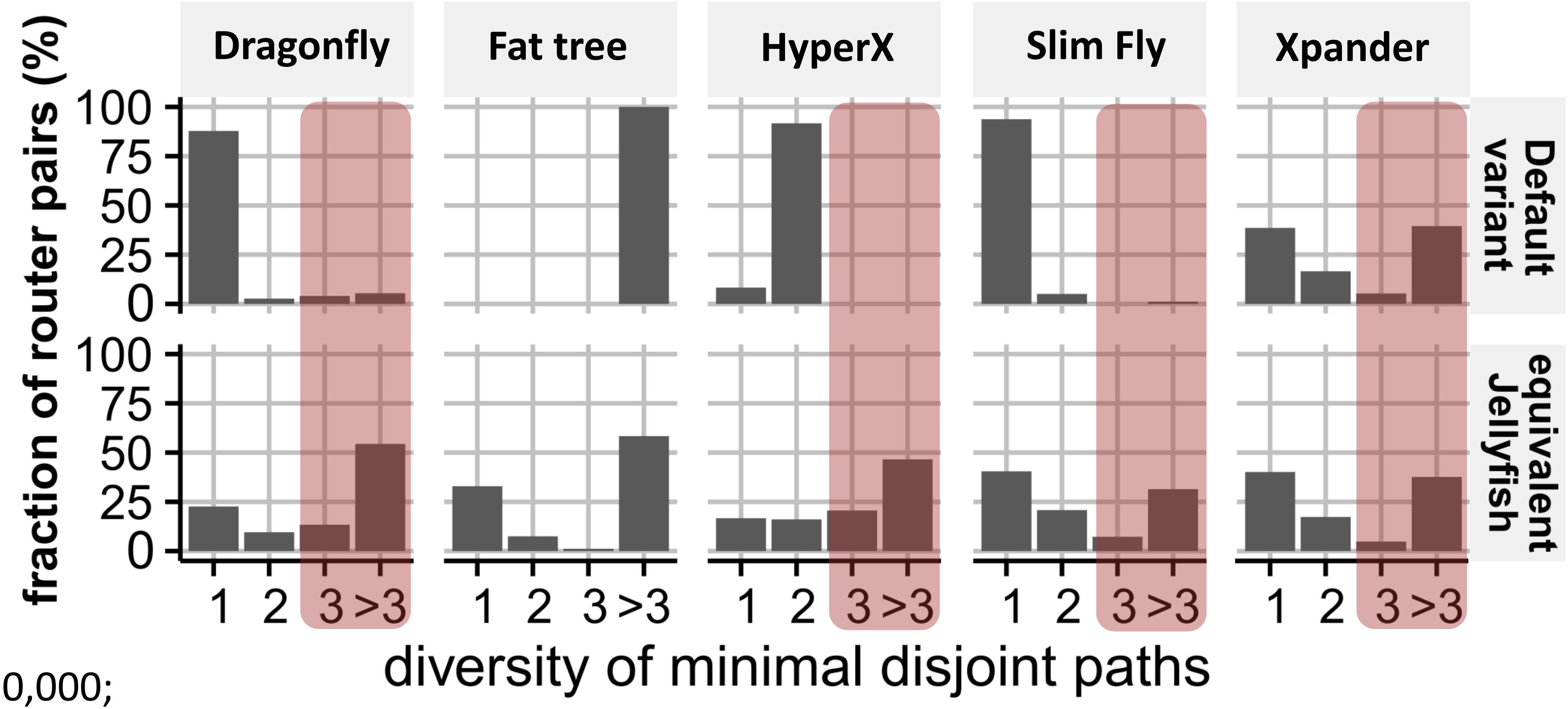

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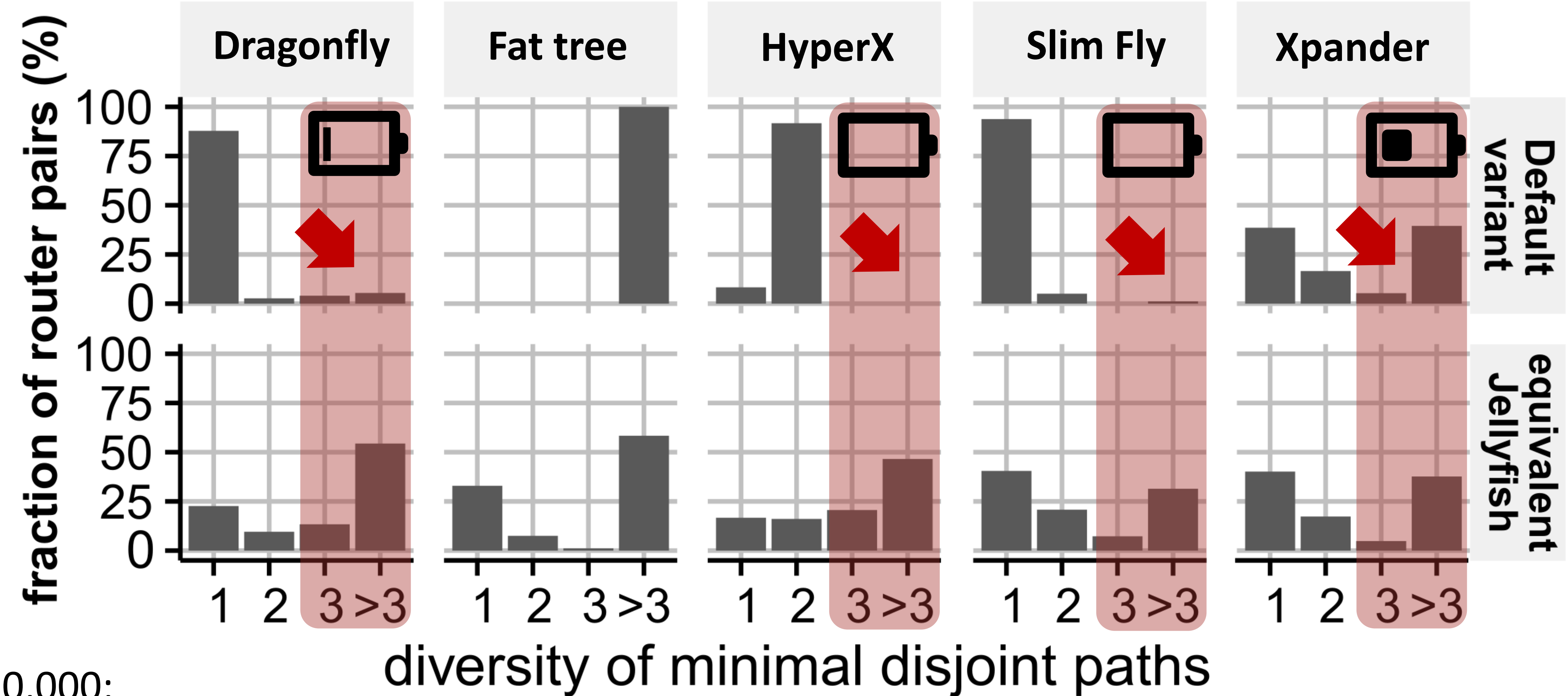

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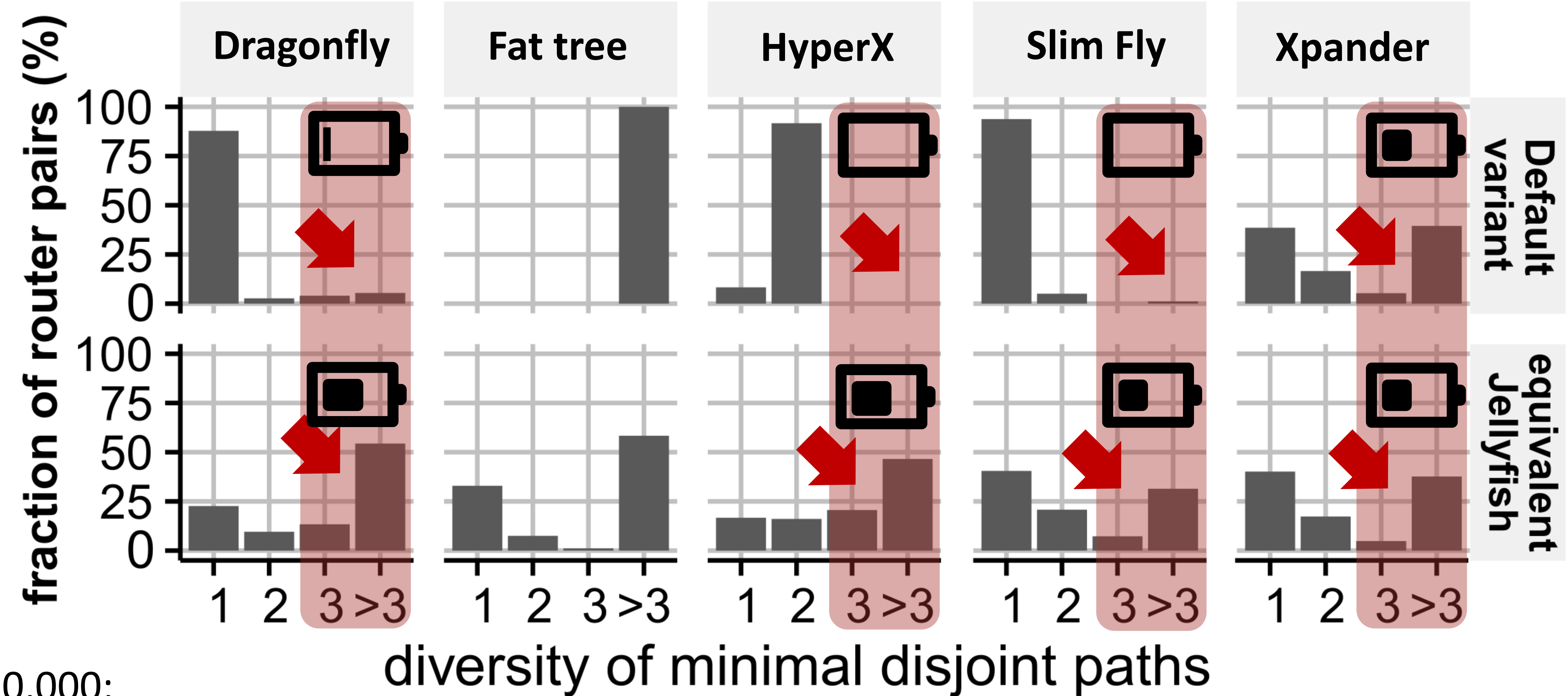

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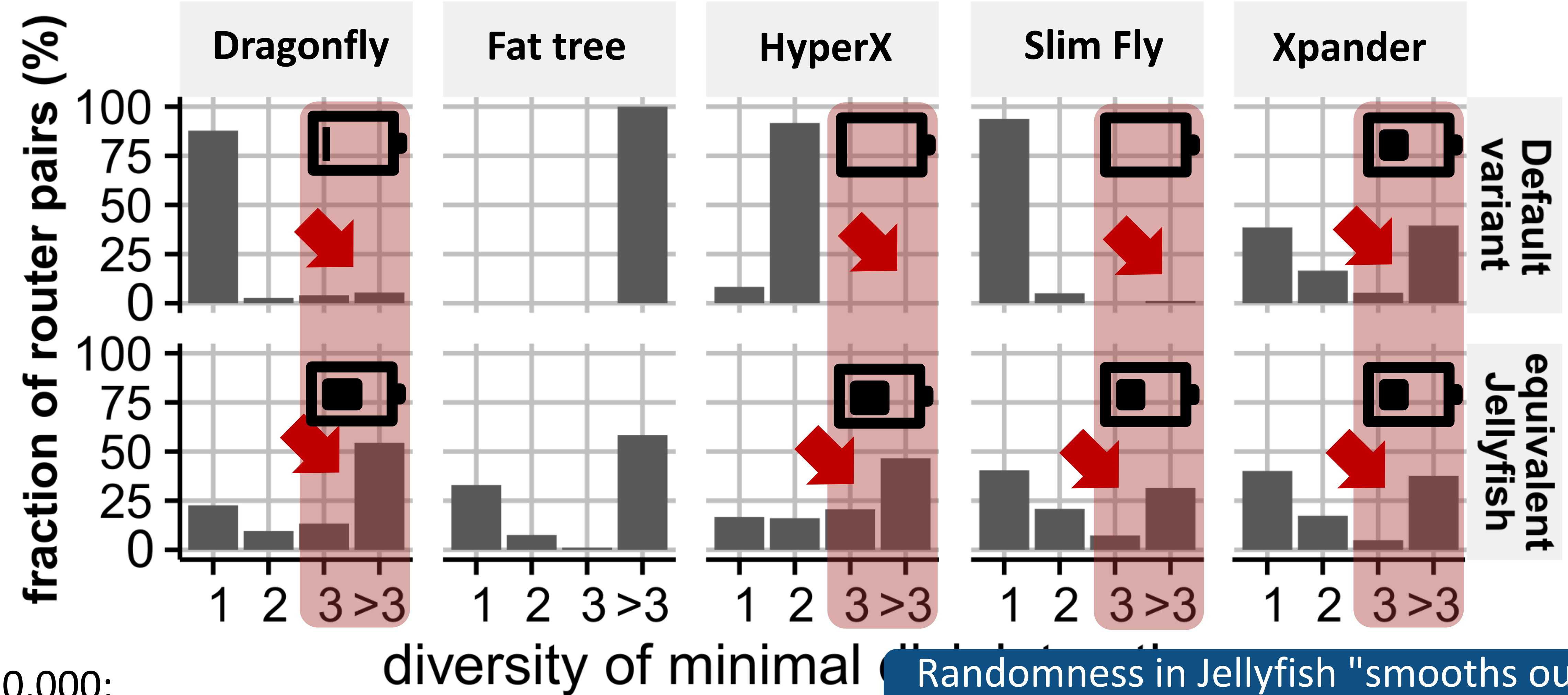
Do we have enough such shortest paths?



N ≈ 10,000; comparable cost

Randomness in Jellyfish "smooths out" distributions of minimal path diversities

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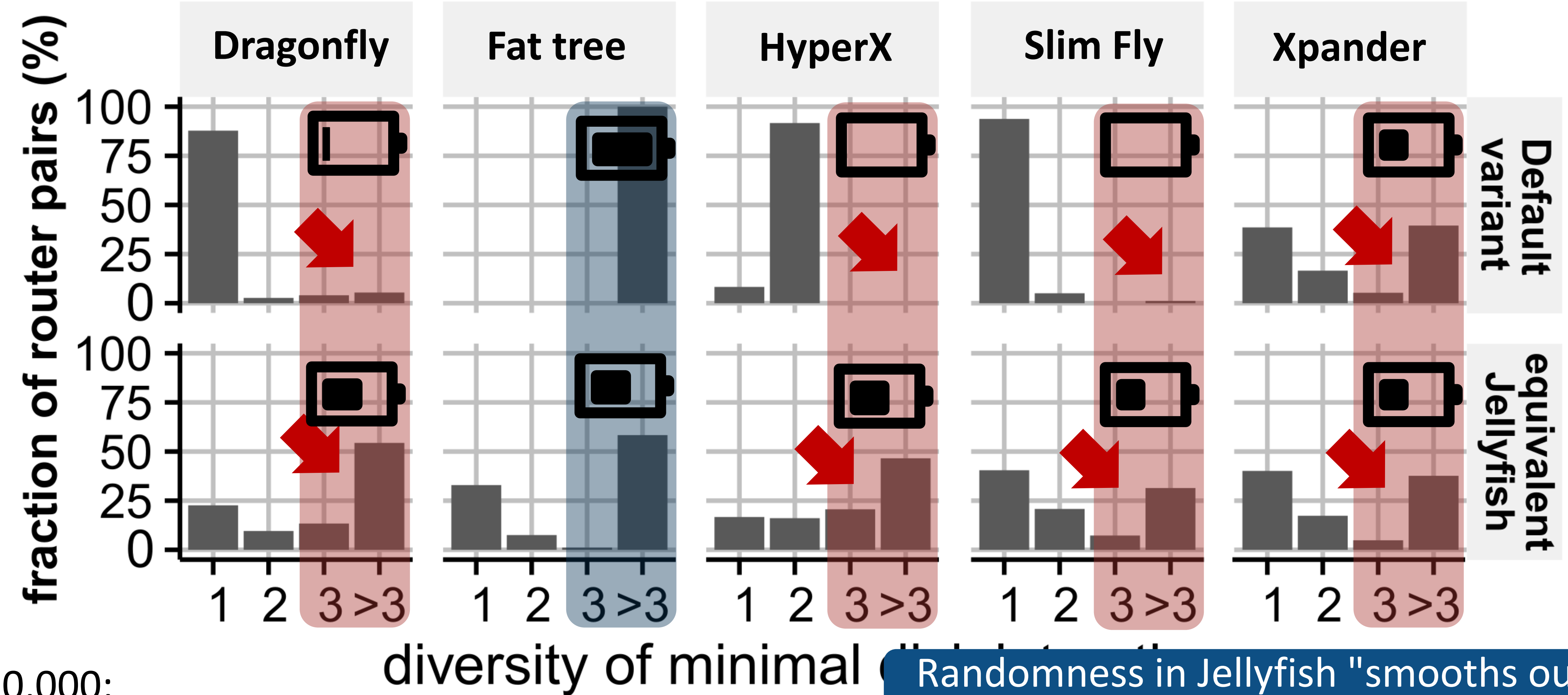

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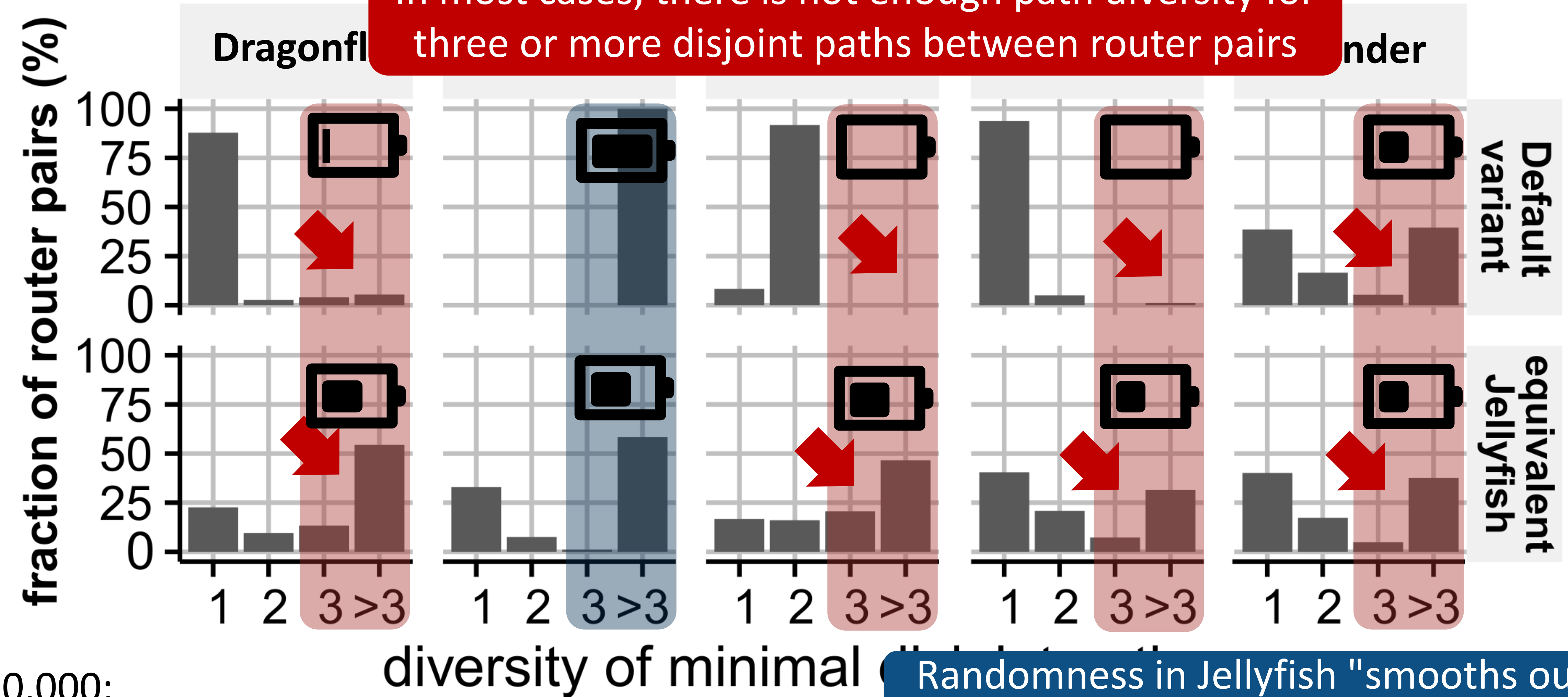
PATH DIVERSITY ANALYSIS

Do we have enough such shortest paths?

In most cases, there is not enough path diversity for three or more disjoint paths between router pairs



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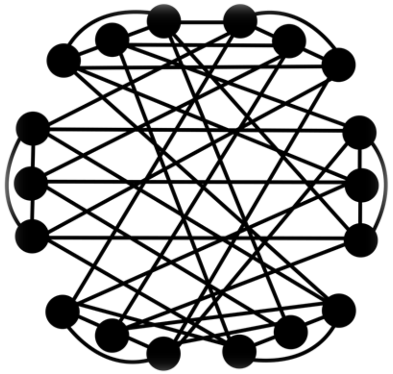
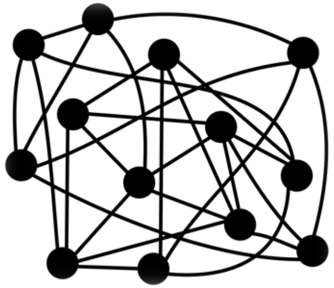
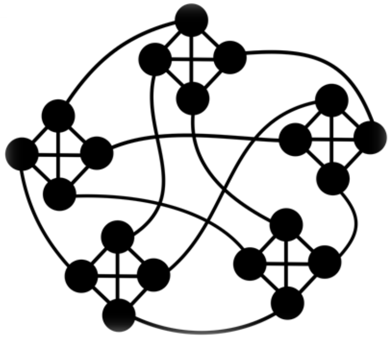
Low-Diameter Network Topologies

Can we use multipathing?
i.e., are the multiple
paths between routers?



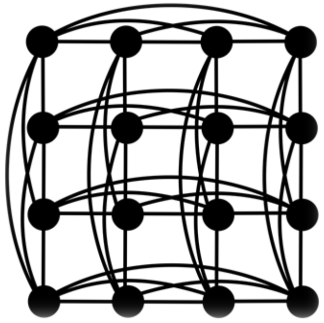




... shortest

... equal length

... Between all
router pairs



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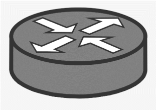

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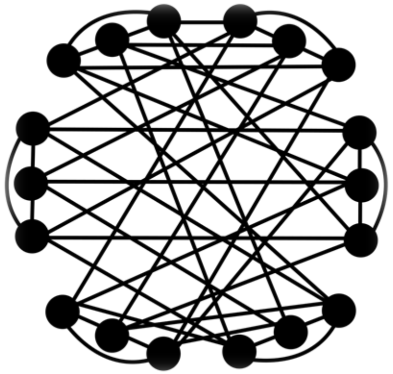

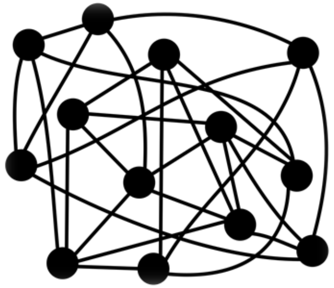

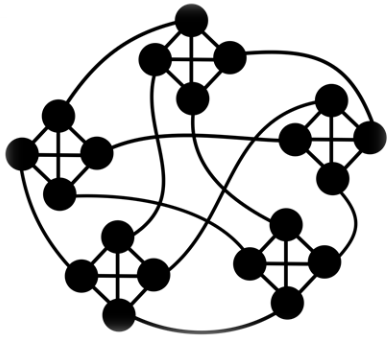

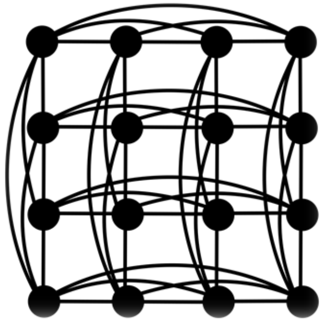

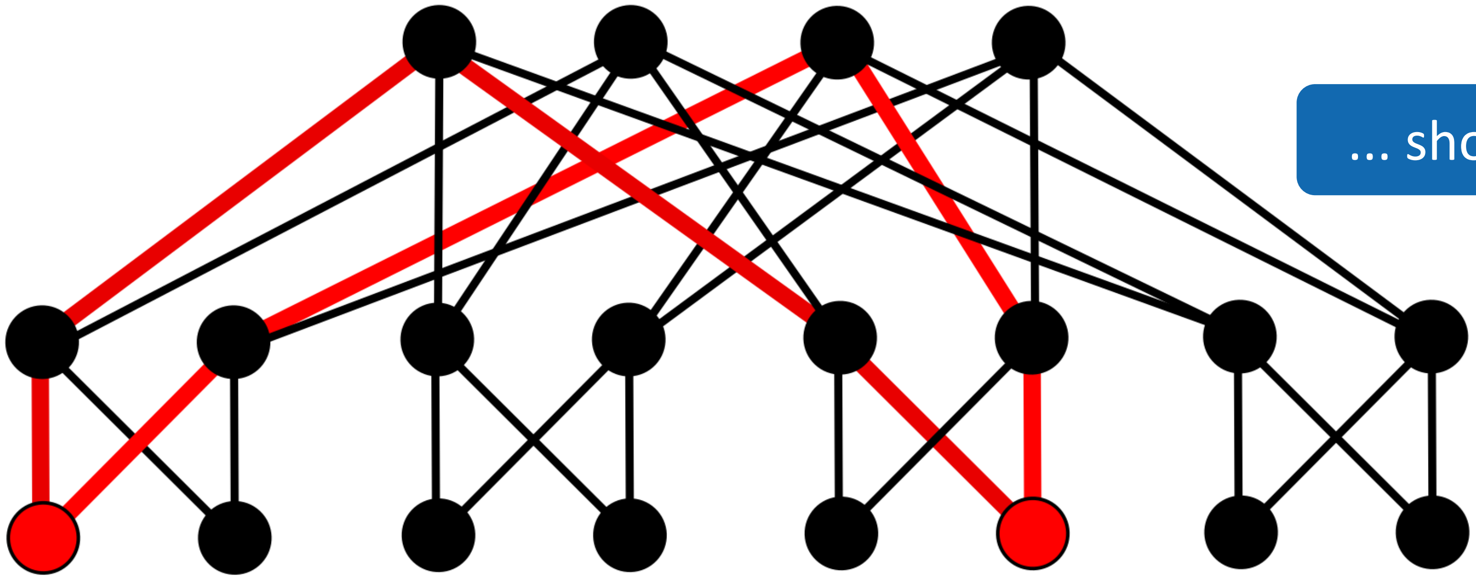

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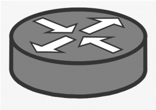
Low-Diameter Network Topologies



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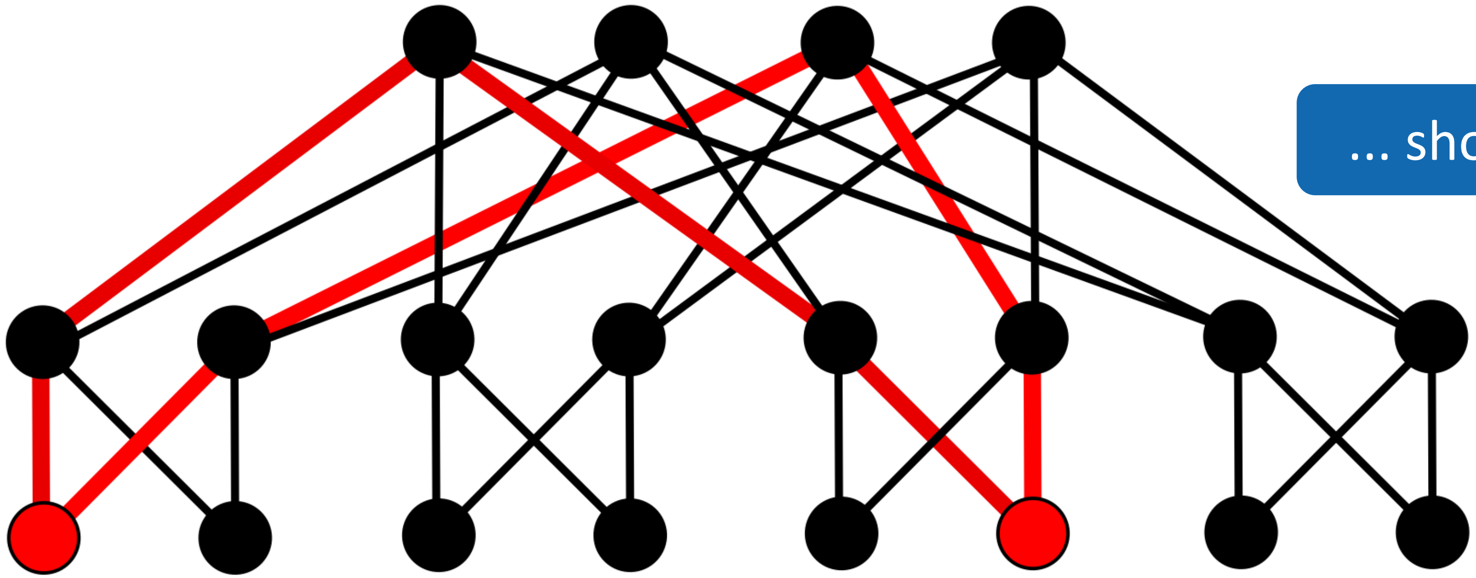

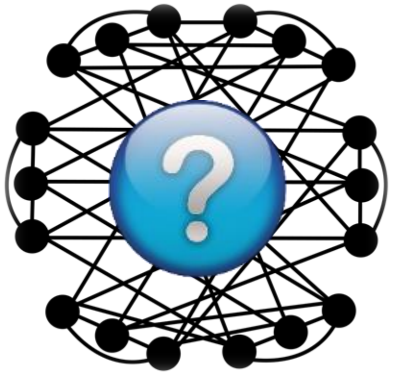

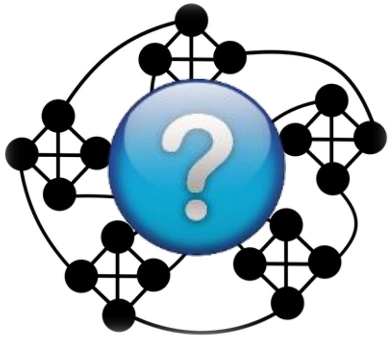

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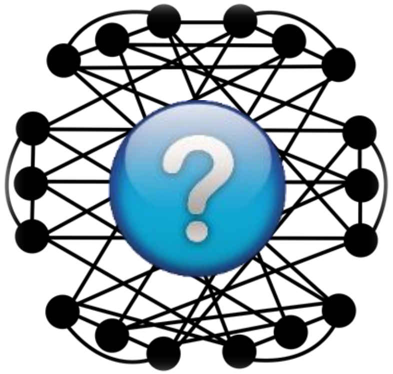

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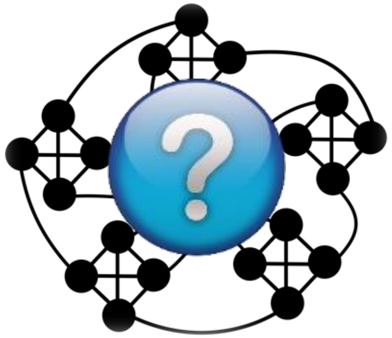
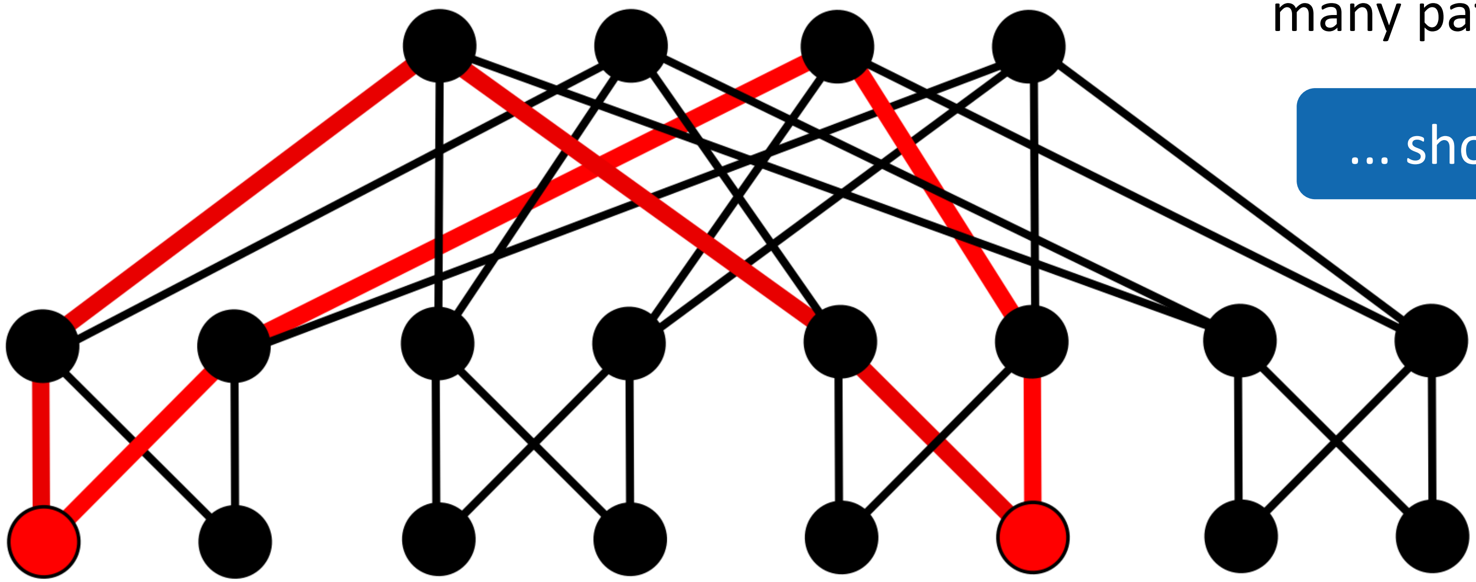


In Fat trees, easily, as we have many paths...

... shortest

... equal length

... Between all router pairs



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What are the problems to be tackled with multipathing?

PATH DIVERSITY ANALYSIS

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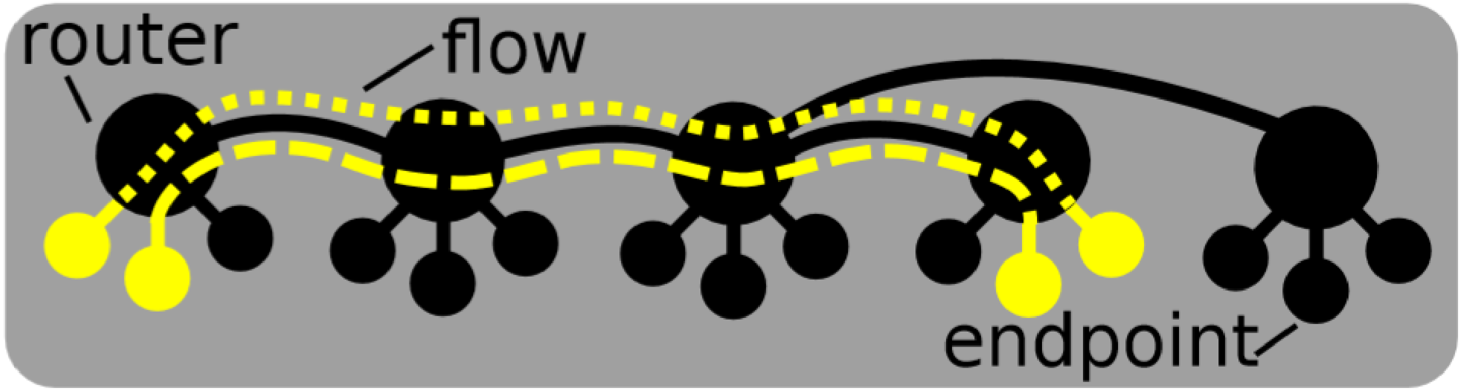

Communicating endpoint pairs mapped to the same routers

Flow collisions

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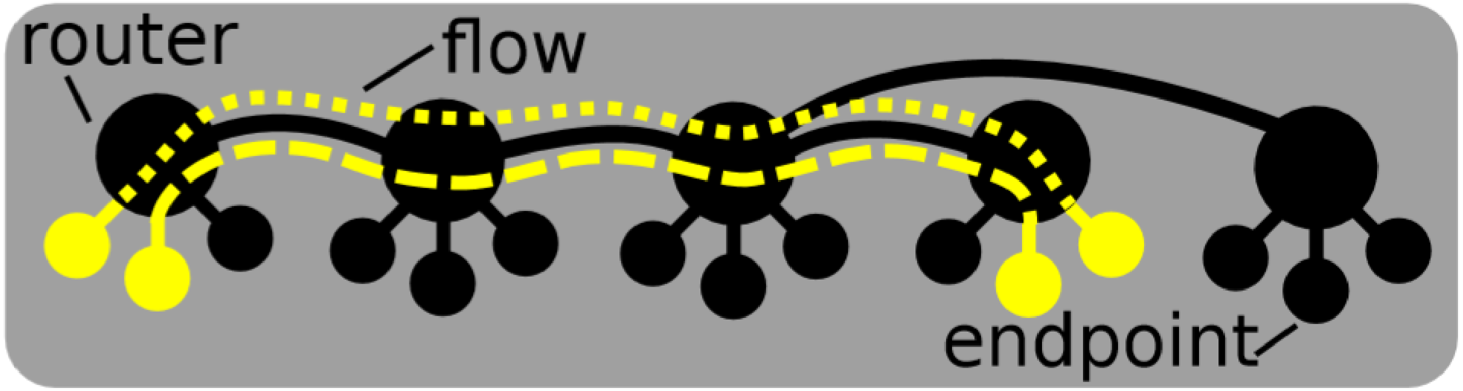

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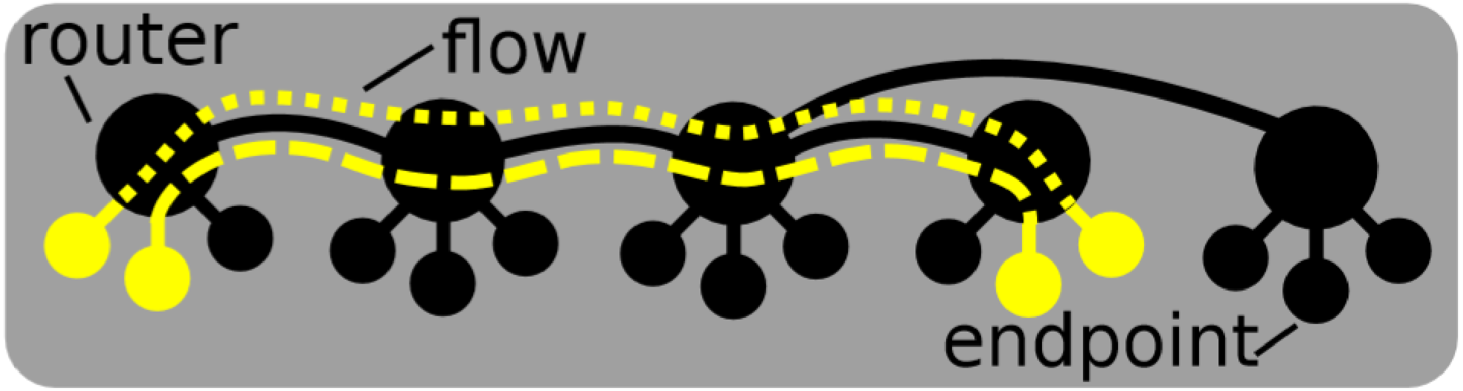

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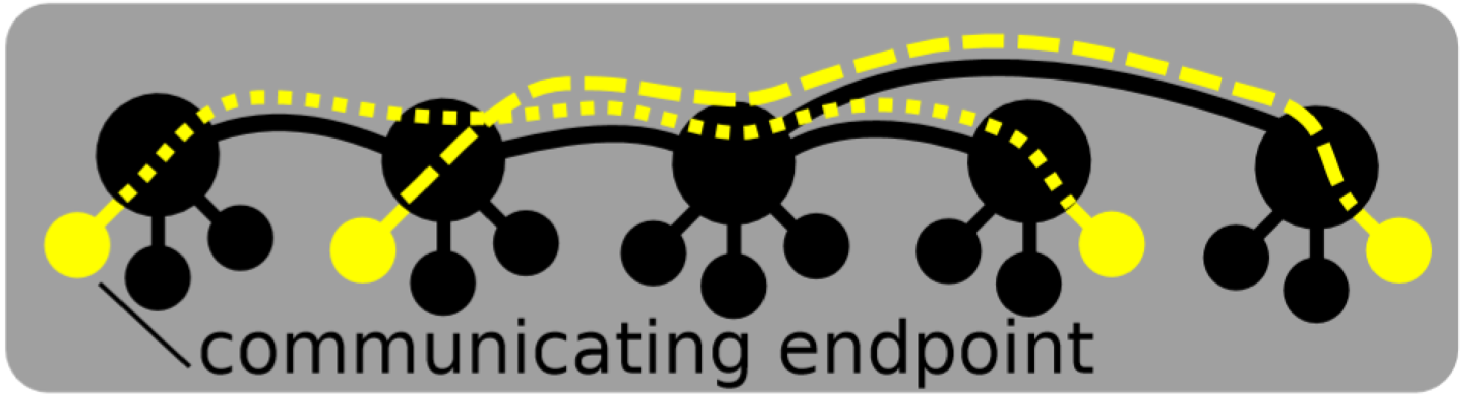

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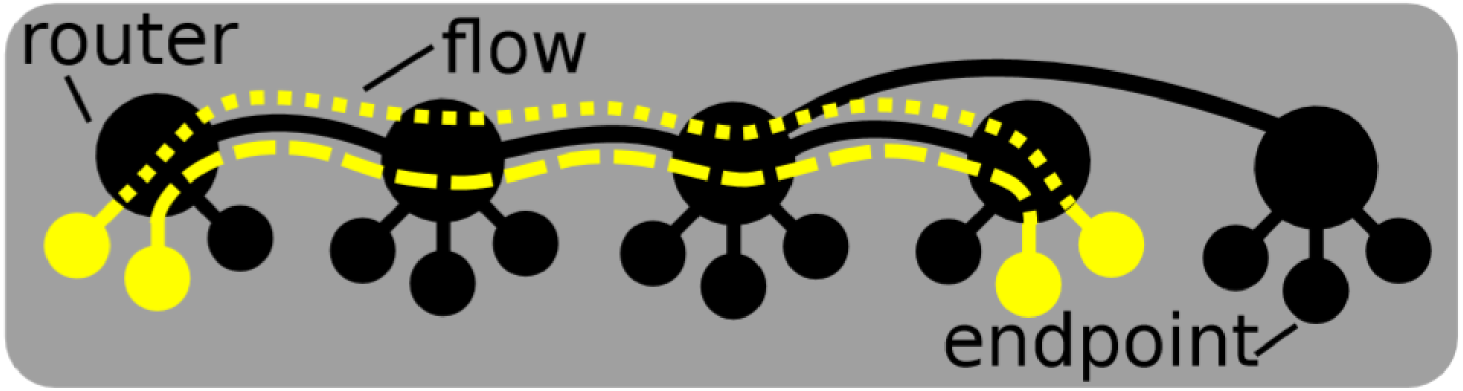

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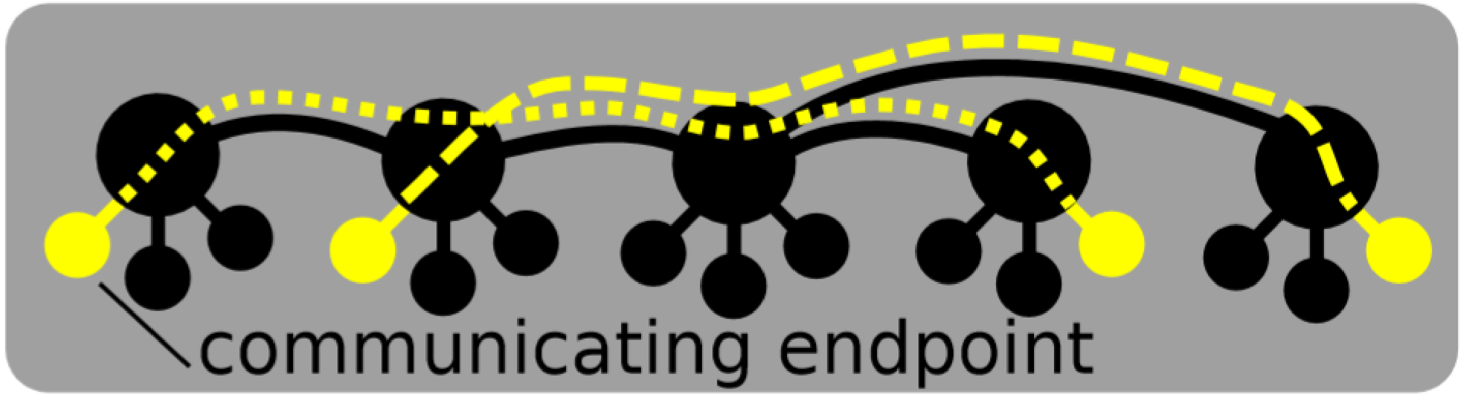

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Flow overlaps

Depend on topology details (router-router connections)

Path Diversity Analysis

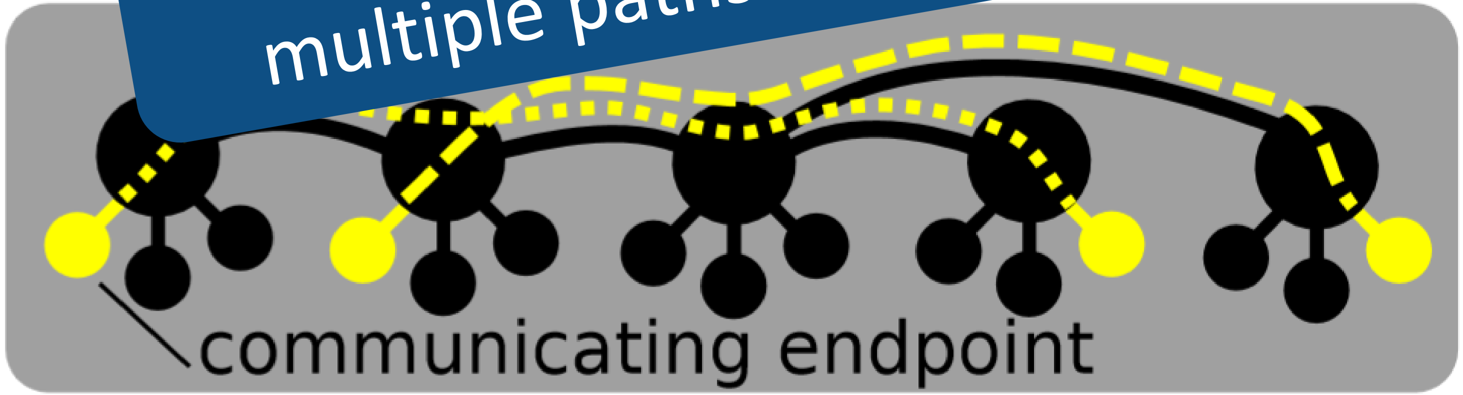
What are the problems to be tackled with multipathing?

Com... ...s

Flow collisions

Depend on workload mapping (assignment of communicating endpoints to routers)

We want to tackle these issues with multipathing. But how many multiple paths do we need…?



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Workload Mapping

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Random workload remapping

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Observation: In low-diameter topologies, locality is less important

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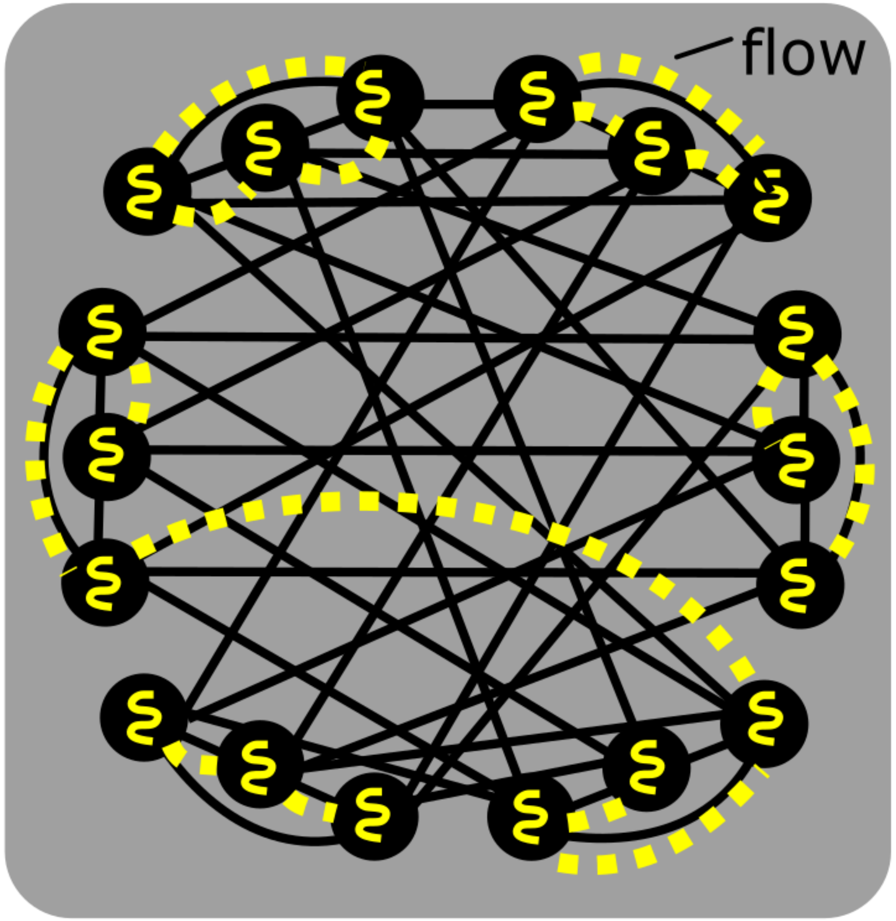
A simple stencil running on a Slim Fly

Before remapping



Workload Mapping

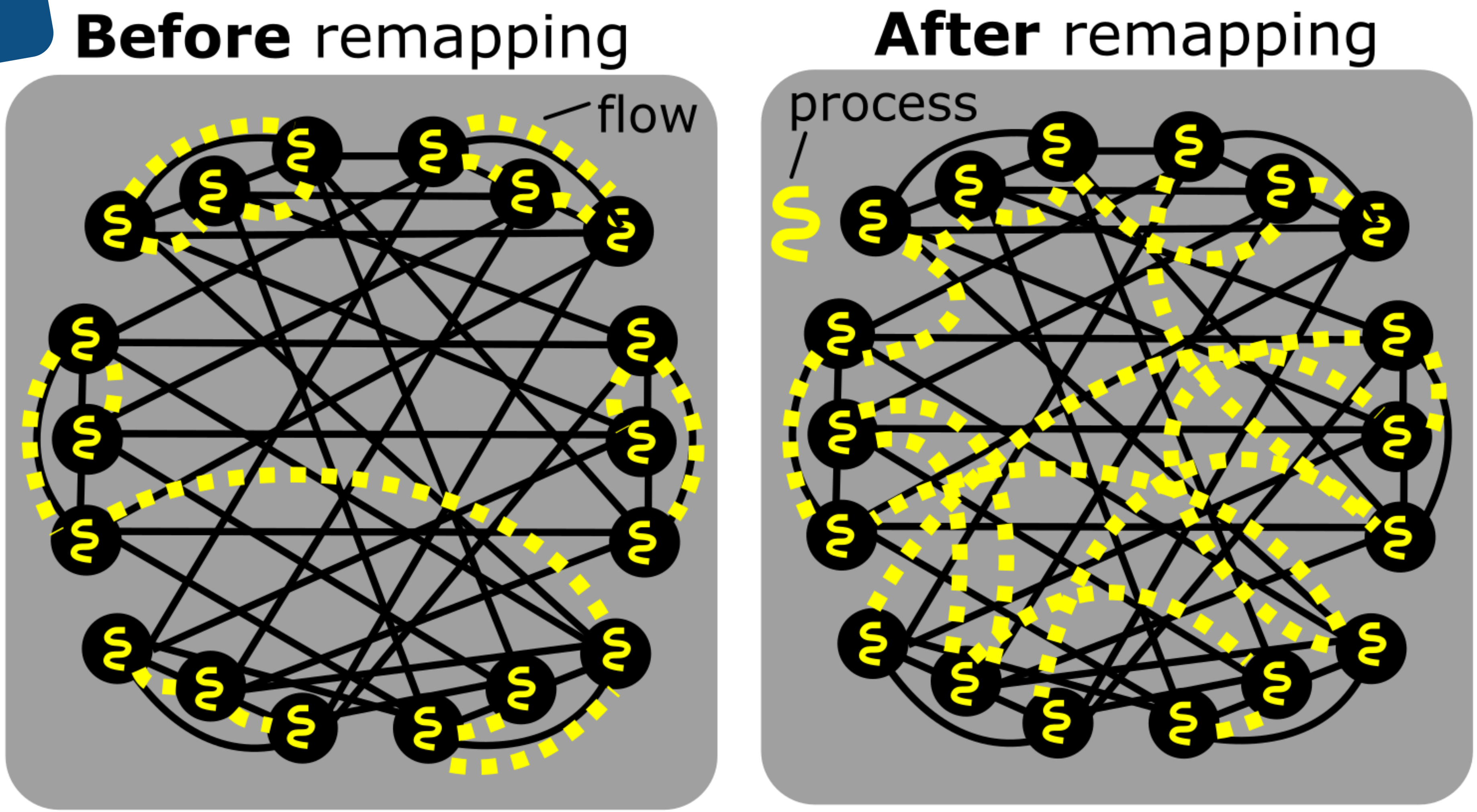
How to further enhance performance?

Random workload remapping

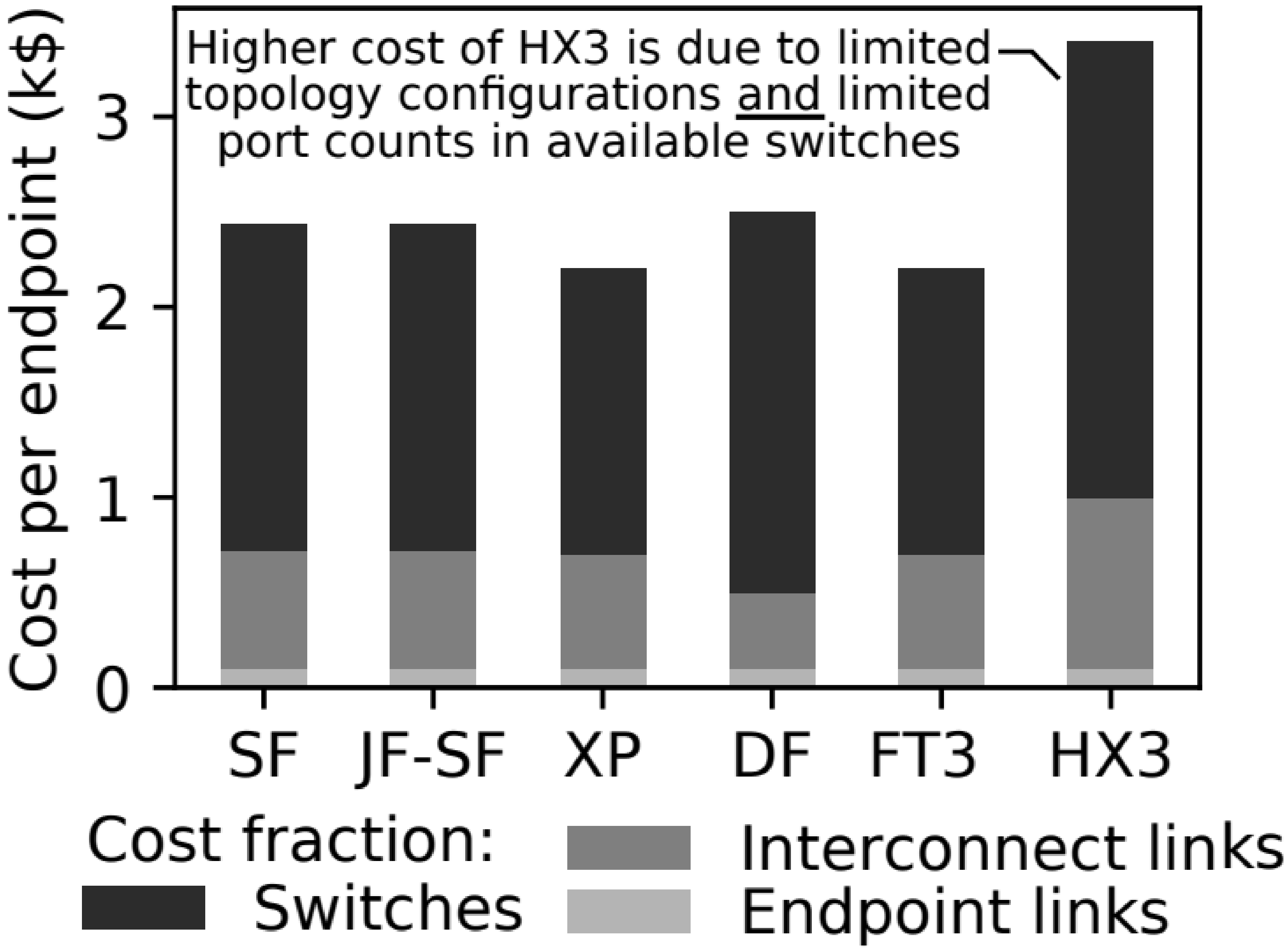
Observation: In low-diameter topologies, locality is less important

Random mapping uses rich diversity of inter-group paths

A simple stencil running on a Slim Fly



COST MODEL


Higher cost of HX3 is due to limited topology configurations and limited port counts in available switches
Cost per endpoint (k$)
0
1
2
3
SF
JF-SF
XP
DF
FT3
HX3
Cost fraction:
Switches
Interconnect links
Endpoint links

EVALUATION

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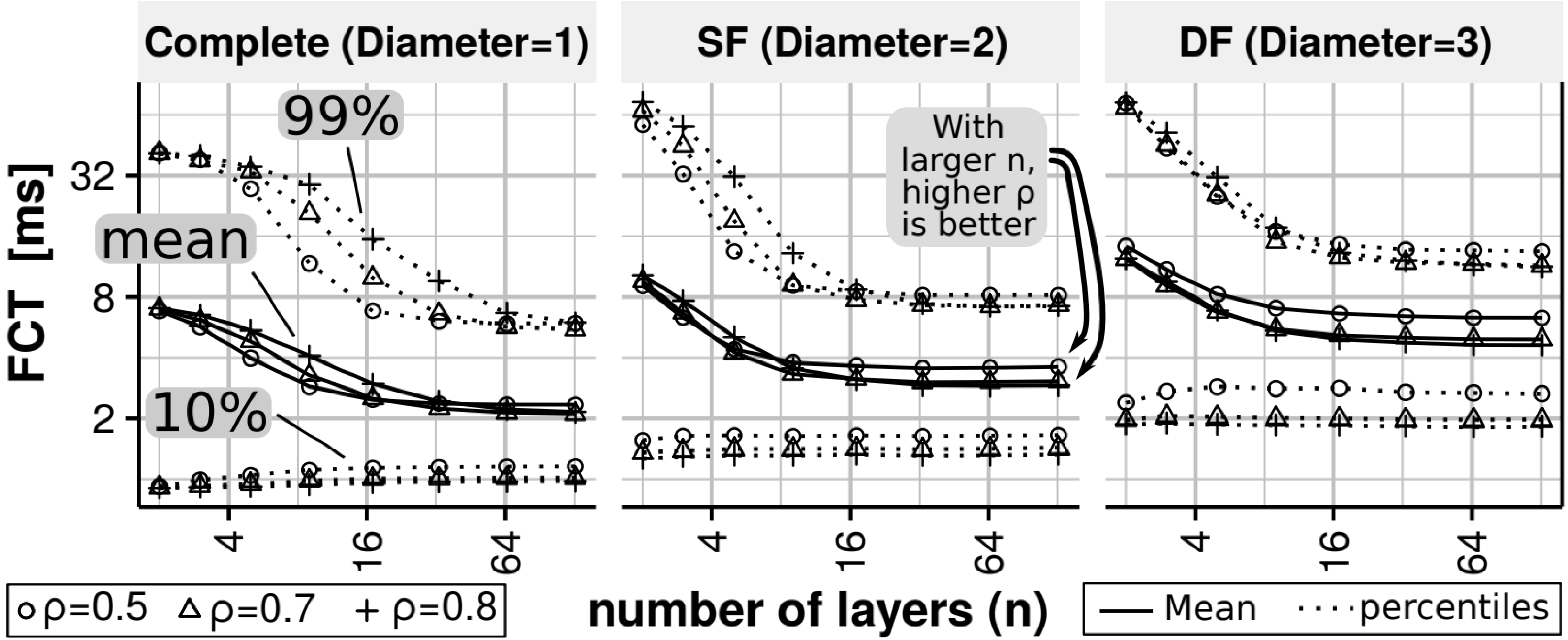
N ≈ 10,000; comparable cost; random uniform traffic; „bare Ethernet"



rho: fraction of links kept in a layer

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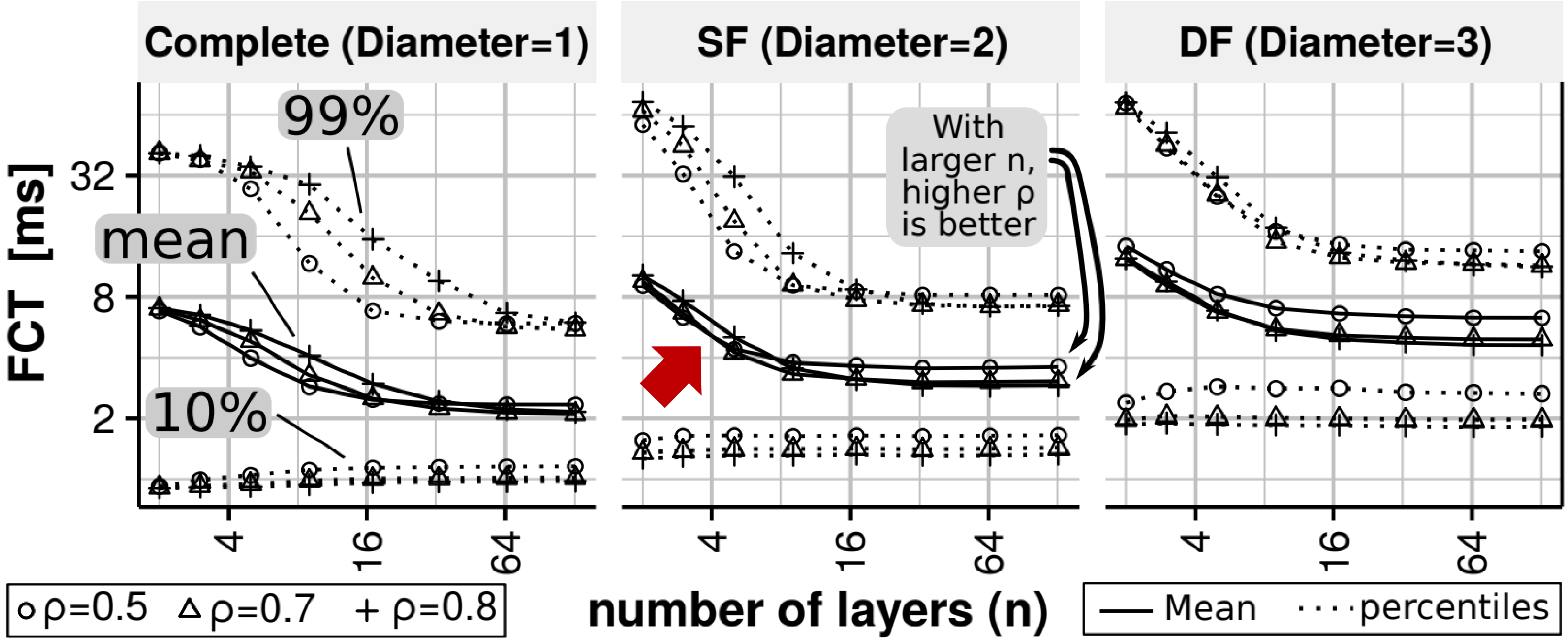

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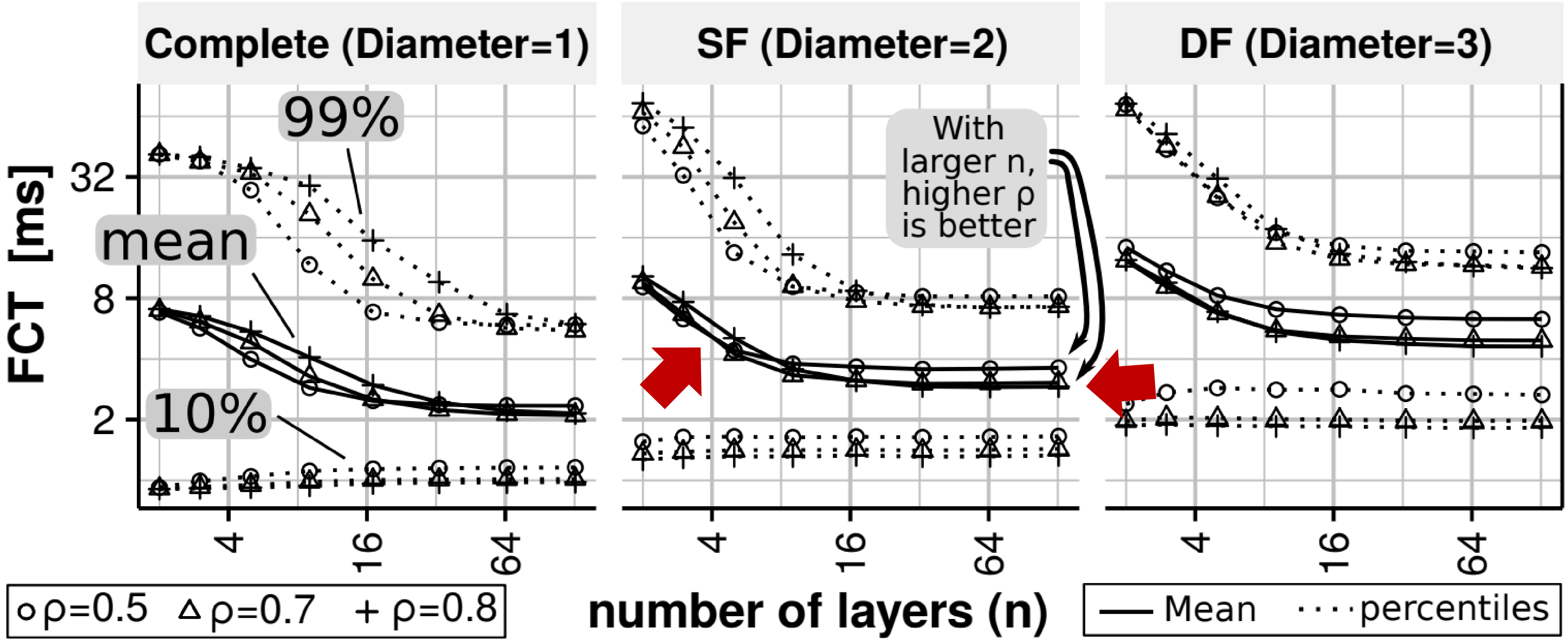

rho: fraction of links kept in a layer

With fewer layers, lower rho is better (sparser layers)

With more layers, higher rho is better (denser layers)

ARE THERE ENOUGH MULTIPLE PATHS IN LOW-DIAMETER TOPOLOGIES?

Part 2

Non- shortest paths

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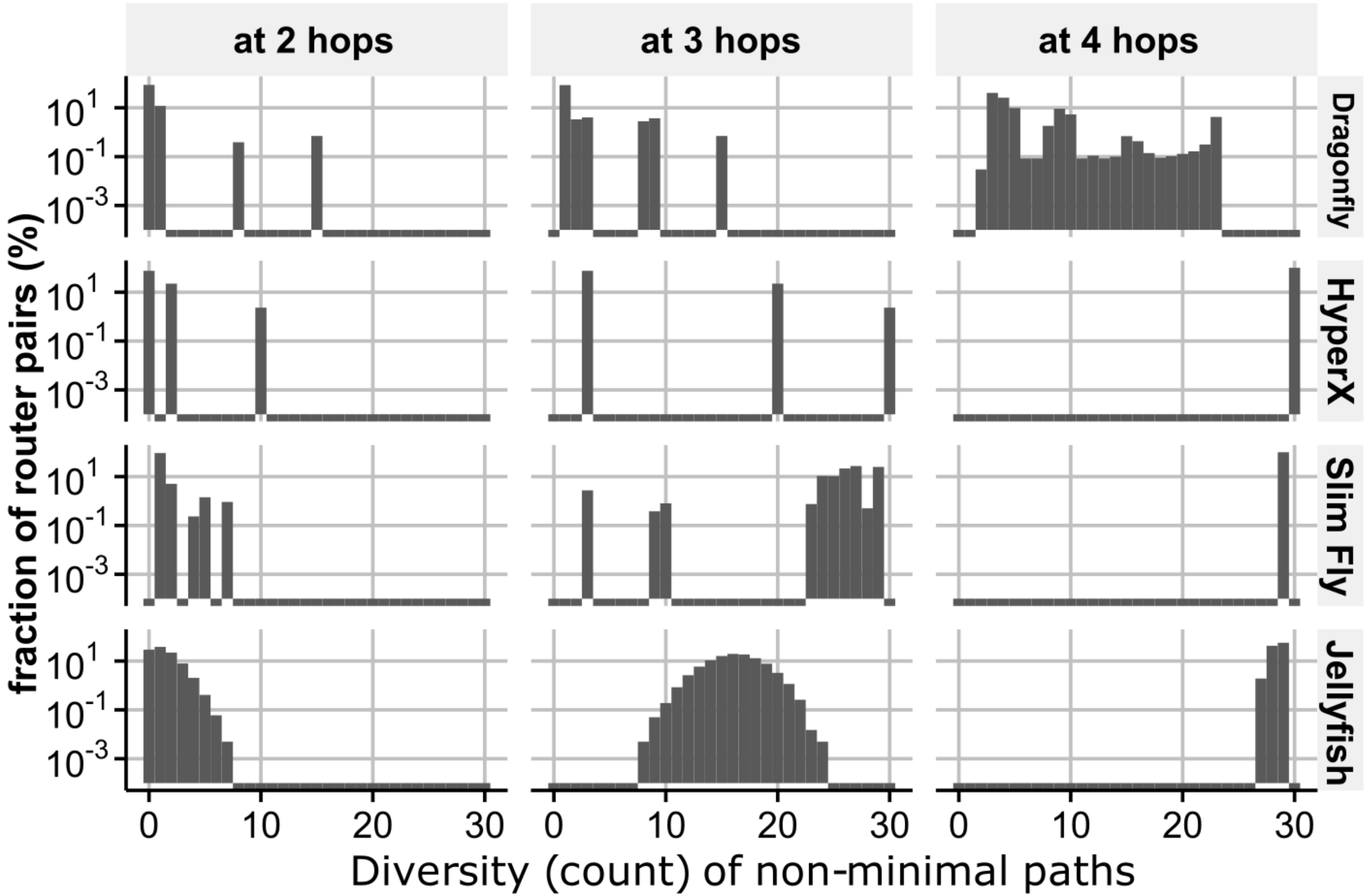

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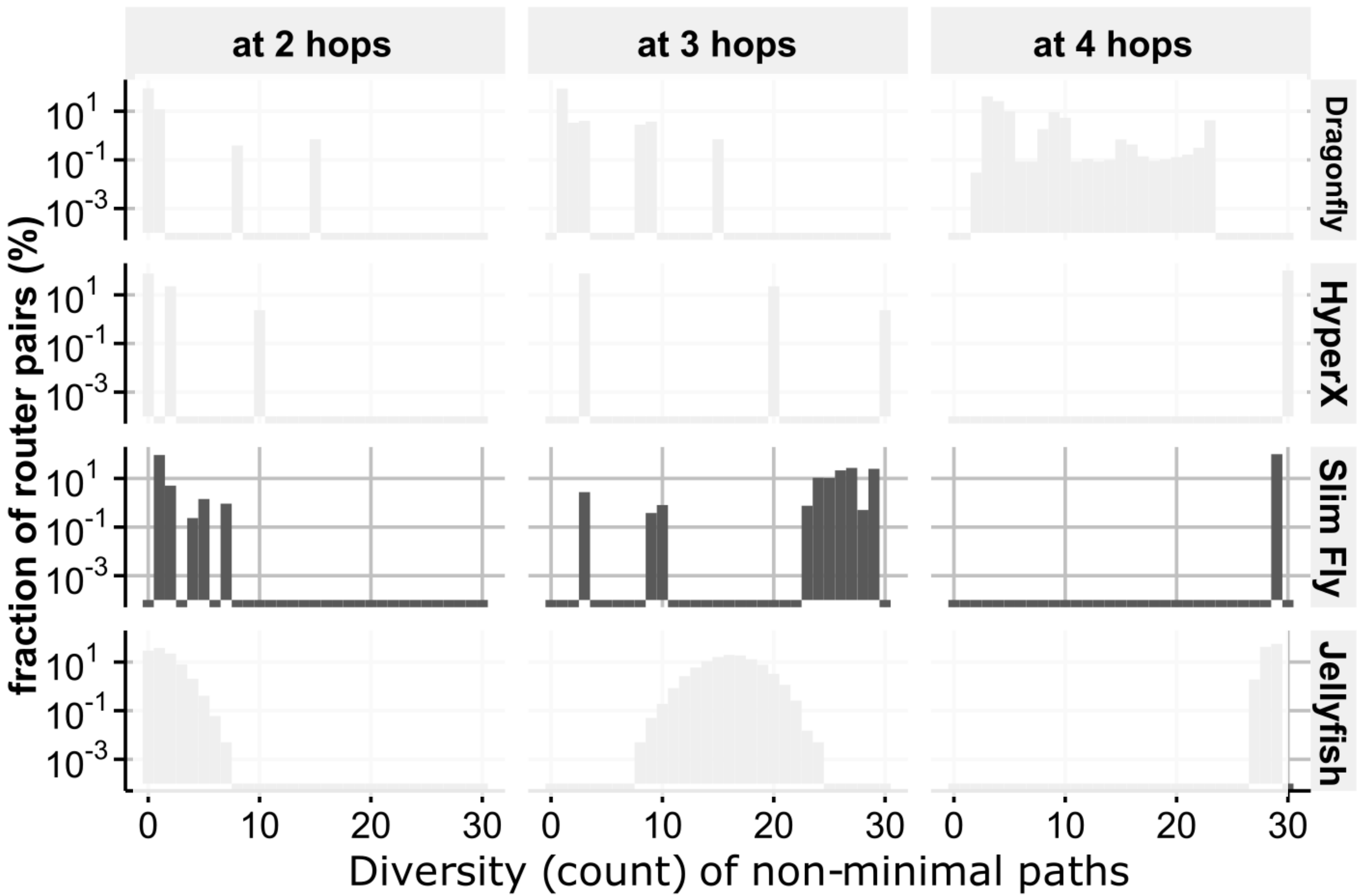

How about non-shortest paths?

Are there enough multiple paths in low-diameter topologies?

Part 2

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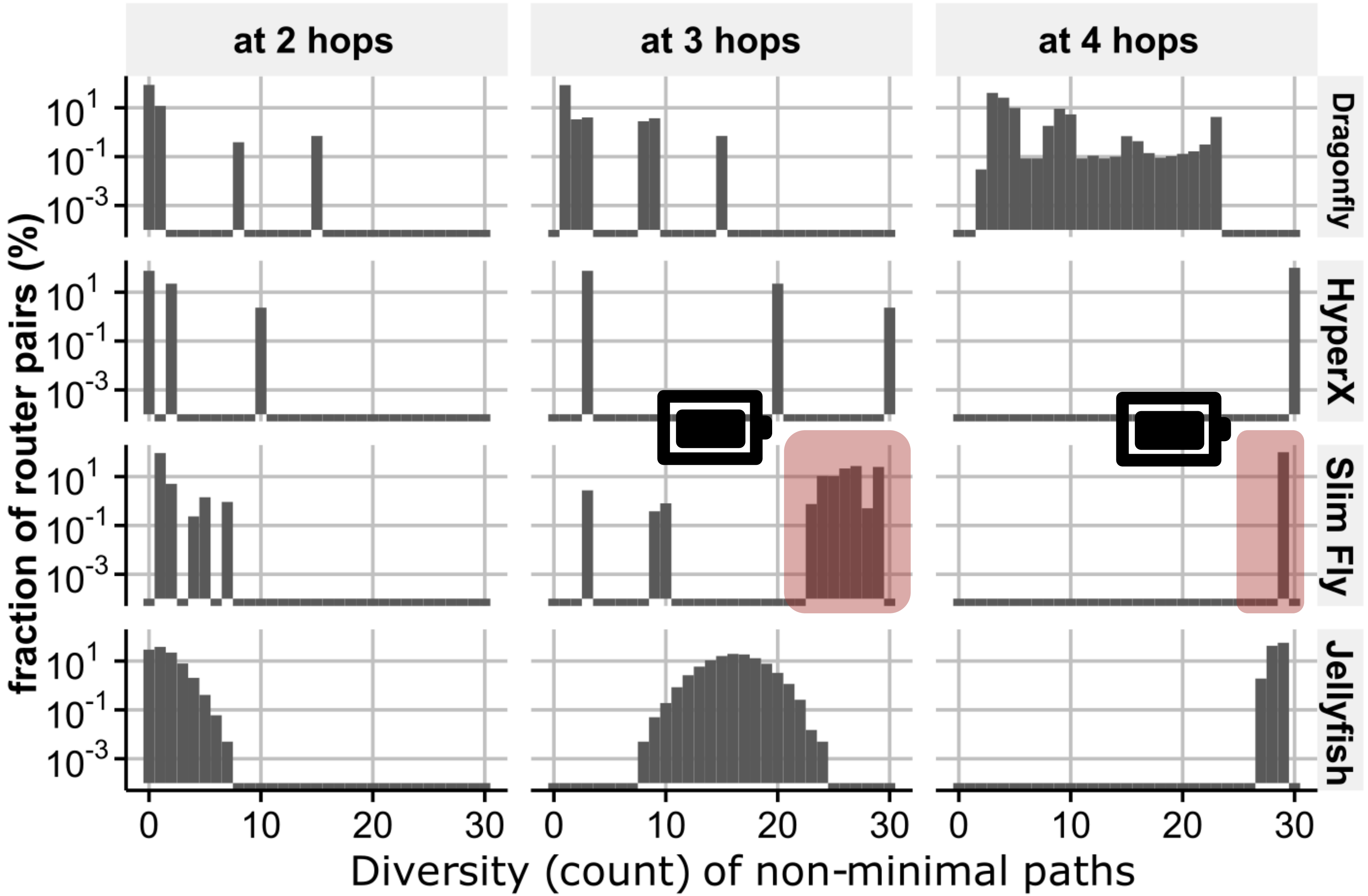

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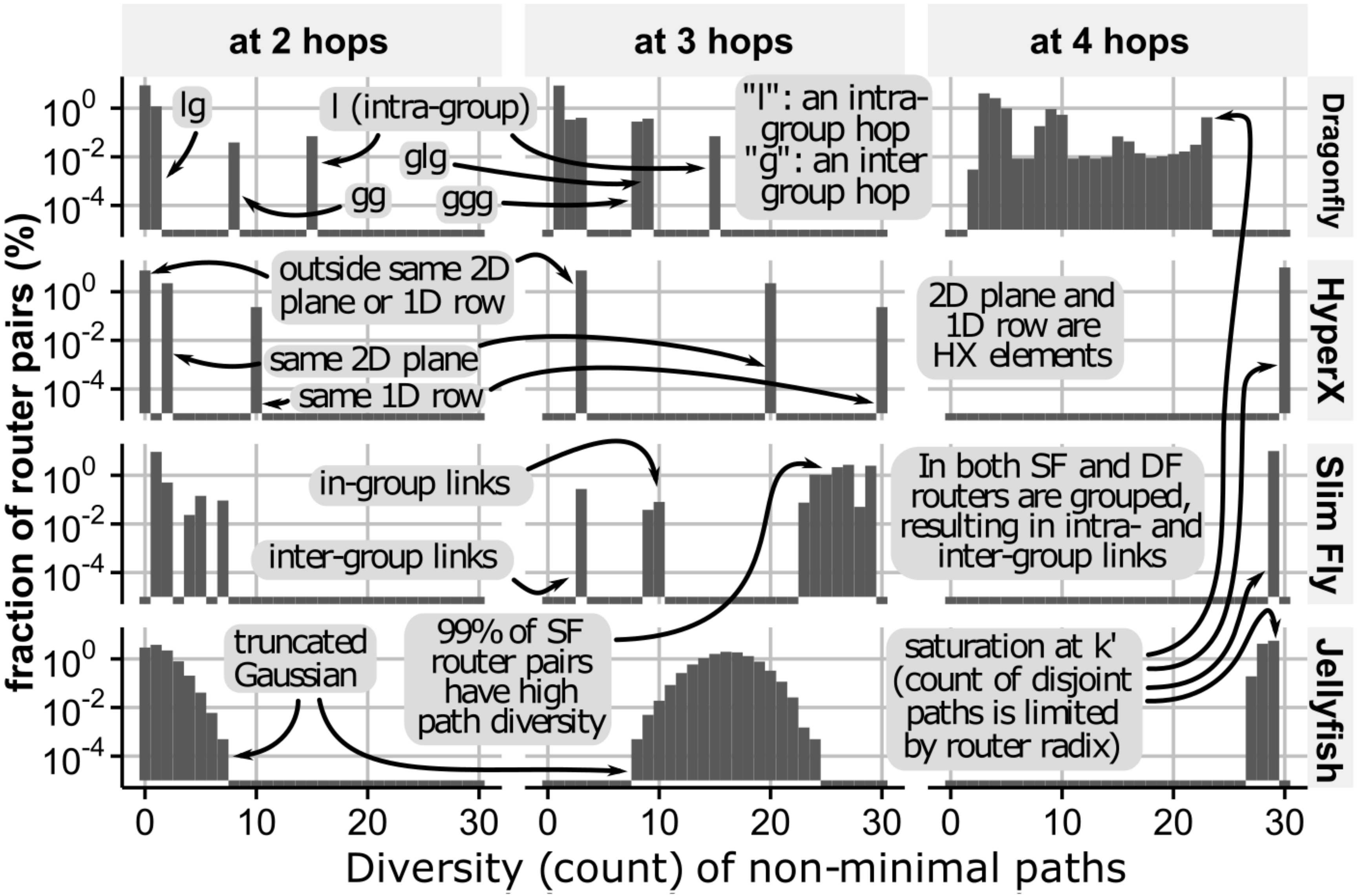

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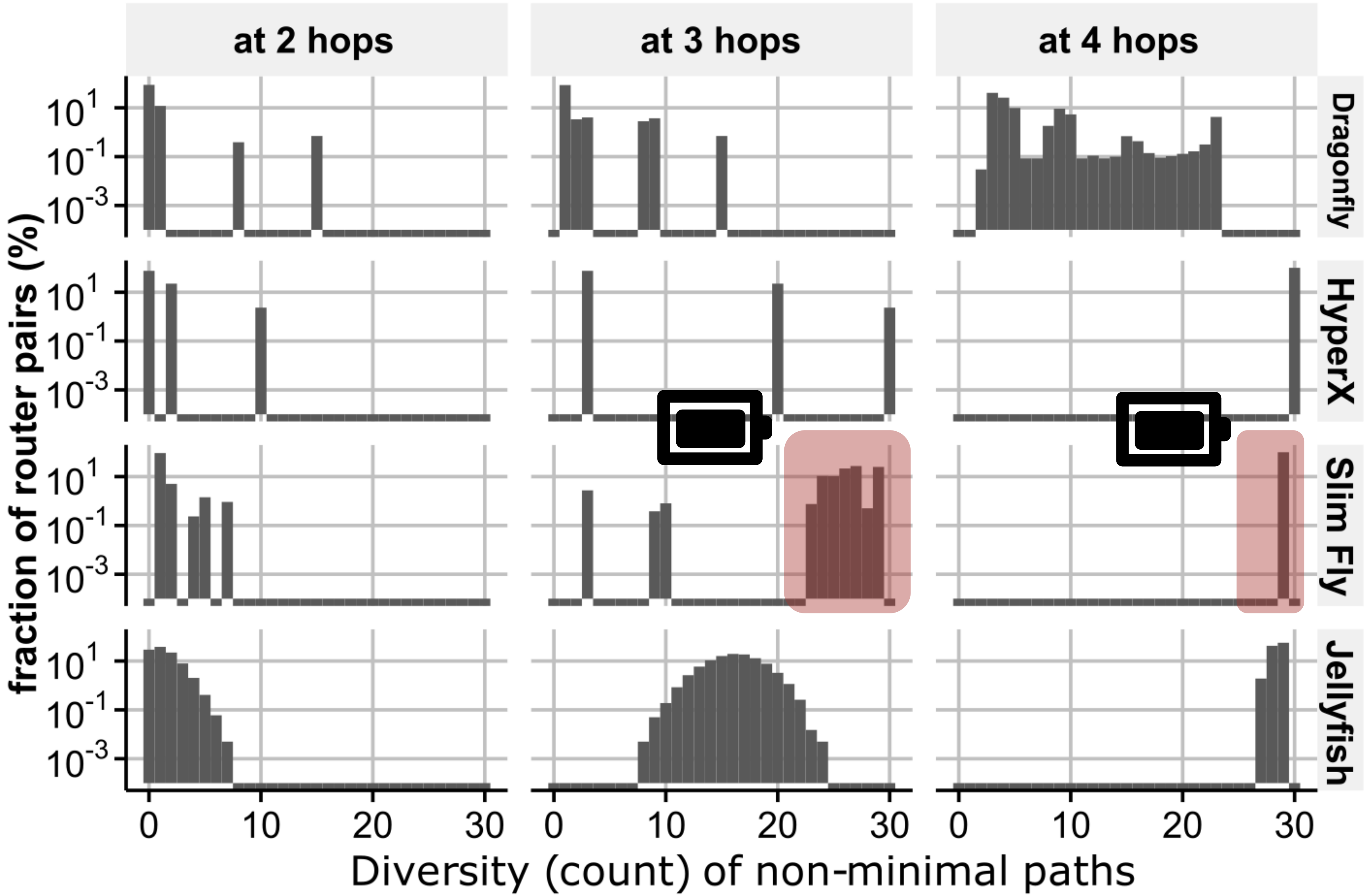

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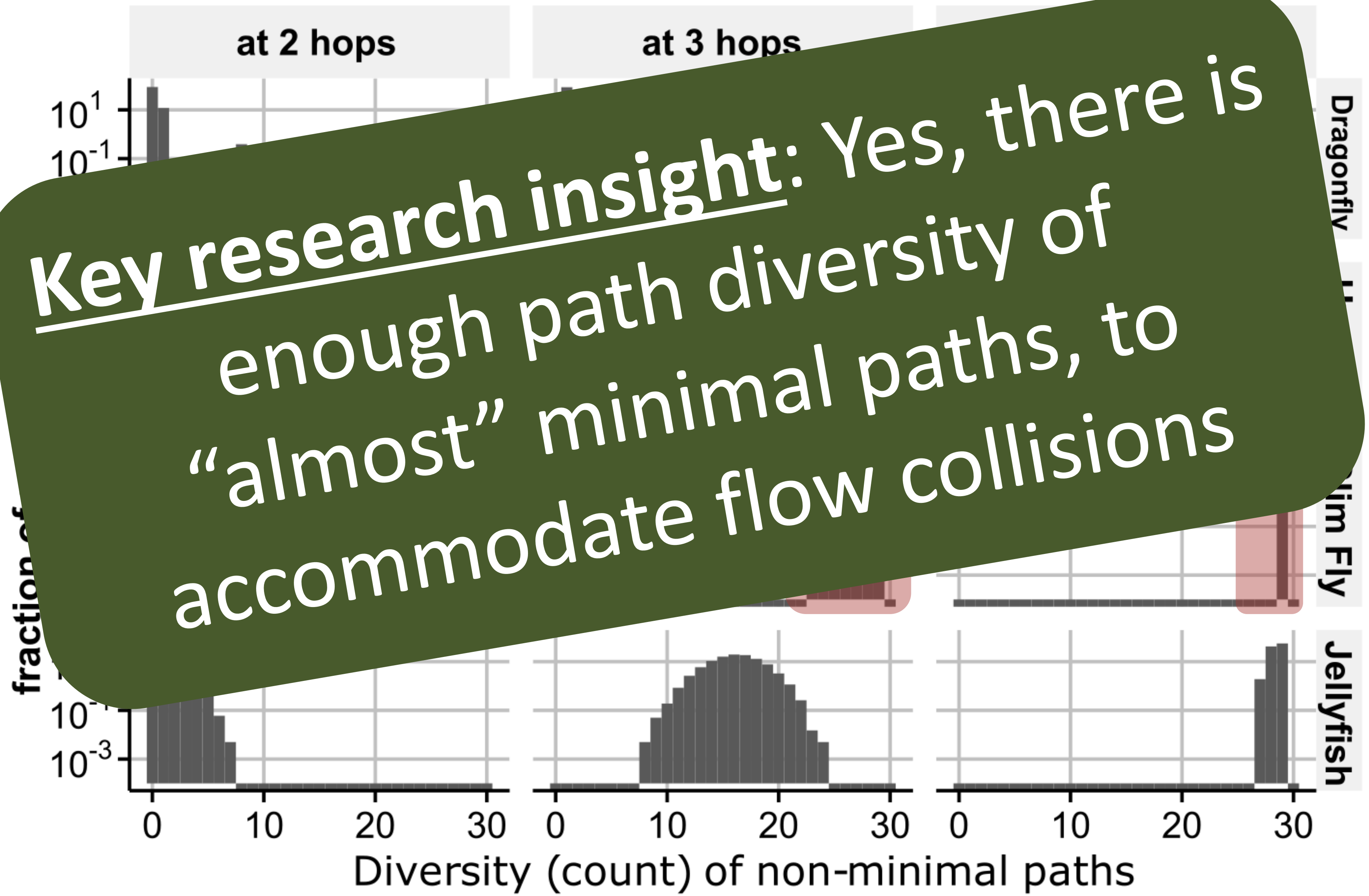
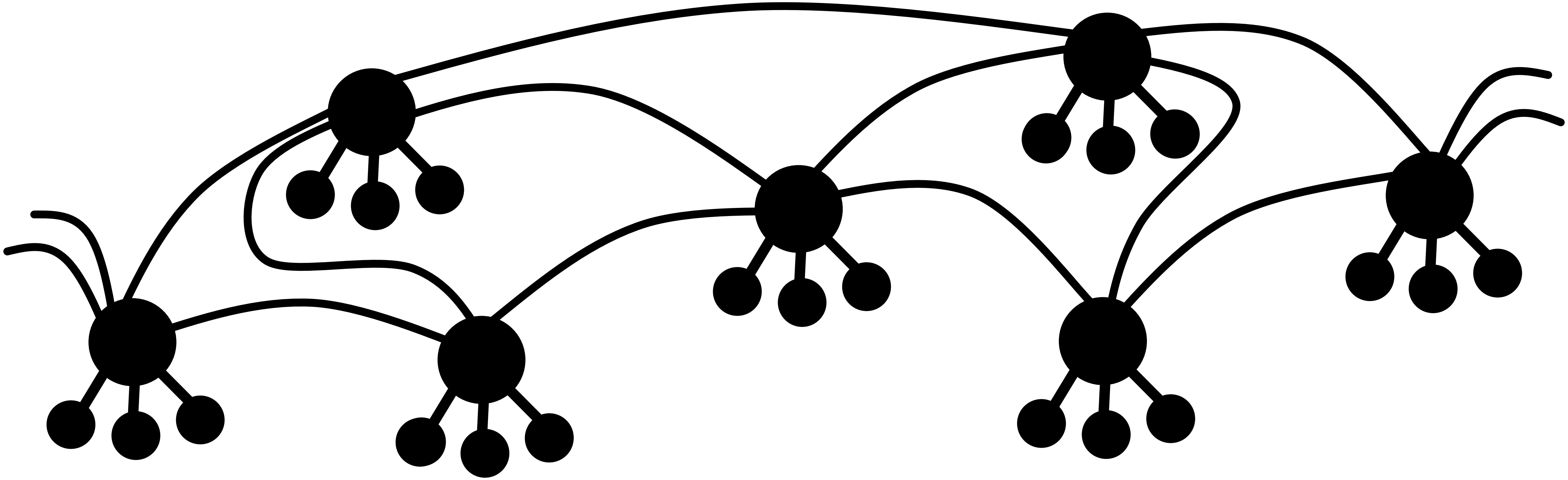


Key research insight: Yes, there is enough path diversity of "almost" minimal paths, to accommodate flow collisions

How about non-shortest paths?

There is much more...



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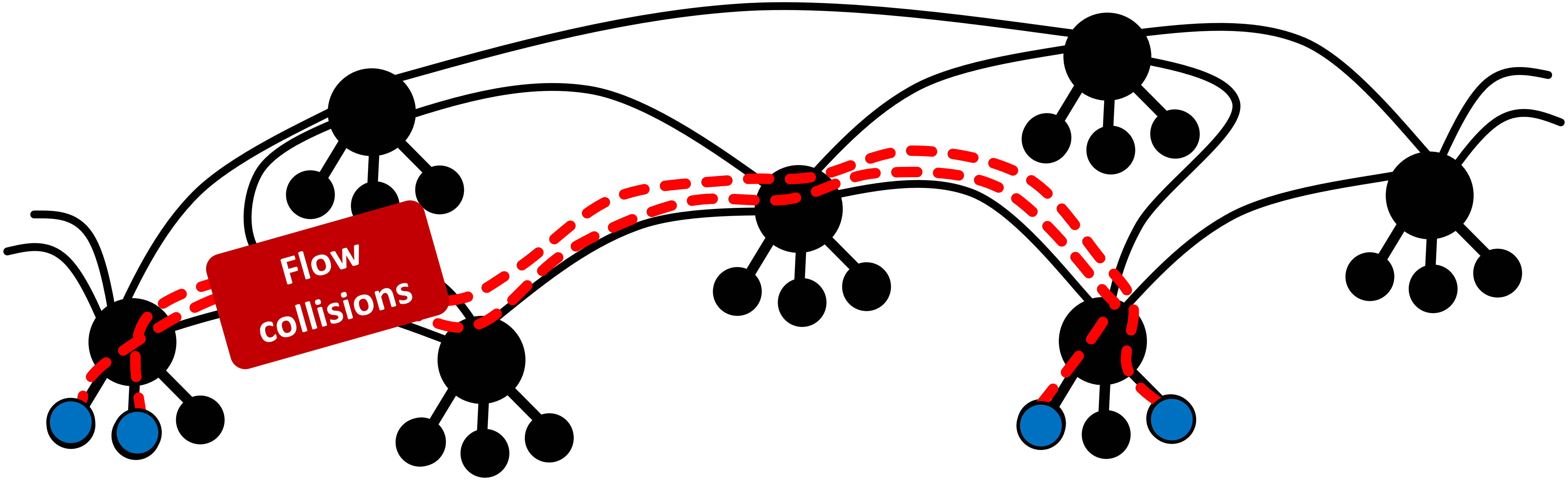

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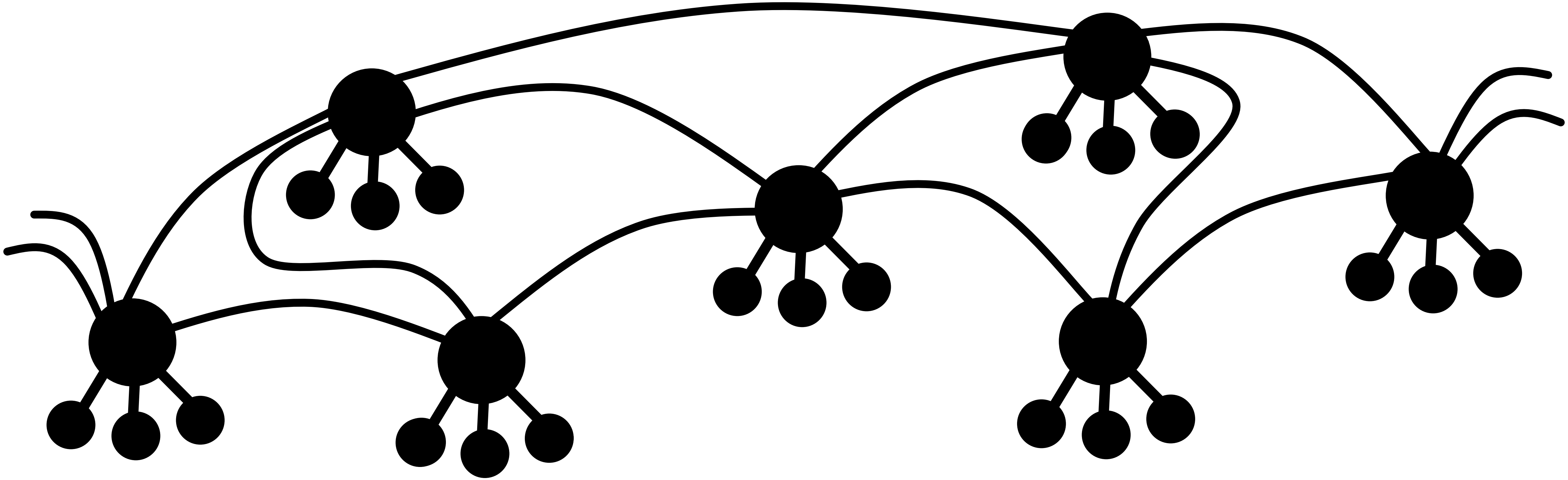

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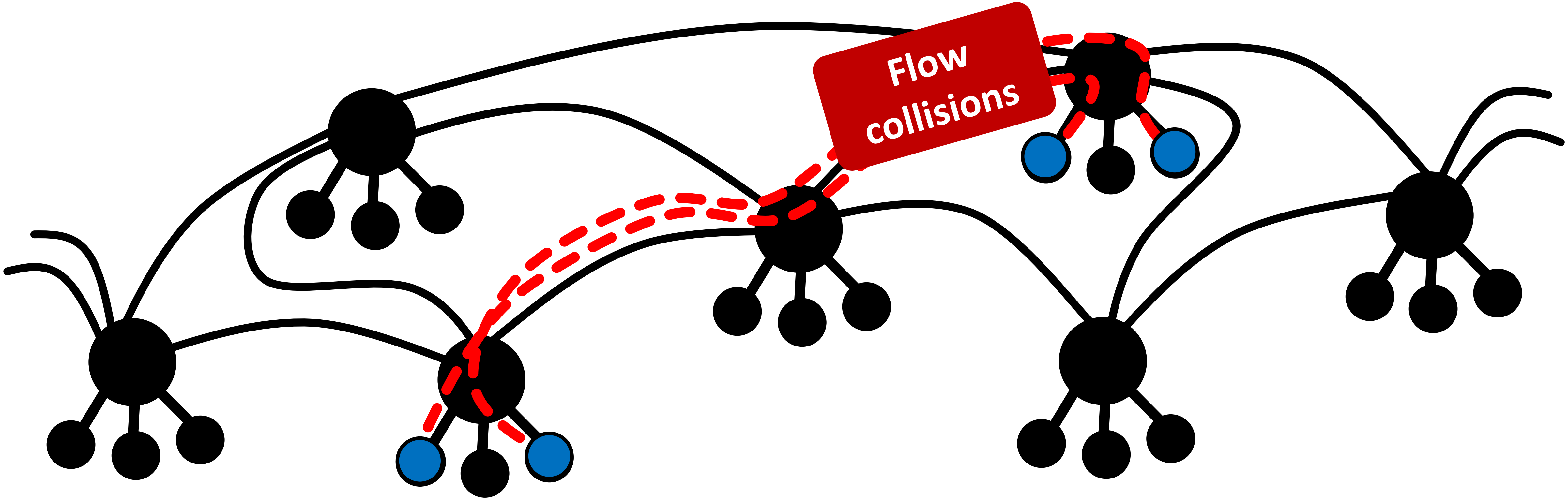

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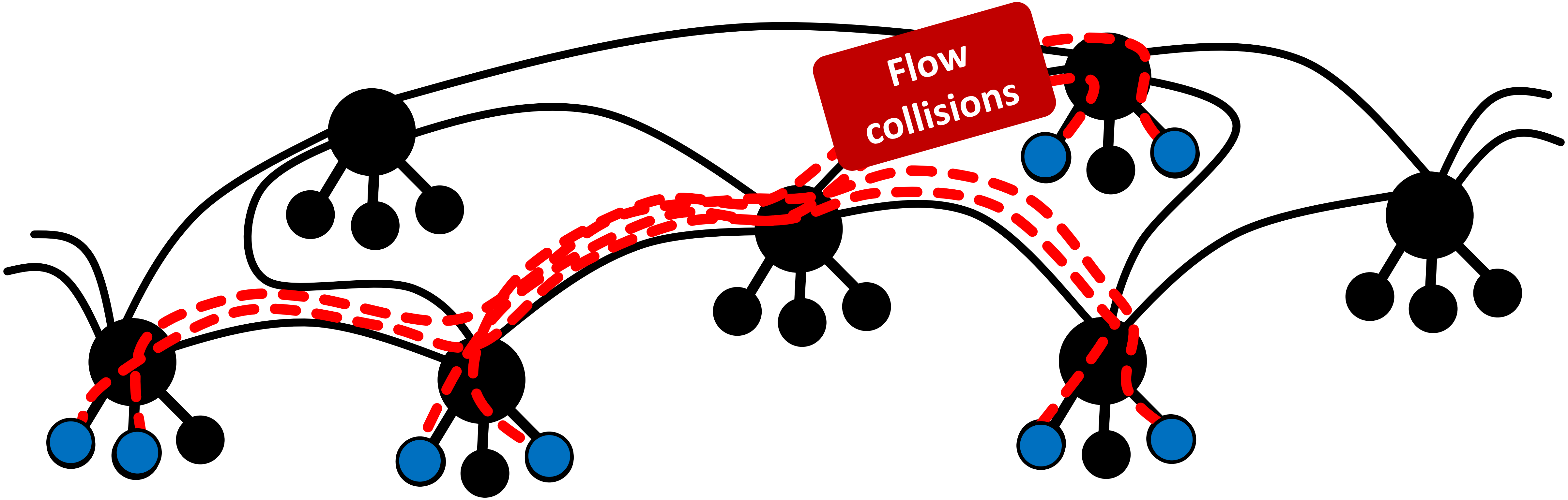

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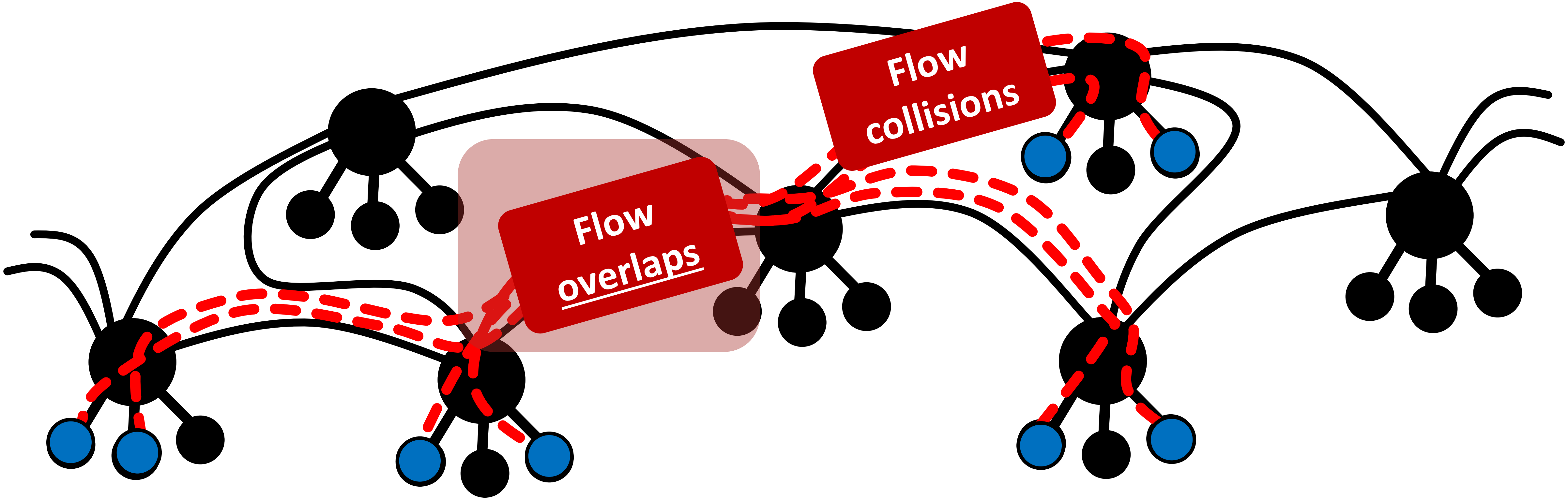

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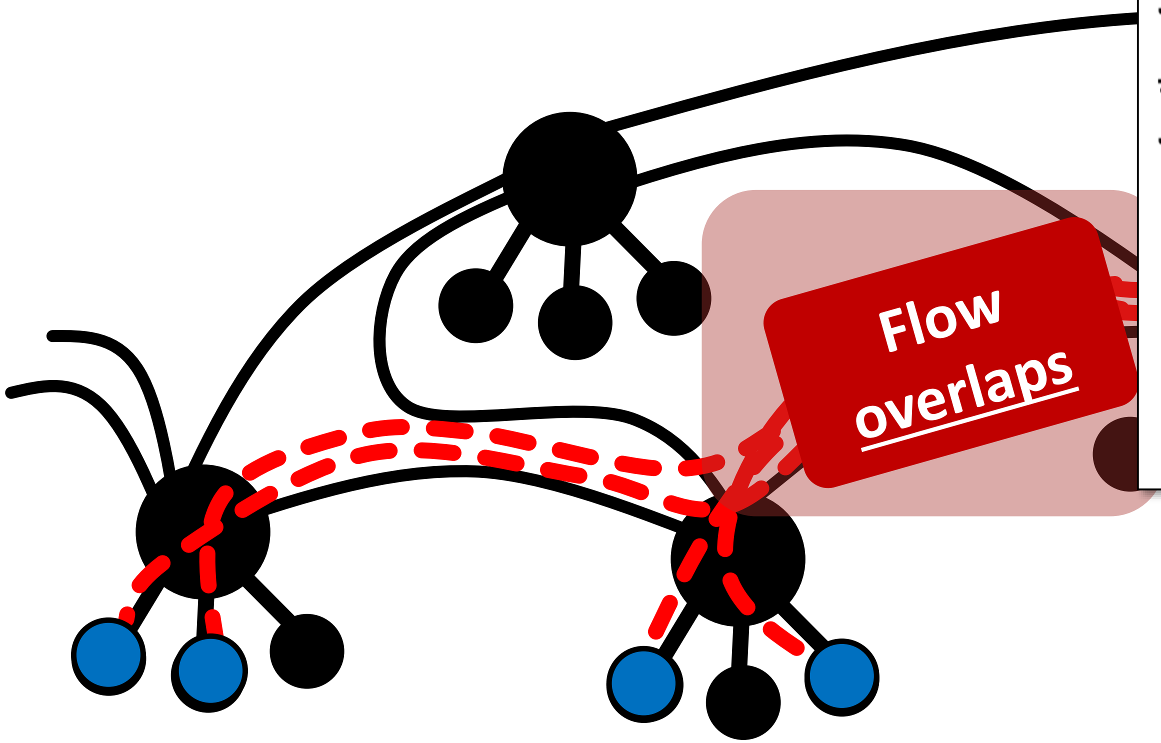

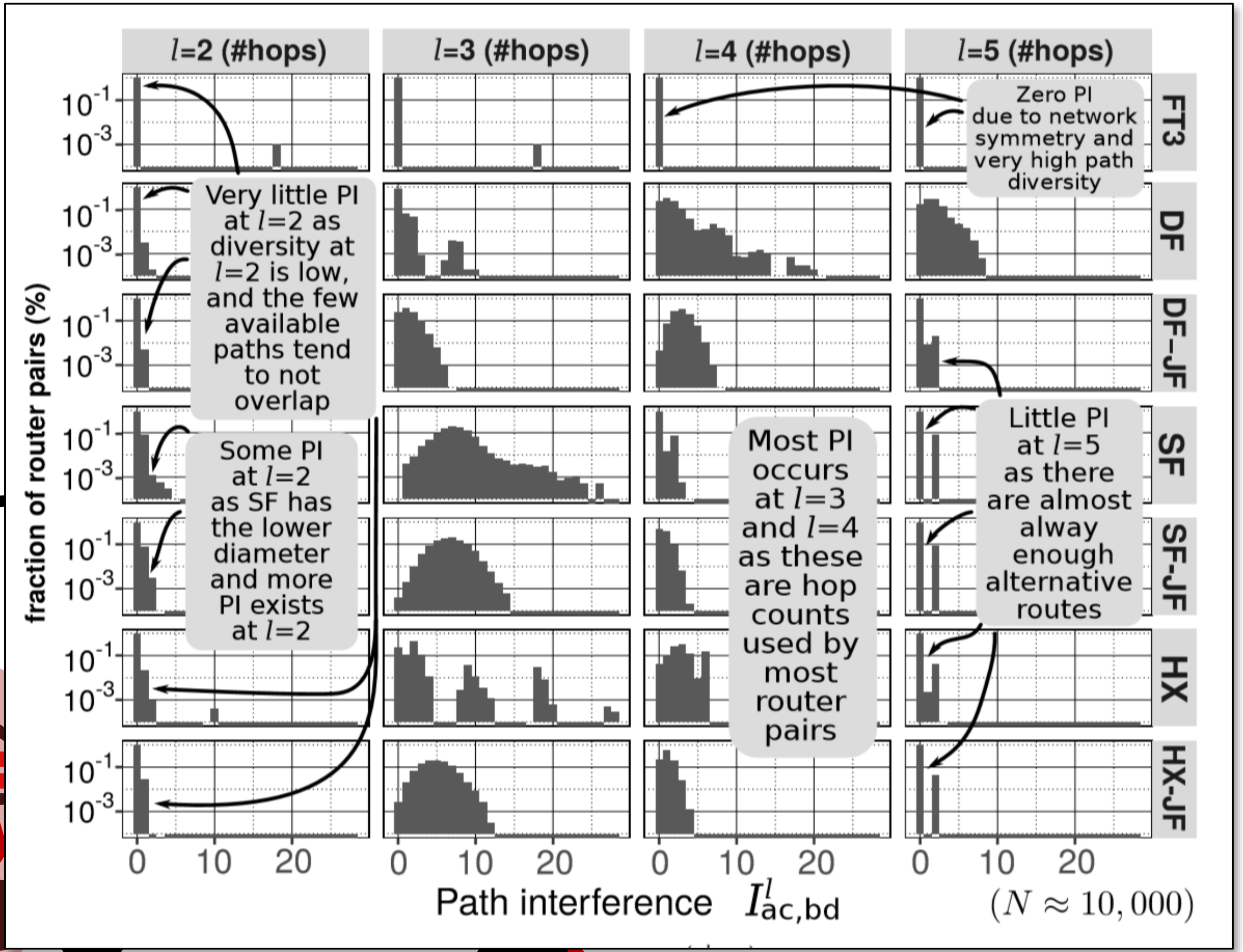

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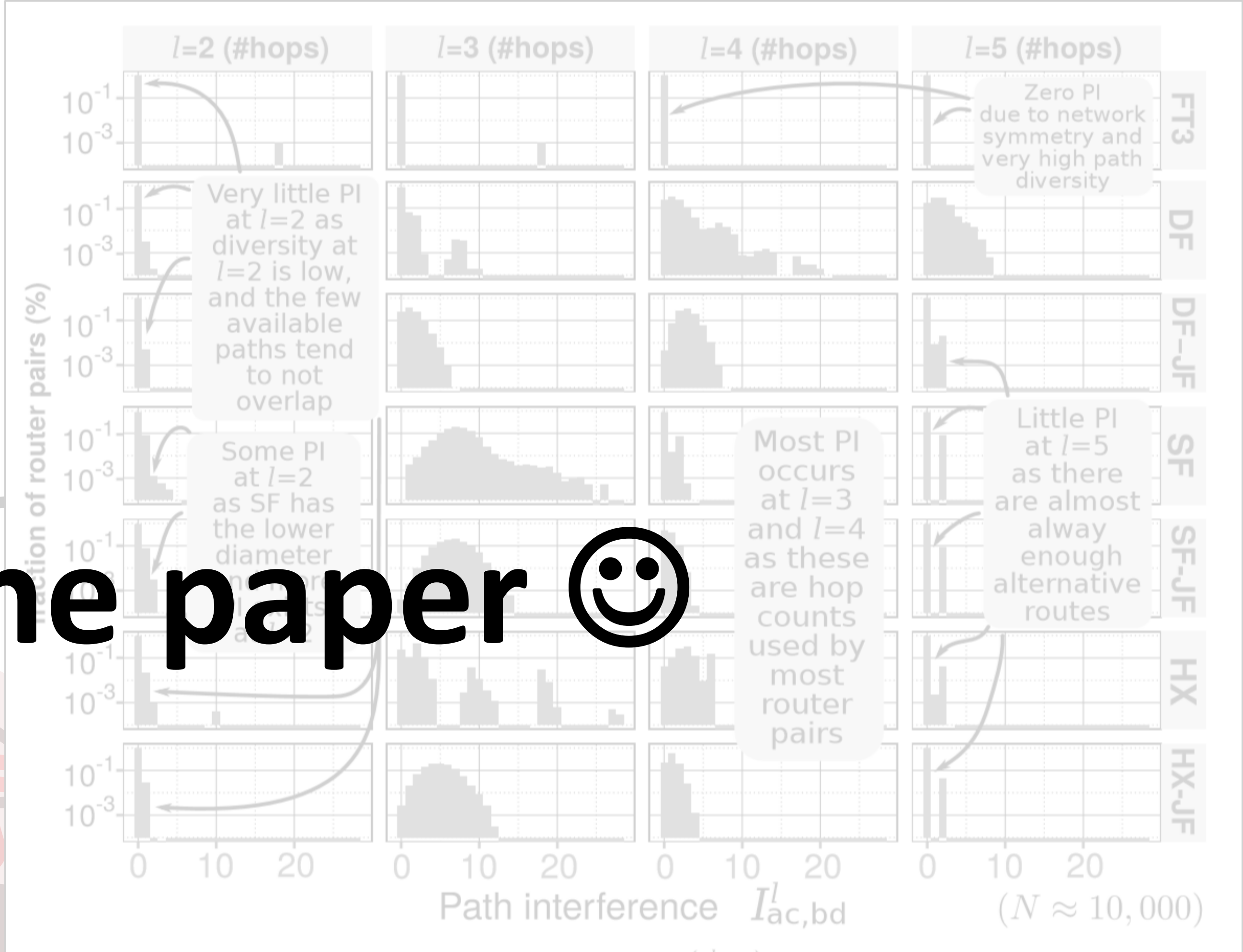

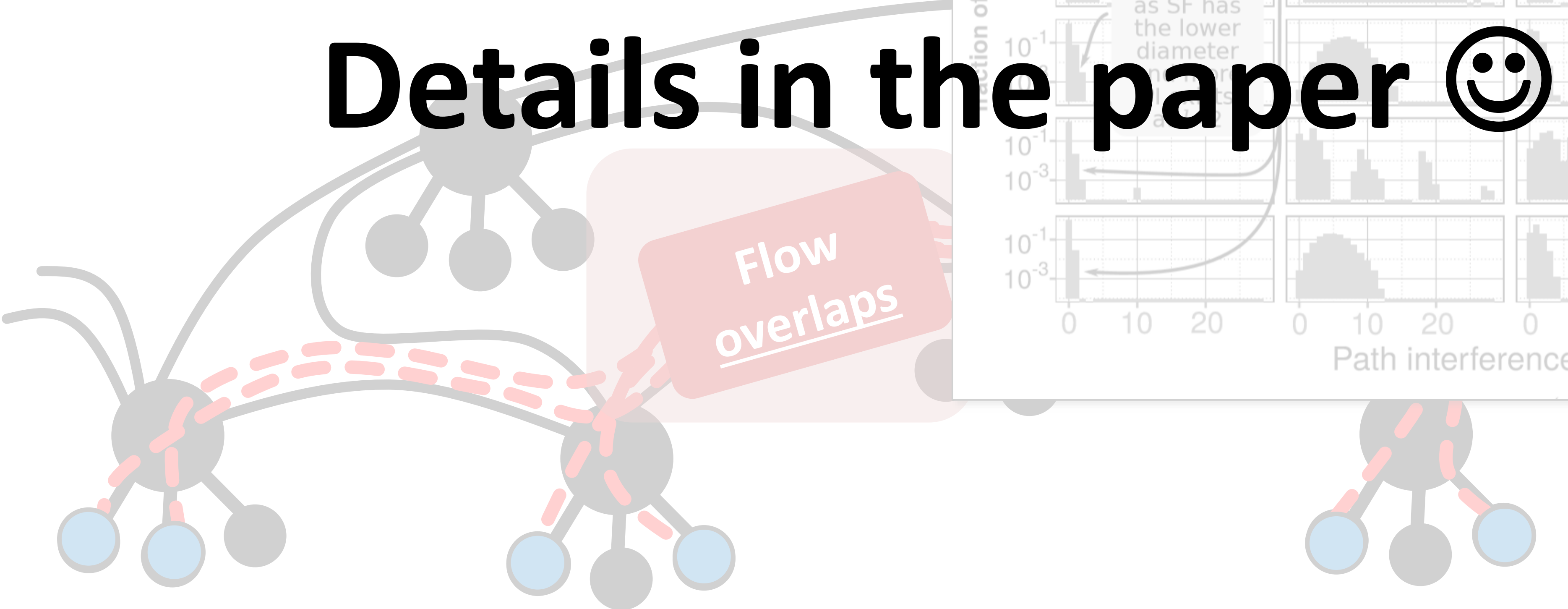

Details in the paper ☺

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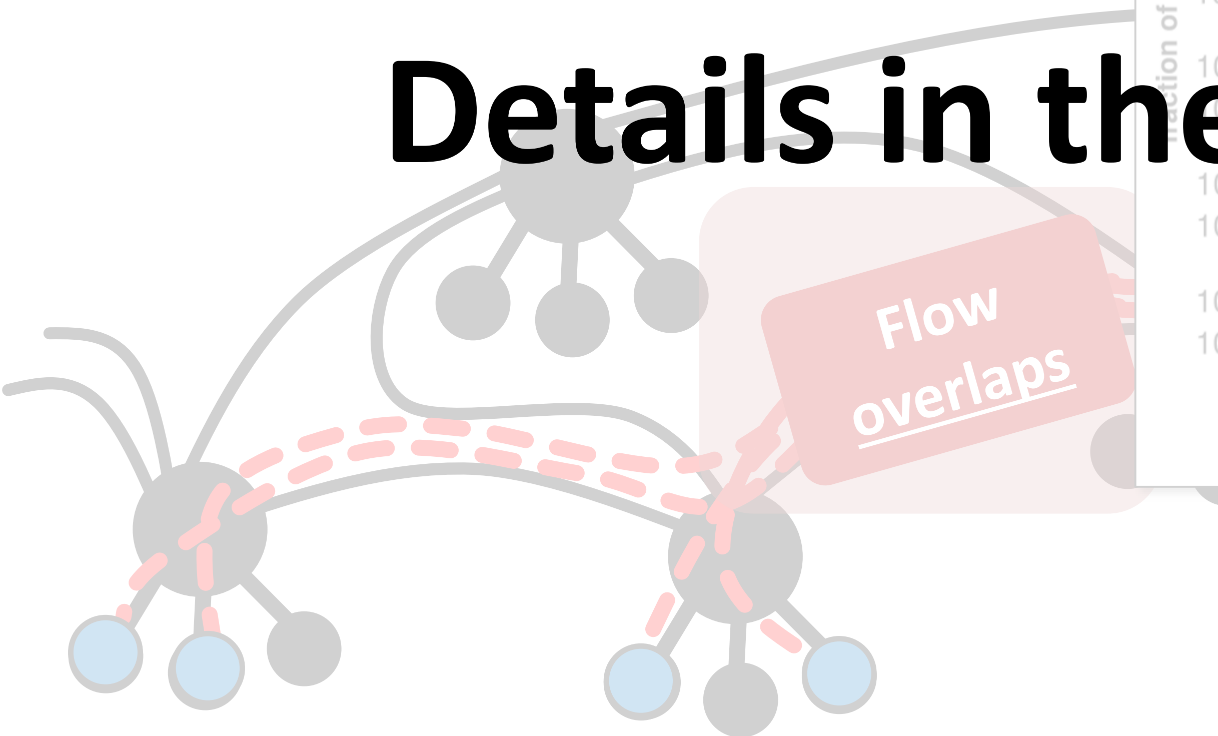

Details in the paper ☺

Let's sum up…

FatPaths architecture: which technology?

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InfiniBand

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Myrinet

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InfiniBand

Myrinet

Ethernet

FatPaths architecture: which technology?

InfiniBand

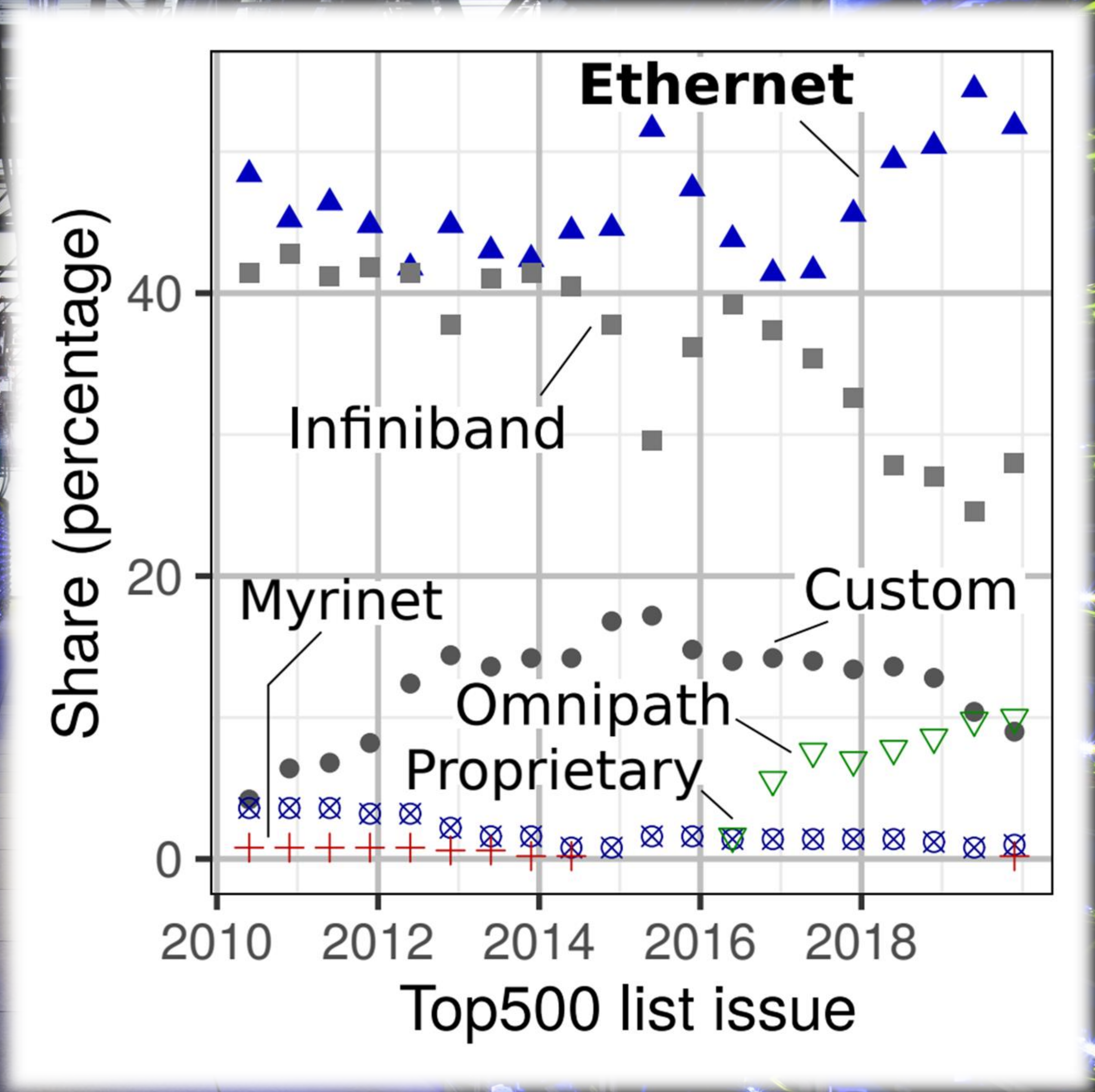
Others

Ethernet

Myrinet

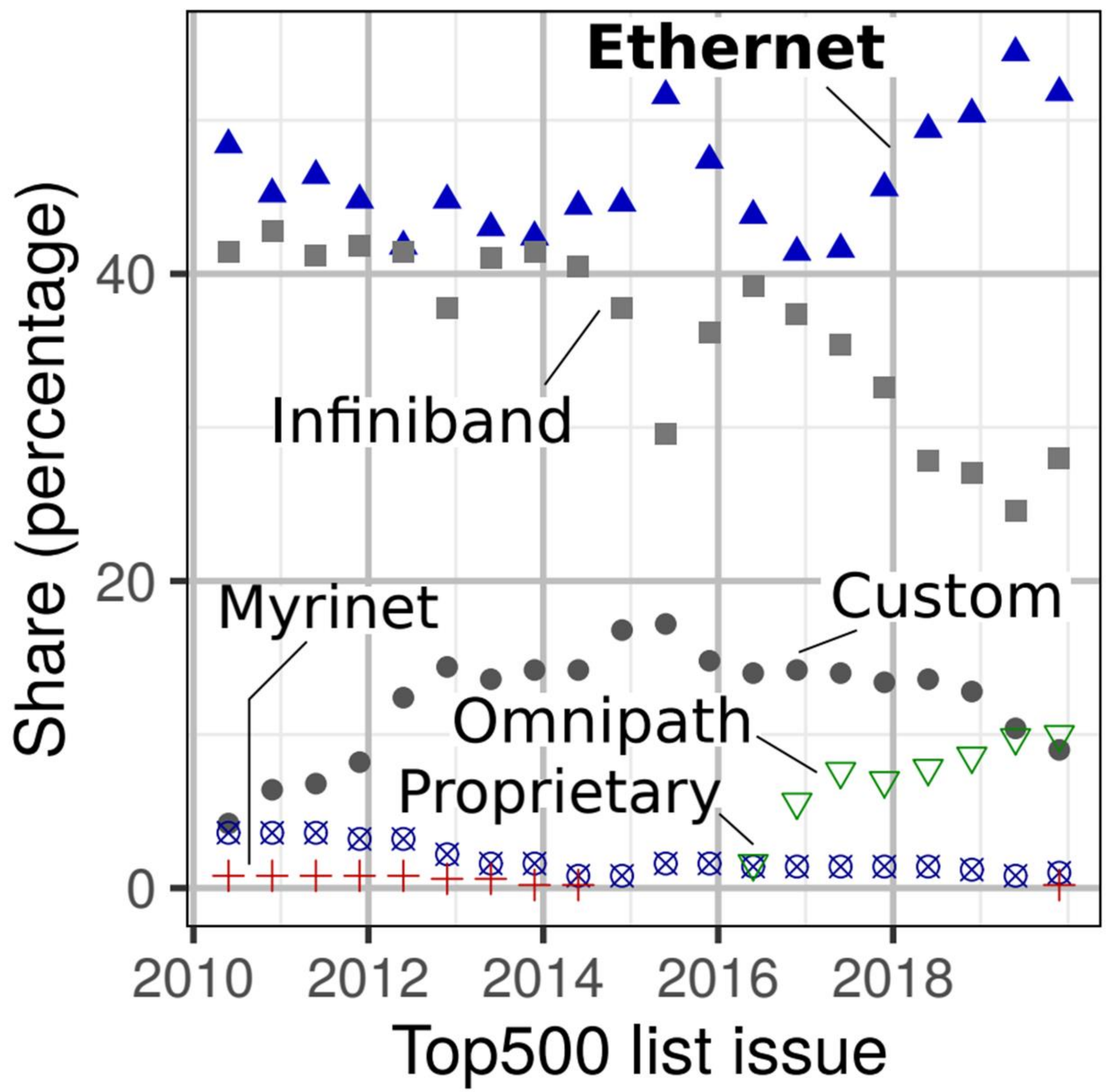
Ethernet & HPC

ETHERNET & HPC



Ethernet & HPC

More than 50% of systems in Top500 use Ethernet



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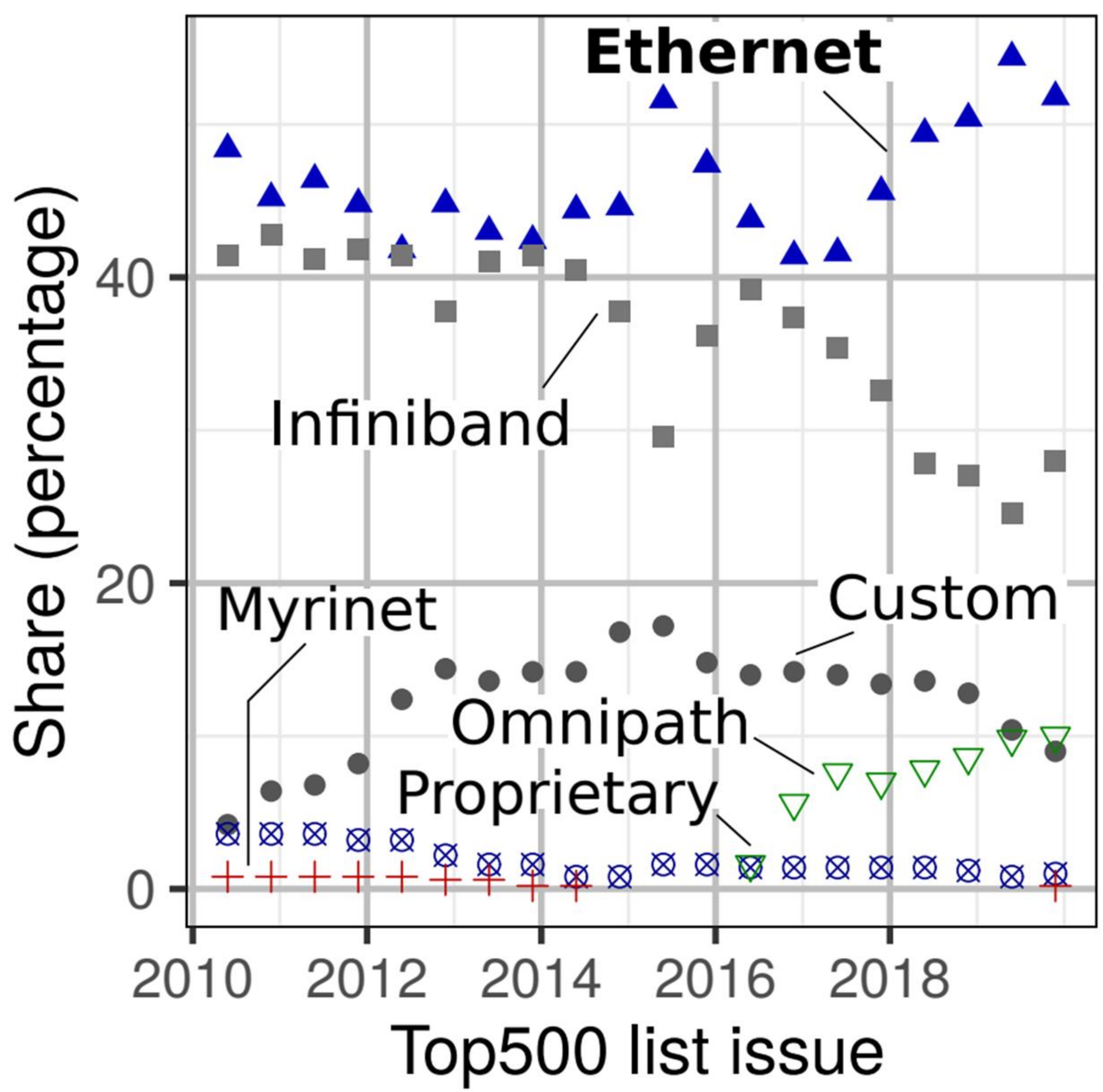

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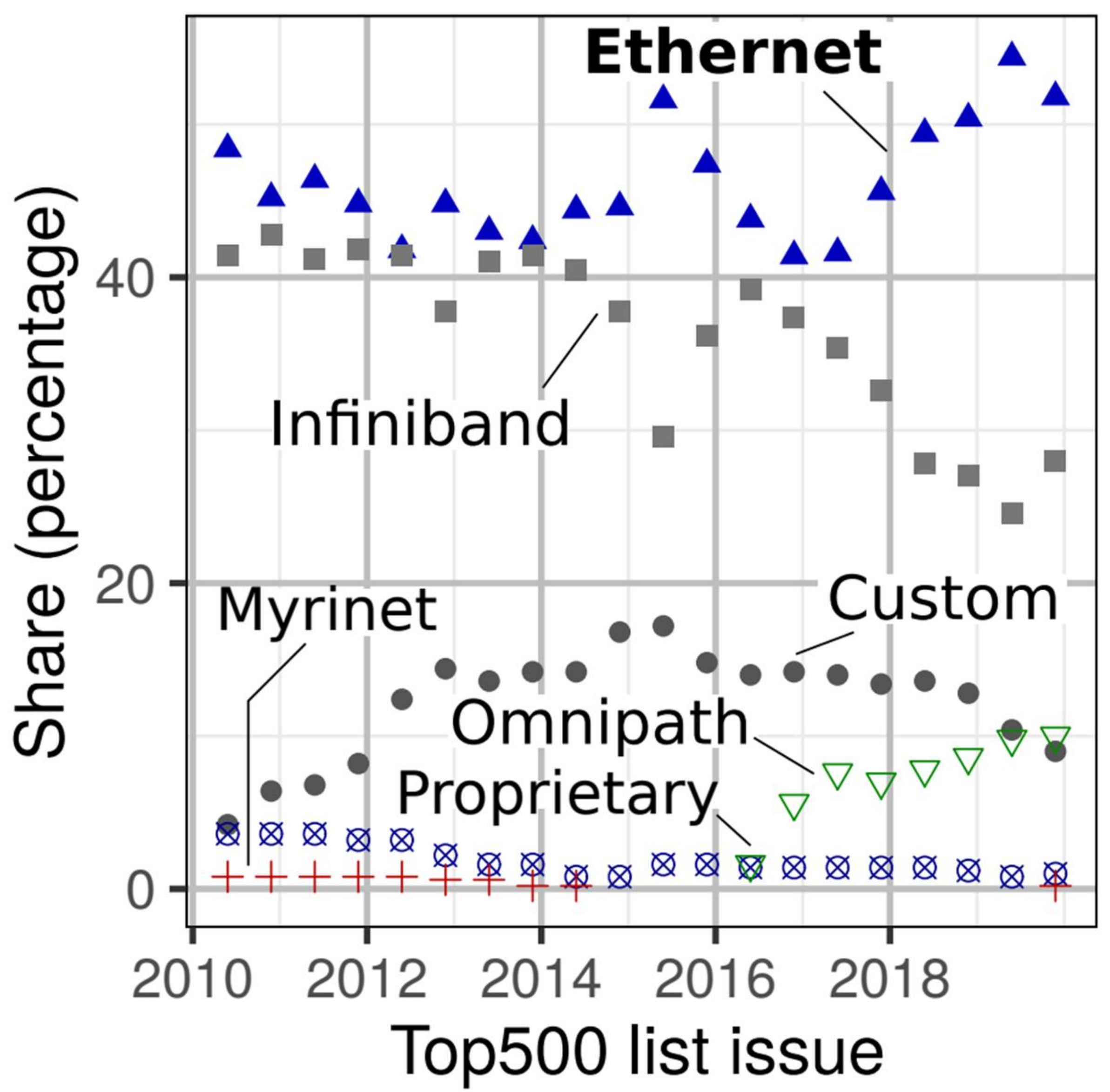

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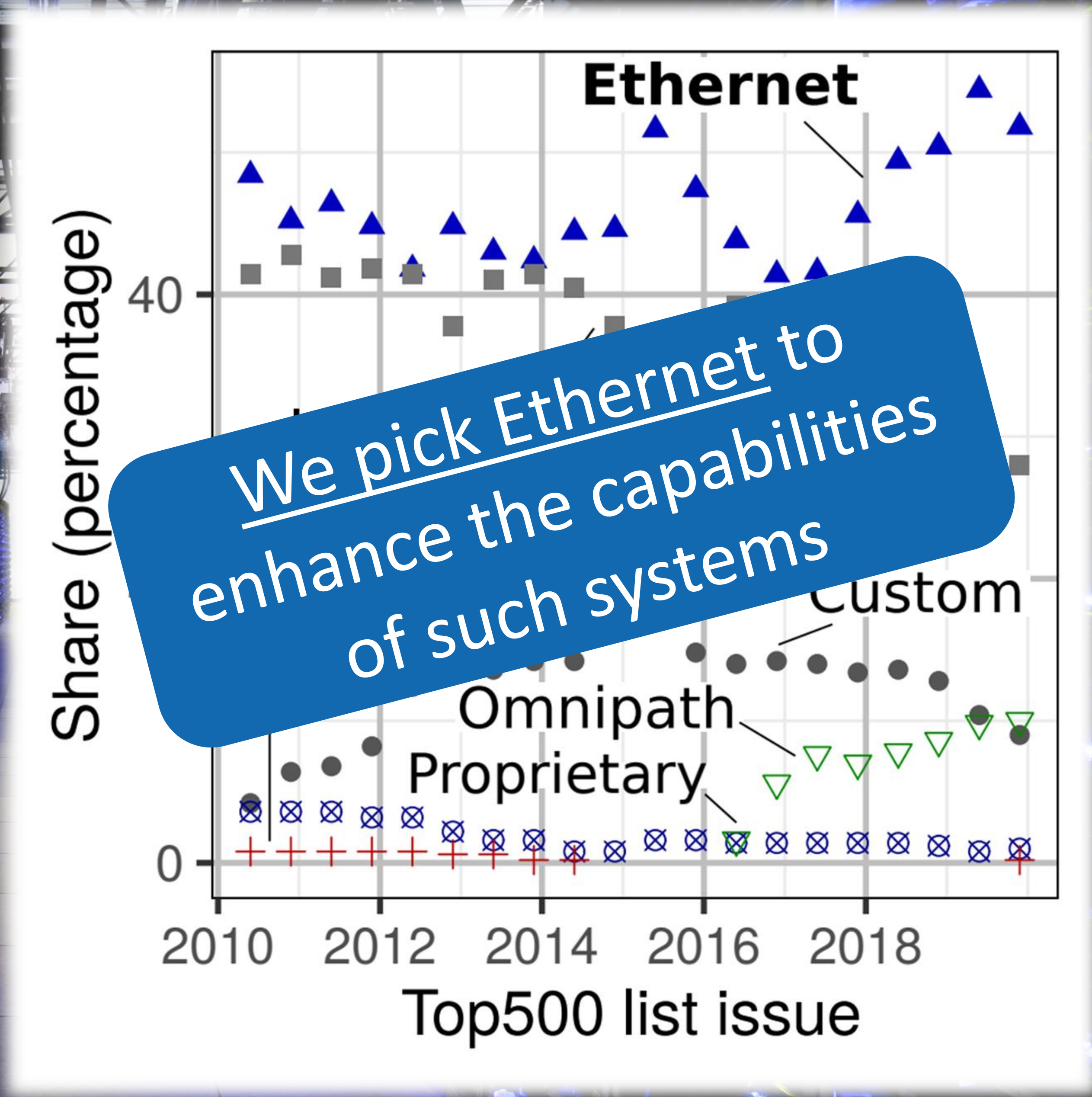

We pick Ethernet to enhance the capabilities of such systems

Ethernet & HPC

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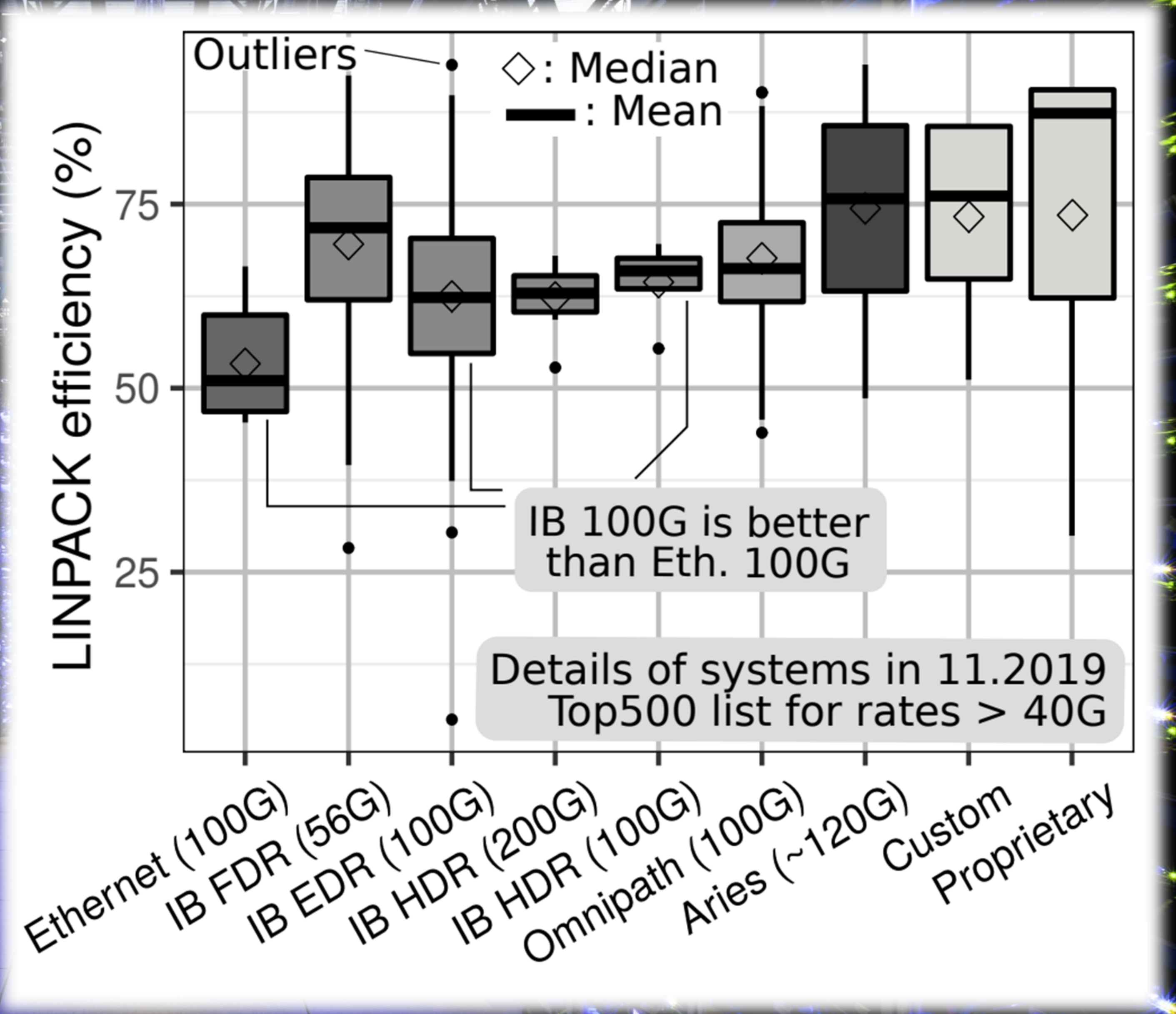

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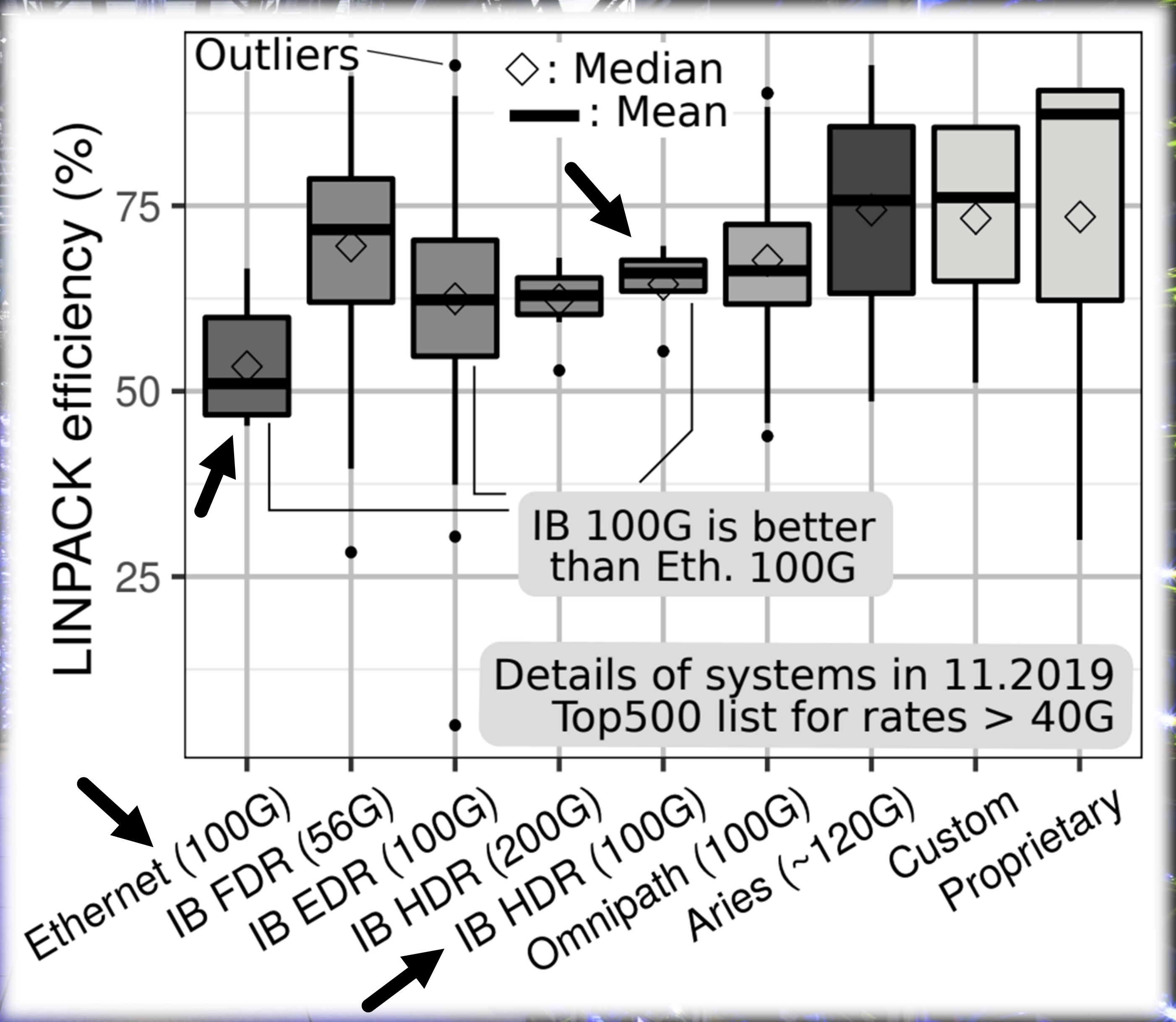

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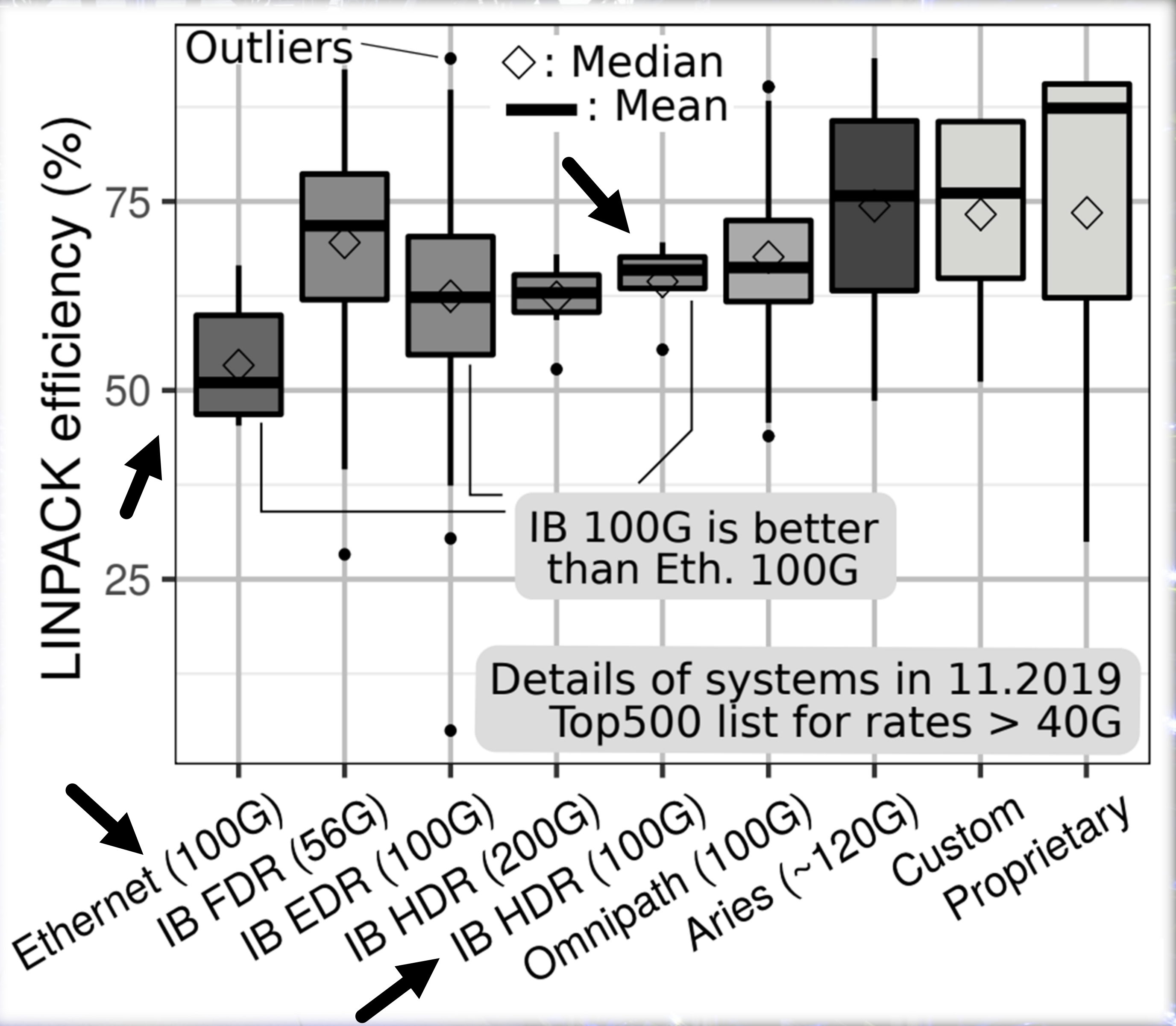

Transport Design

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How to maximize performance of the transport layer?

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Adapt recent flow control for fat trees [1]

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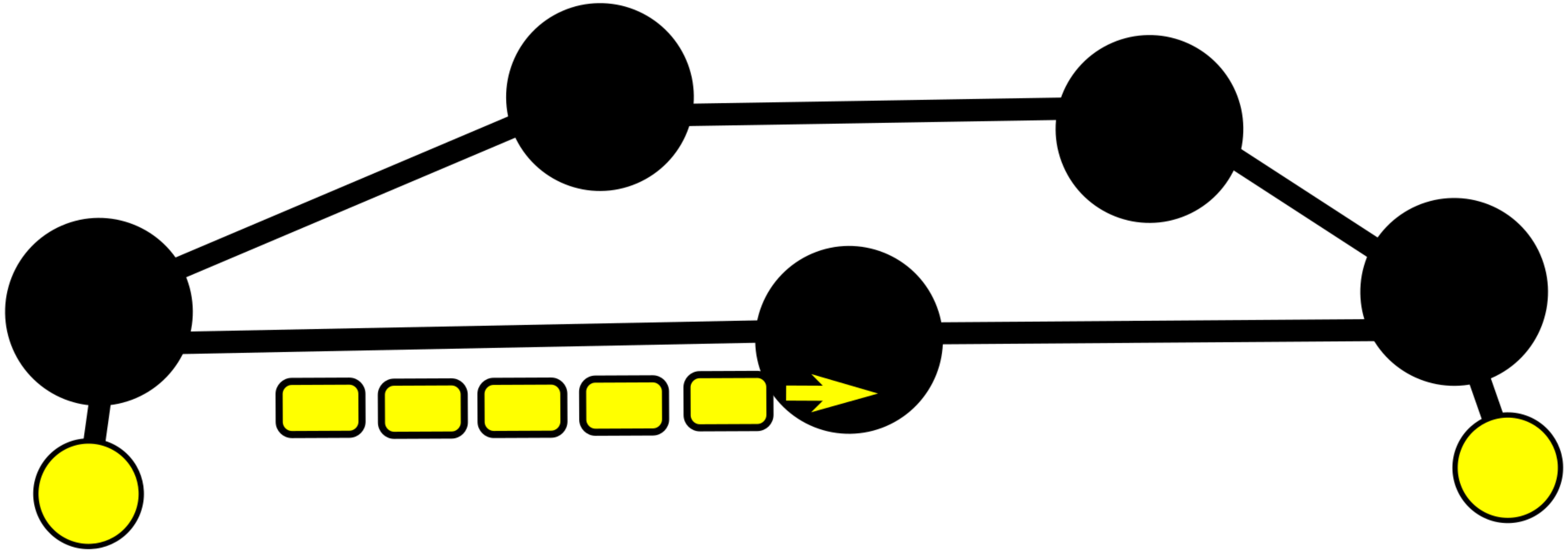

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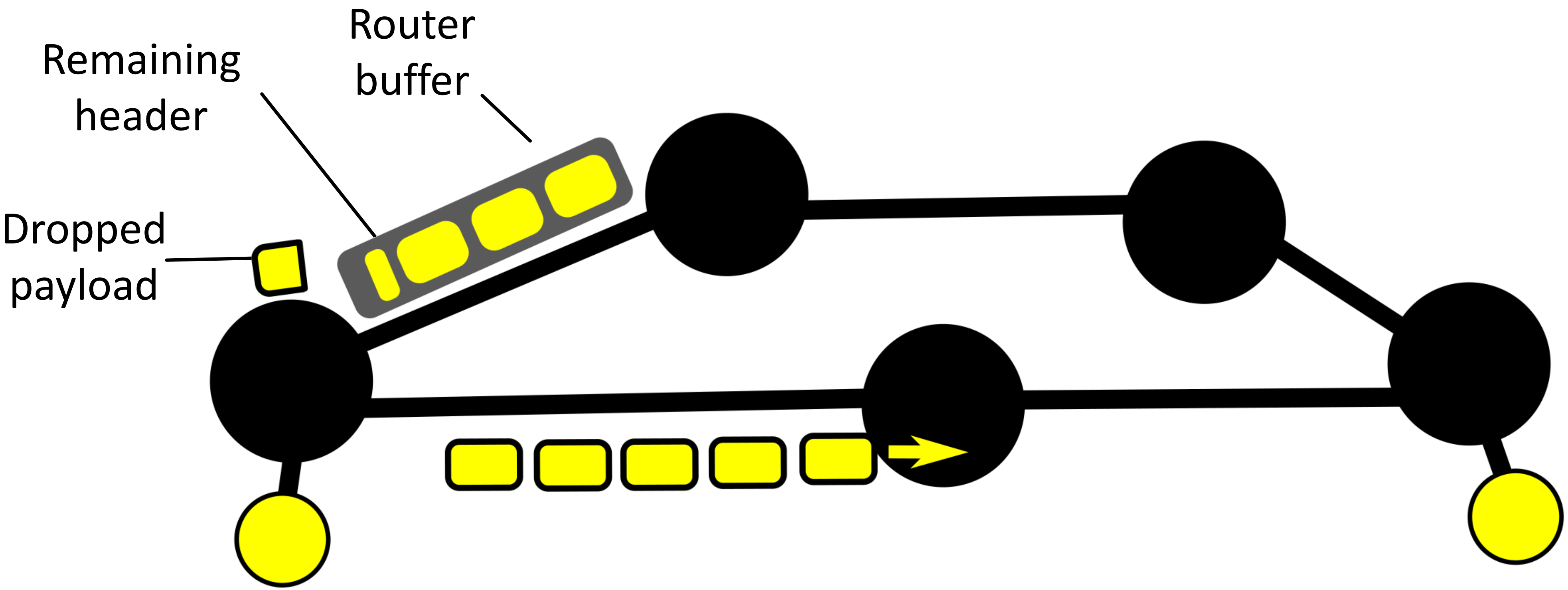

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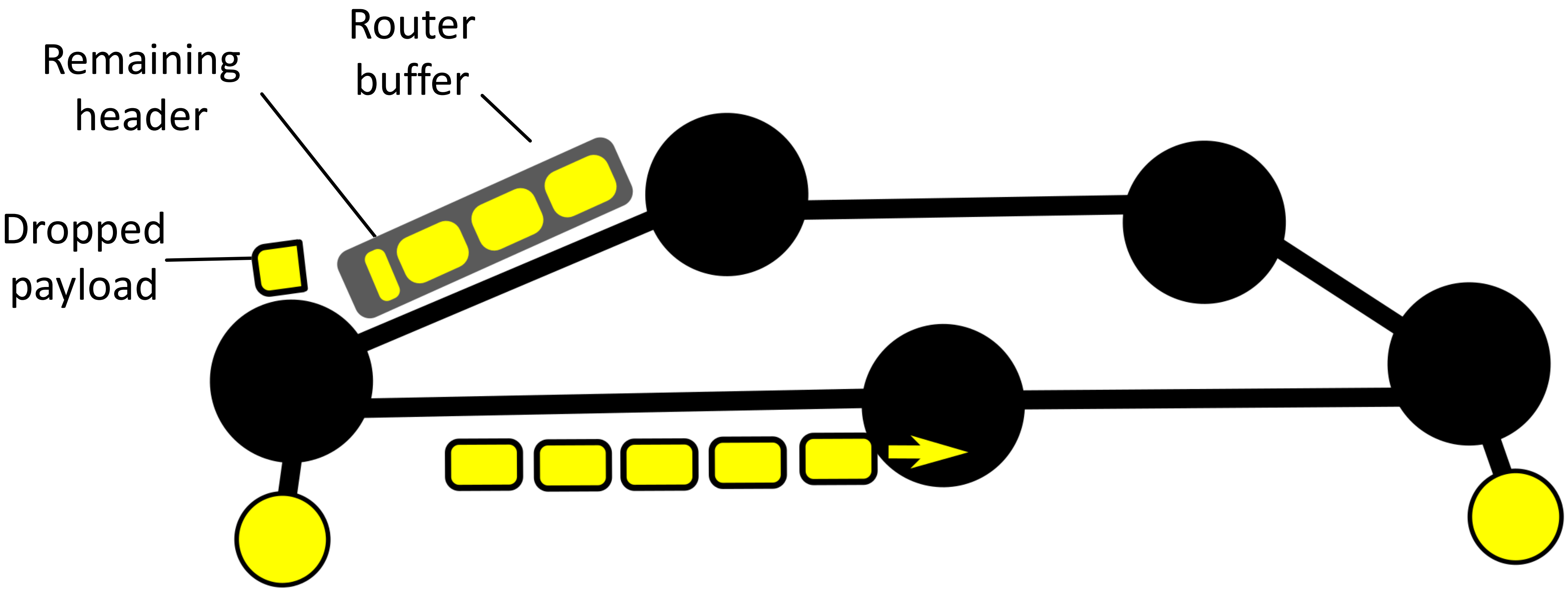

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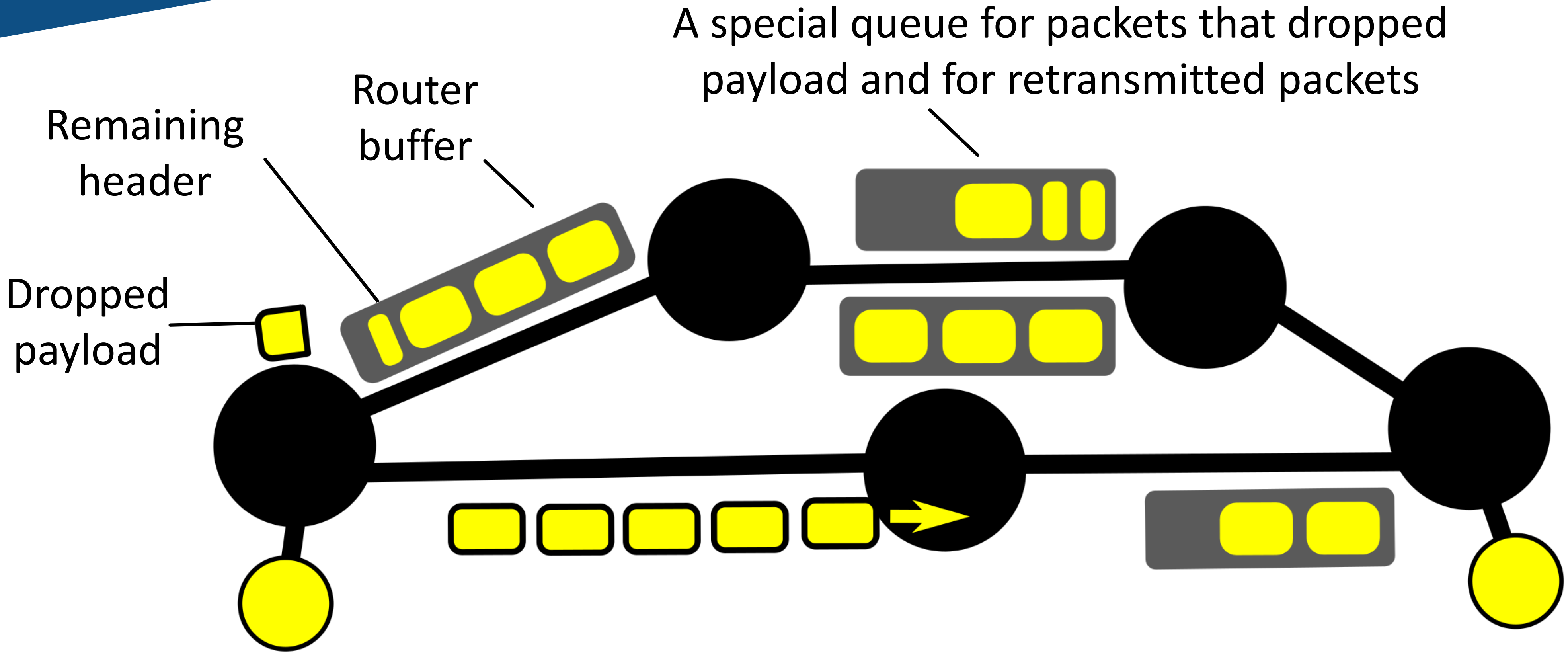

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N ≈ 10,000; comparable cost; random uniform traffic; “bare Ethernet” setting

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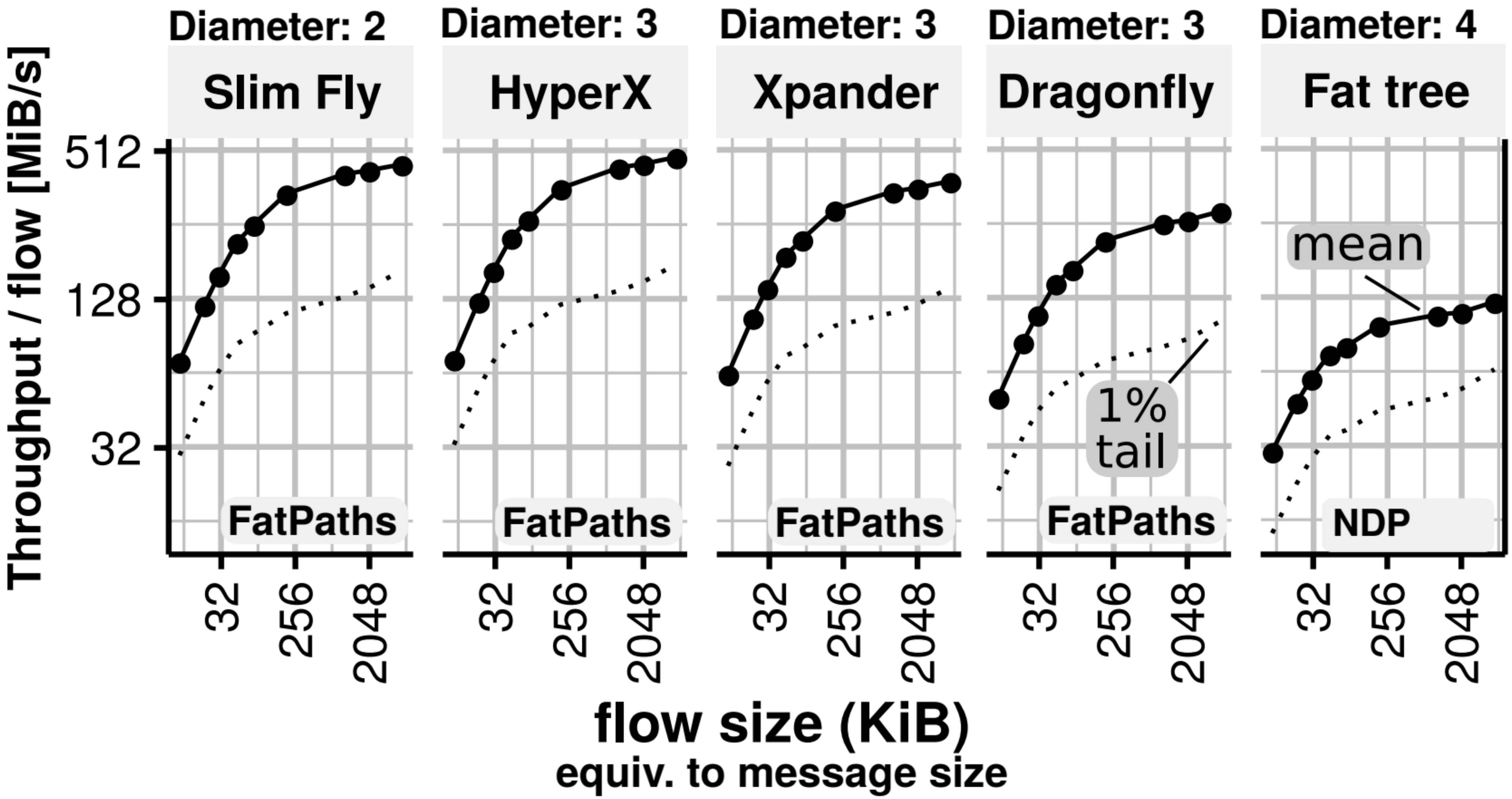
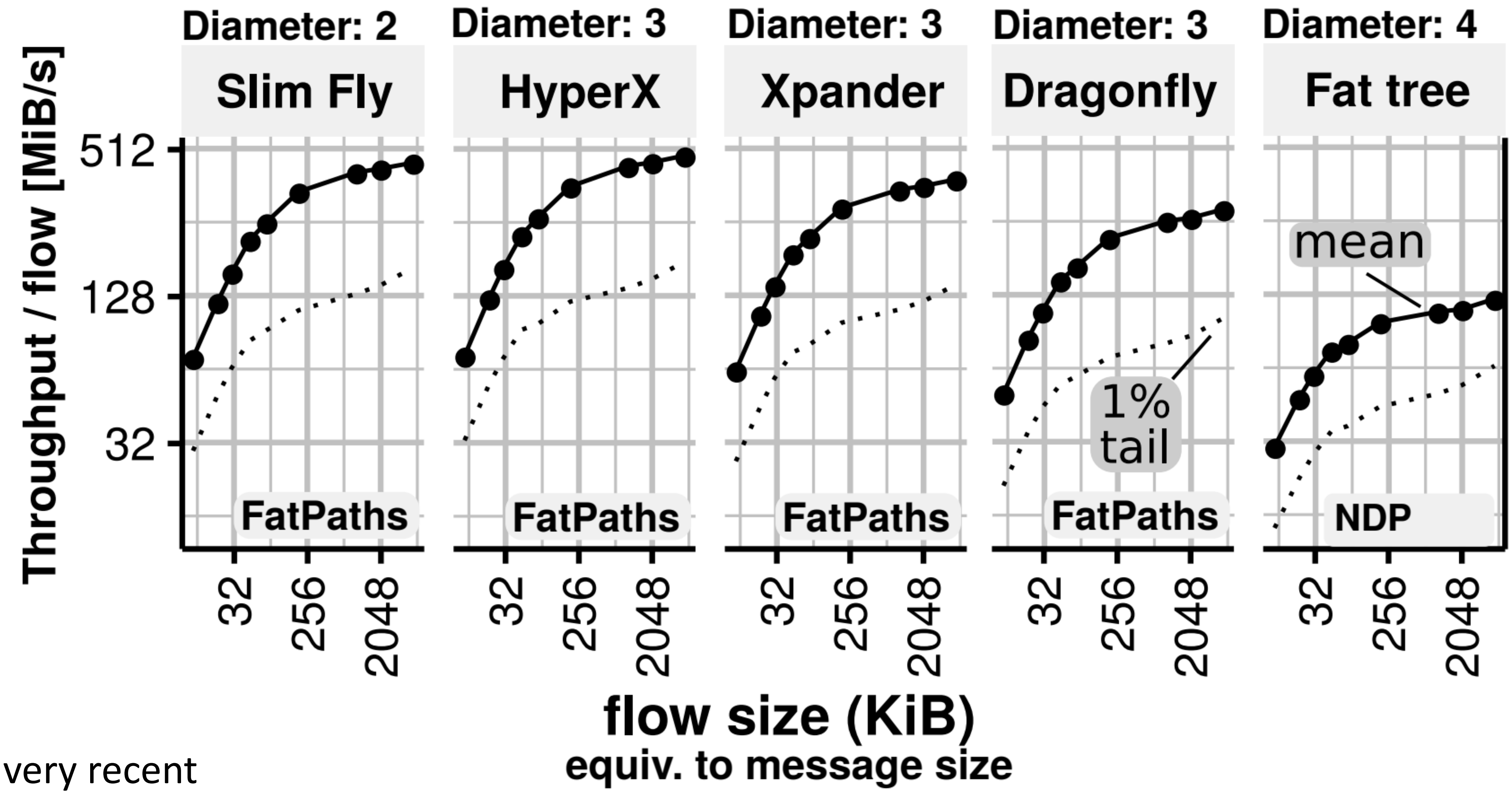


Evaluation

N ≈ 10,000; comparable cost; random uniform traffic; “bare Ethernet” setting



NDP: a very recent baseline for fat trees

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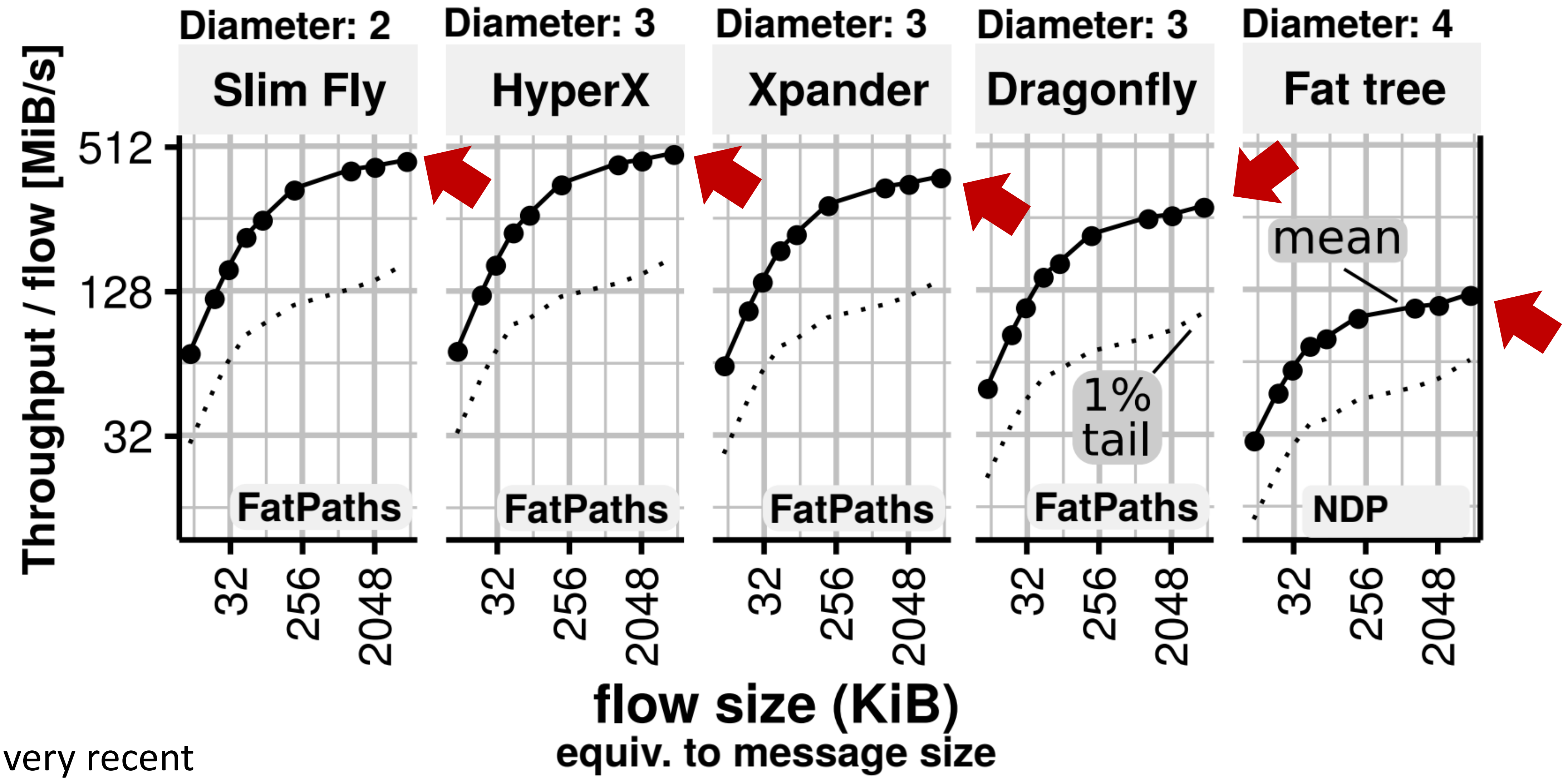

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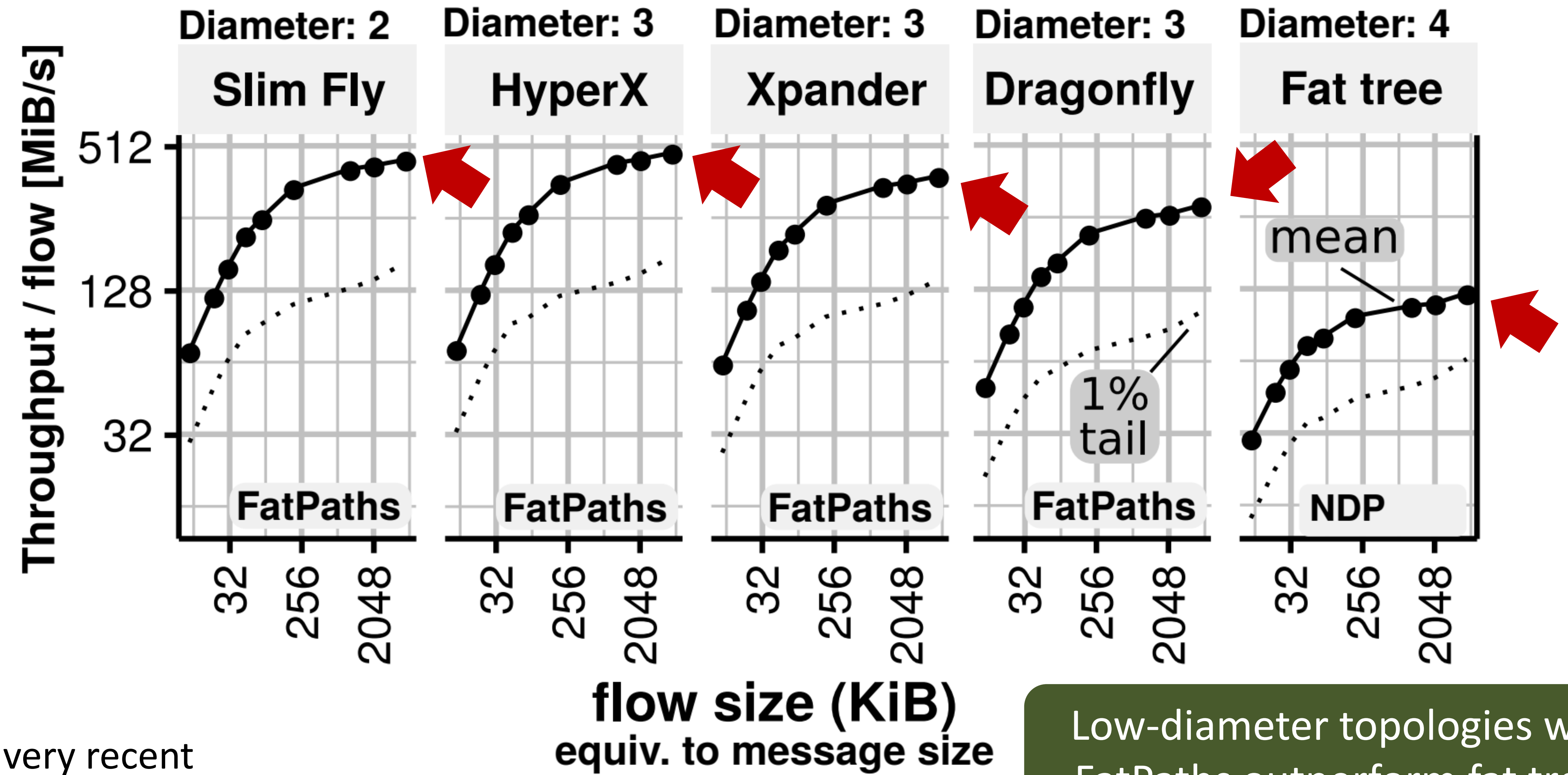

NDP: a very recent baseline for fat trees

Low-diameter topologies with FatPaths outperform fat trees

EVALUATION

N ≈ 10,000; comparable cost; random uniform traffic; "full TCP" setting

Diameter: 3	Diameter: 4	Diameter: 3	Diameter: 3	Diameter: 2	Diameter: 3
Dragonfly	**Fat tree**	**HyperX**	**Jellyfish**	**Slim Fly**	**Xpander**

ECMP: traditional static load balancing
LetFlow: recent adaptive load balancing

Speedups are measured over ECMP
rho: fraction of links kept in a layer

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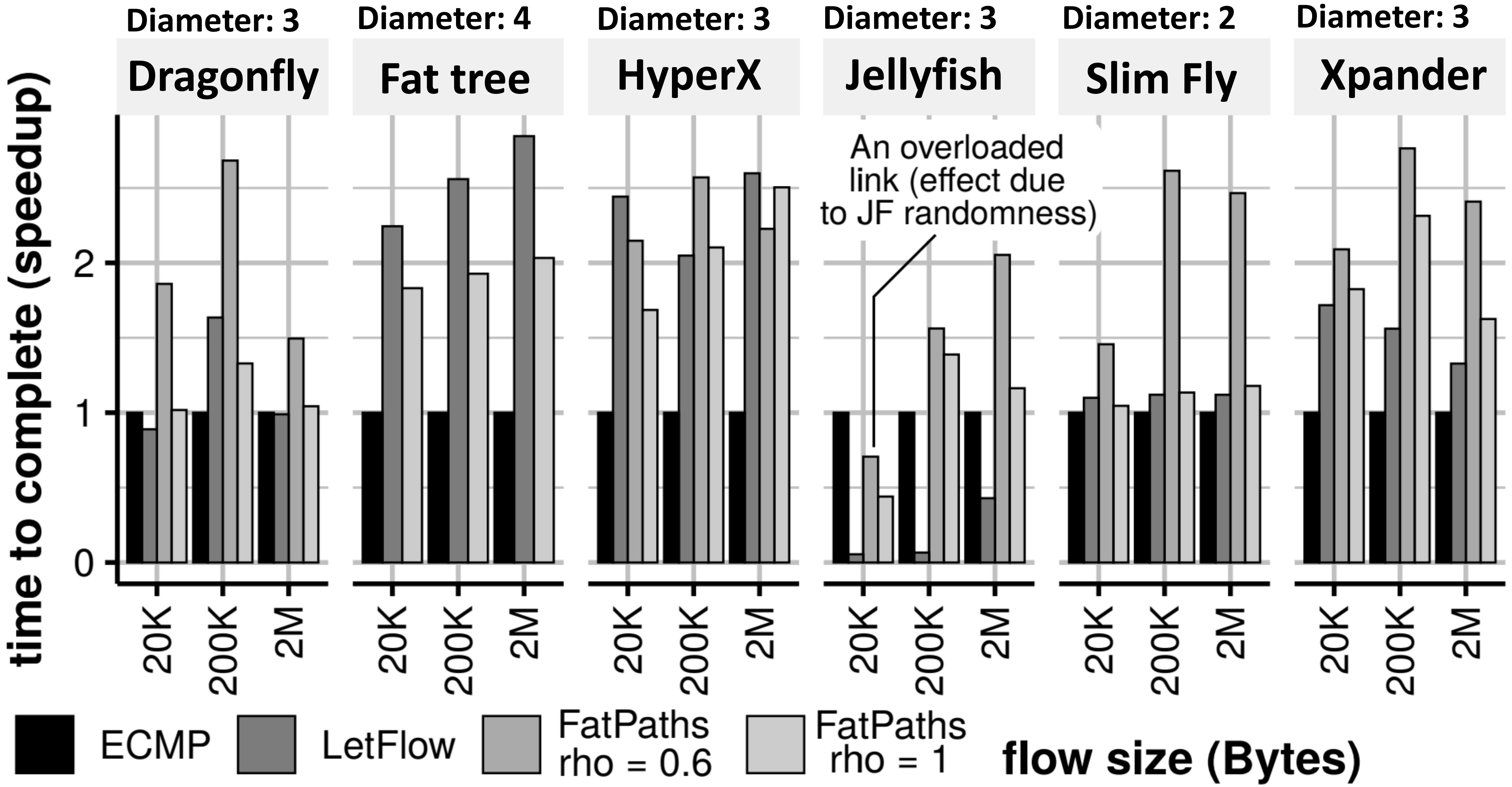
N ≈ 10,000; comparable cost; random uniform traffic; "full TCP" setting



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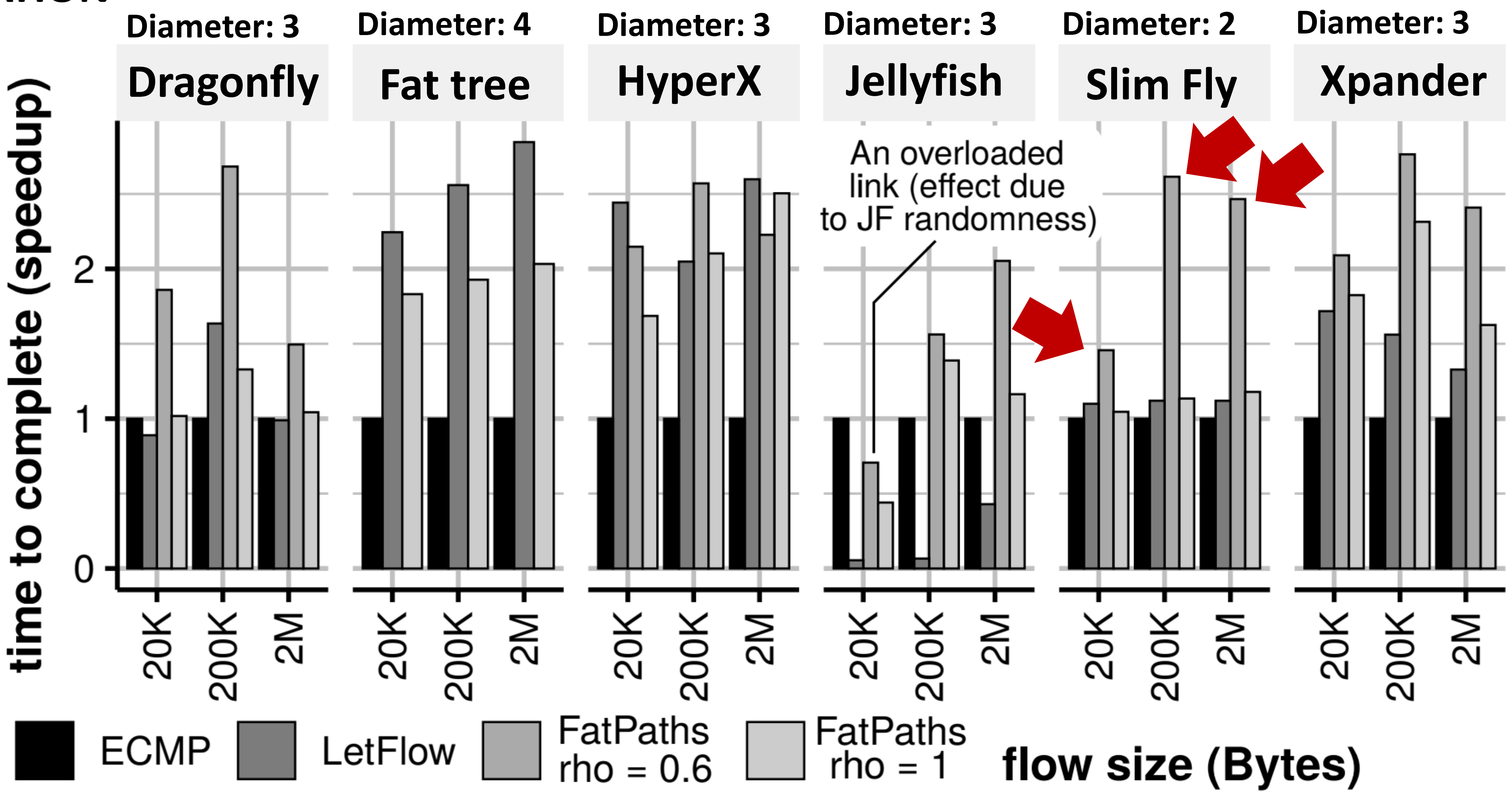

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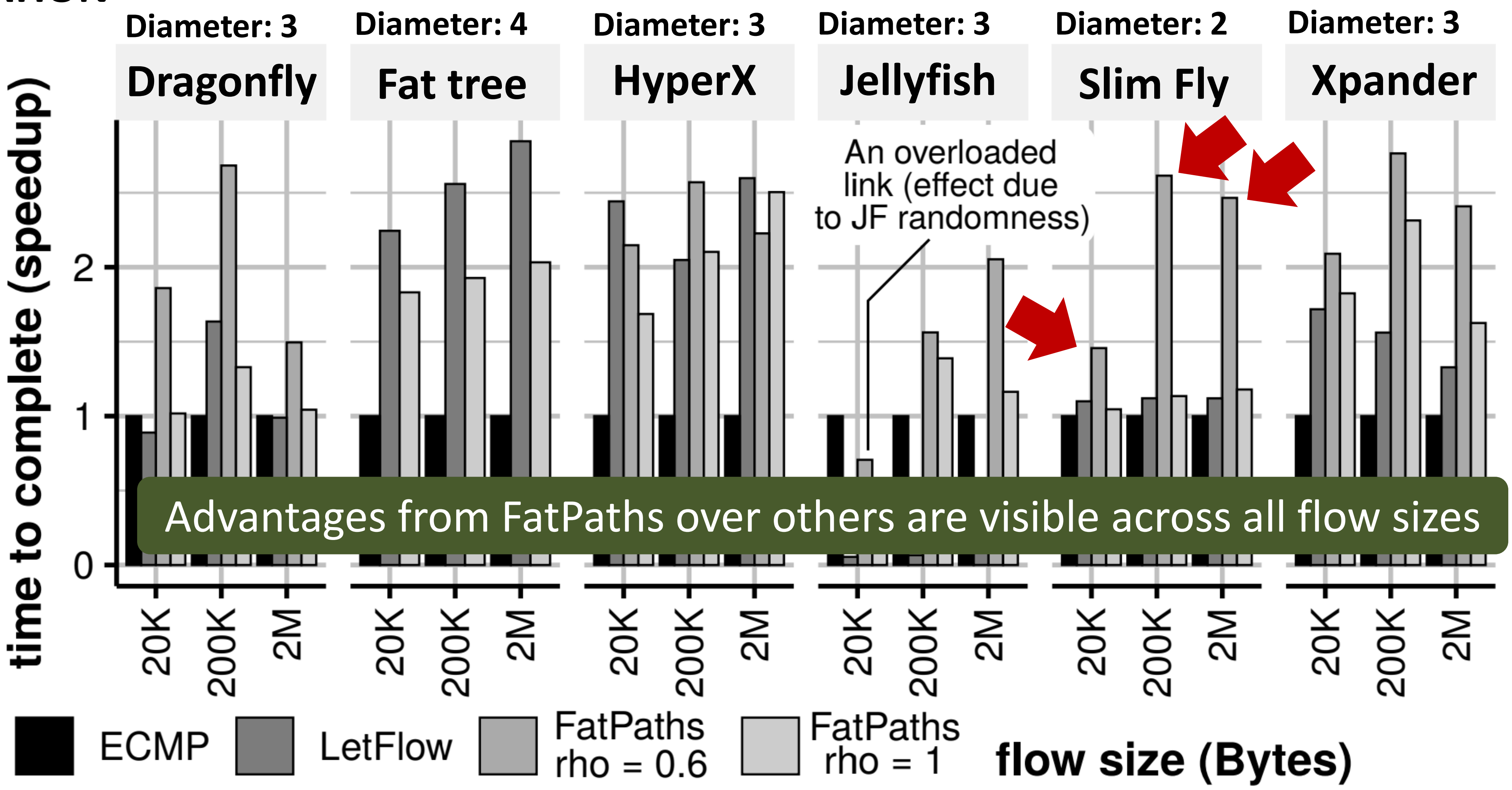

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Survey of routing protocols

Survey of routing protocols

Focus: path diversity in routing

SURVEY OF ROUTING PROTOCOLS

Focus: path diversity in routing

Routing Scheme (Name, Abbreviation, Reference)	Stack Layer	Supported path diversity aspect						
		SP	NP	SM	MP	DP	ALB	AT
(1) SIMPLE ROUTING PROTOCOLS (often used as building blocks):								
Valiant load balancing (VLB) [17]	L2–L3	👎	👍	👎	👎	👎	👎	👍
Simple Spanning Tree (ST) [18]	L2	👎^{S}	👎^{S}	👎	👎	👎	👎	👍
Simple routing, e.g., OSPF [19]–[22]	L2, L3	👍	👎	👎	👎	👎	👎	👍
UGAL [23]	L2–L3	👍	👍	👎	👎	👎	👍	👍
ECMP [11], OMP [24], Pkt. Spraying [25]	L2, L3	👍	👎	👎	👍	👎	👎	👍
(2) ROUTING ARCHITECTURES:								
DCell [26]	L2–L3	👎	👍	👎	👎	👎	👎	👎
Monsoon [27]	L2, L3	🖒	🖒	👎	🖒	👎	👎	👎
PortLand [9]	L2	👍	👎	👎	👍	👎	👎	👎
DRILL [28], LocalFlow [29], DRB [30]	L2	👍	👎	👎	👍	👎	👍	👎
VL2 [31]	L3	👍	👎	👎	👍	👎	🖒	👎
Architecture by Al-Fares et al. [32]	L2–L3	👍	👎	👎	👍	👍	👍	👎
BCube [33]	L2–L3	👍	👎	👎	👍	👍	👎	👎
SEATTLE [34], others* [35]–[38]	L2	👍	👎	👎	👎	👎	👎	👍
VIRO [39]	L2–L3	👎^{S}	👎^{S}	👎	👎	👎	👎	👍
Ethernet on Air [40]	L2	👎^{S}	👎^{S}	👎	🖒^{R}	👎	👎	👍
PAST [41]	L2	🖒^{S}	🖒^{S}	👎	👎	👍	👎	👍
MLAG, MC-LAG, others [42]	L2	🖒	🖒	👎	🖒^{R}	👎	👎	👍
MOOSE [43]	L2	👍	👎	👎	🖒	👎	👎	👍
MPA [44]	L3	👍	👍	👎	👍	👎	👎	👍
AMP [45]	L3	👍	👎	👎	👍	👎	👍	👍
MSTP [46], GOE [47], Viking [48]	L2	👎^{S}	👎^{S}	👎	👍	👎	👎	👍
SPB [49], TRILL [50], Shadow MACs [51]	L2	👍	👎^{R}	👎	👍	👎	👎	👍
SPAIN [52]	L2	🖒^{S}	🖒^{S}	🖒^{S}	👍	👍	👎	👍
(3) Schemes for exposing/encoding paths (can be combined with FatPaths):								
XPath [53]	L3	👍	🖒	🖒	👍	👍	🖒	👍
Source routing for flexible DC fabric [54]	L3	👍	🖒^{R}	🖒^{R}	👎	👎	👎	🖒†
(3) FatPaths [This work]	L2–L3	👍	👍	👍	👍	👍	👍	👍

Survey of routing protocols

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(1) Taxonomy of „path diversity support” in routing

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PortLand [9]	L2	👍	👎	👎	👍	👎	👎	👎
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VIRO [39]	L2–L3	👎^{S}	👎^{S}	👎	👎	👎	👎	👍
Ethernet on Air [40]	L2	👎^{S}	👎^{S}	👎	◐^{R}	👎	👎	👍
PAST [41]	L2	◐^{S}	◐^{S}	👎	👎	👍	👎	👍
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MPA [44]	L3	👍	👍	👎	👍	👎	👎	👍
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(3) FatPaths [This work]	L2–L3	👍	👍	👍	👍	👍	👍	👍

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AMP [45]	L3	👍	👎	👎	👍	👎	👍	👍
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VIRO [39]	L2–L3	👎^{S}	👎^{S}	👎	👎	👎	👎	👍
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PAST [41]	L2	(👍)^{S}	(👍)^{S}	👎	👎	👍	👎	👍
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AMP [45]	L3	👍	👎	👎	👍	👎	👍	👍
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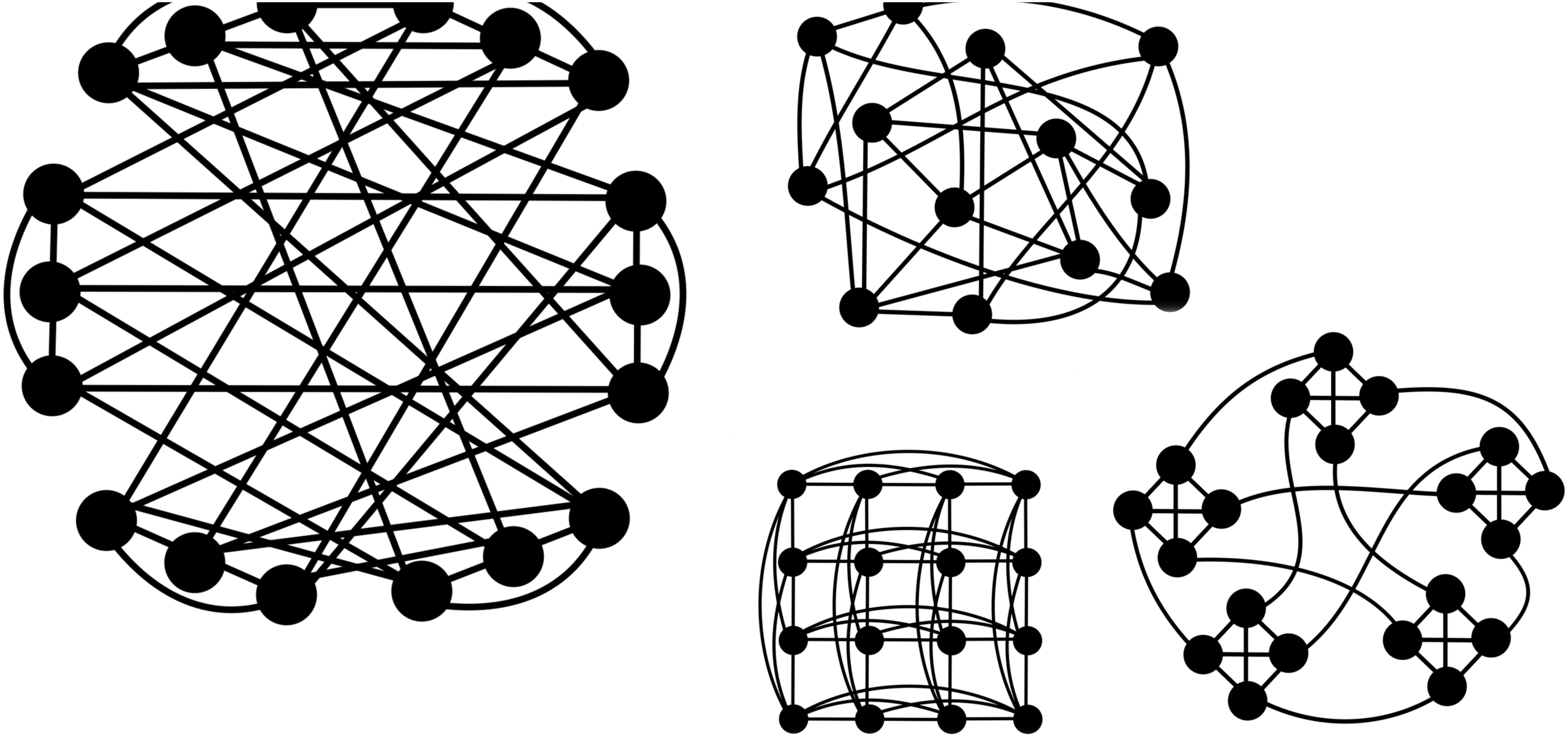
SPB [49], TRILL [50], Shadow MACs [51]	L2	👍	👎^{R}	👎	👍	👎	👎	👍
SPAIN [52]	L2	(👍)^{S}	(👍)^{S}	(👍)^{S}	👍	👍	👎	👍
(3) Schemes for exposing/encoding paths (can be combined with FatPaths):								
XPath [53]	L3	👍	(👍)	(👍)	👍	👍	(👍)	👍
Source routing for flexible DC fabric [54]	L3	👍	(👍)^{R}	(👍)^{R}	👎	👎	👎	(👍)†
(3) FatPaths [This work]	L2–L3	👍	👍	👍	👍	👍	👍	👍

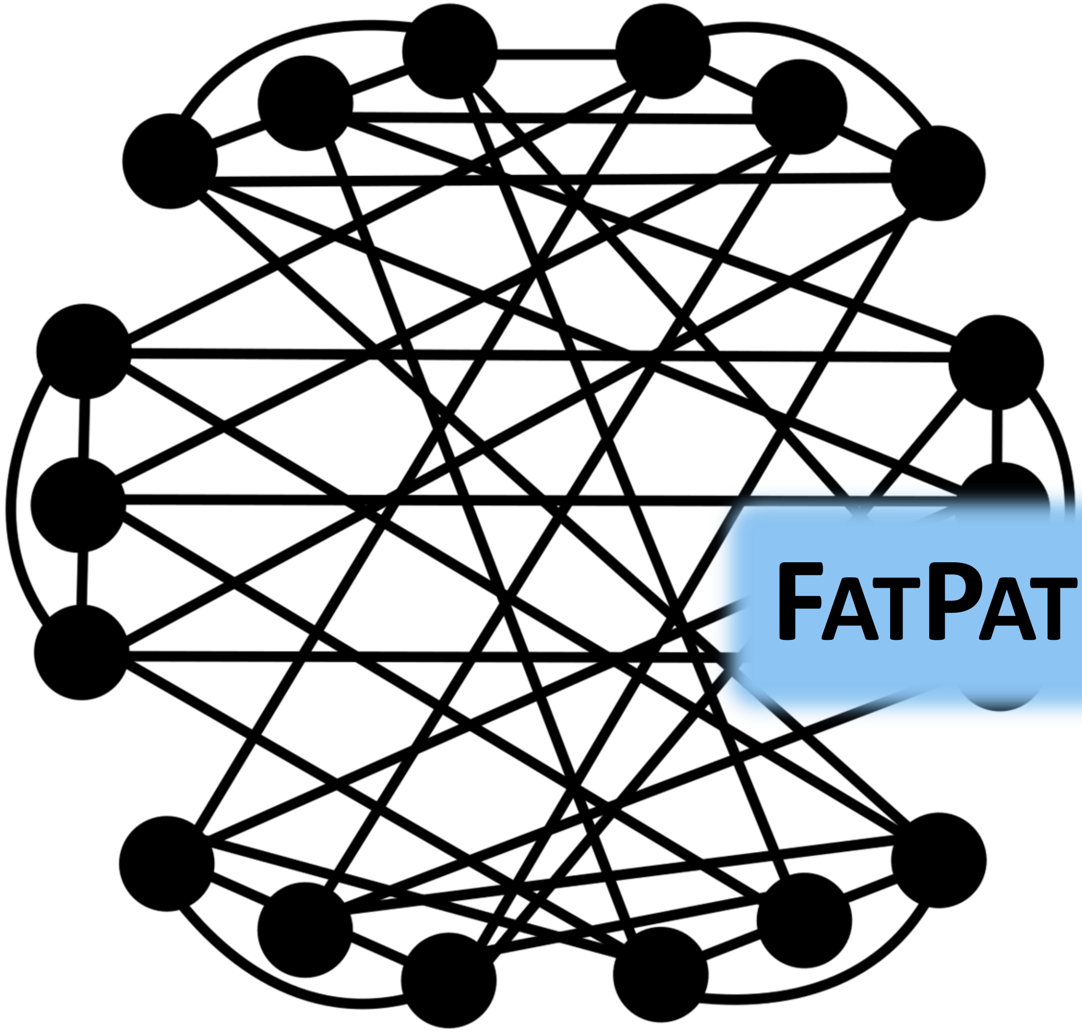
1

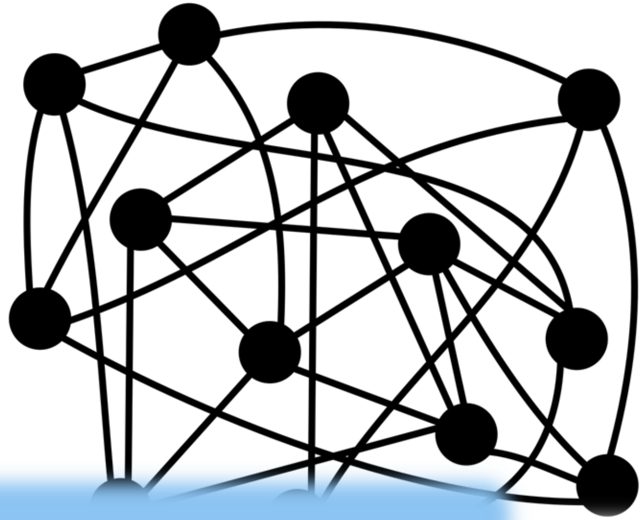
High-Performance Routing with Multipathing and Path Diversity in Supercomputers and Data Centers

Maciej Besta[1], Jens Domke[2], Marcel Schneider[1], Marek Konieczny[3], Salvatore Di Girolamo[1], Timo Schneider[1], Ankit Singla[1], Torsten Hoefler[1]

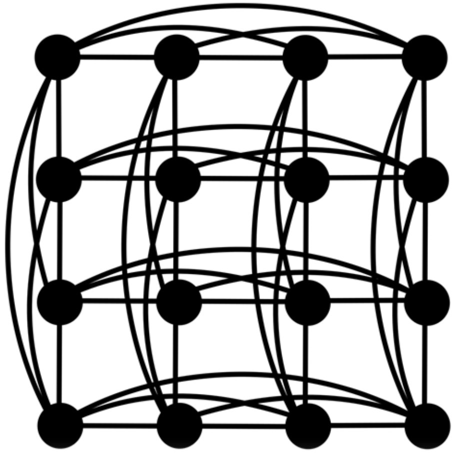
[1]Department of Computer Science, ETH Zurich; [2]RIKEN Center for Computational Science (R-CCS)
[3]Department of Computer Science, Electronics and Telecommunications; AGH-UST

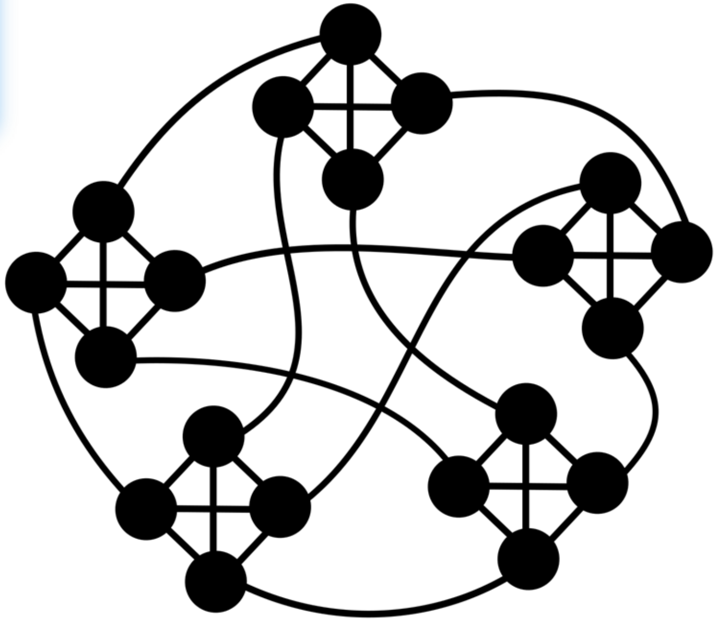




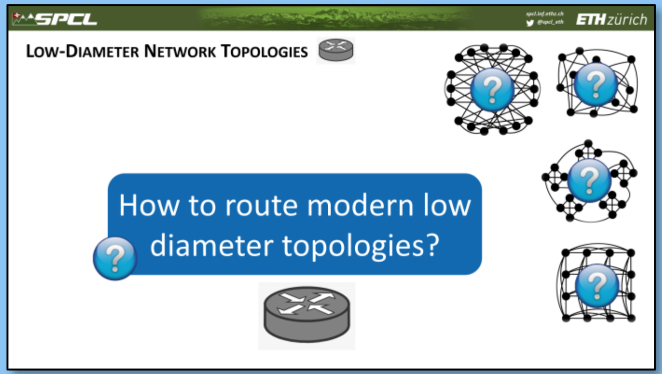


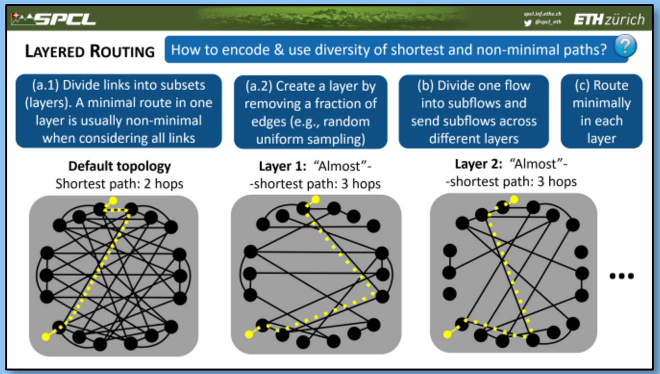
FatPaths Overview

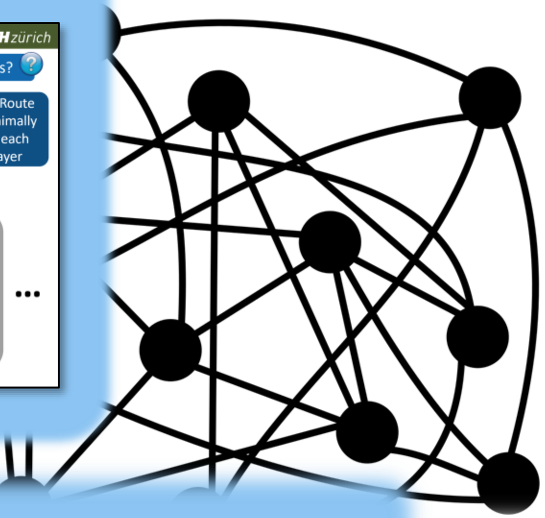


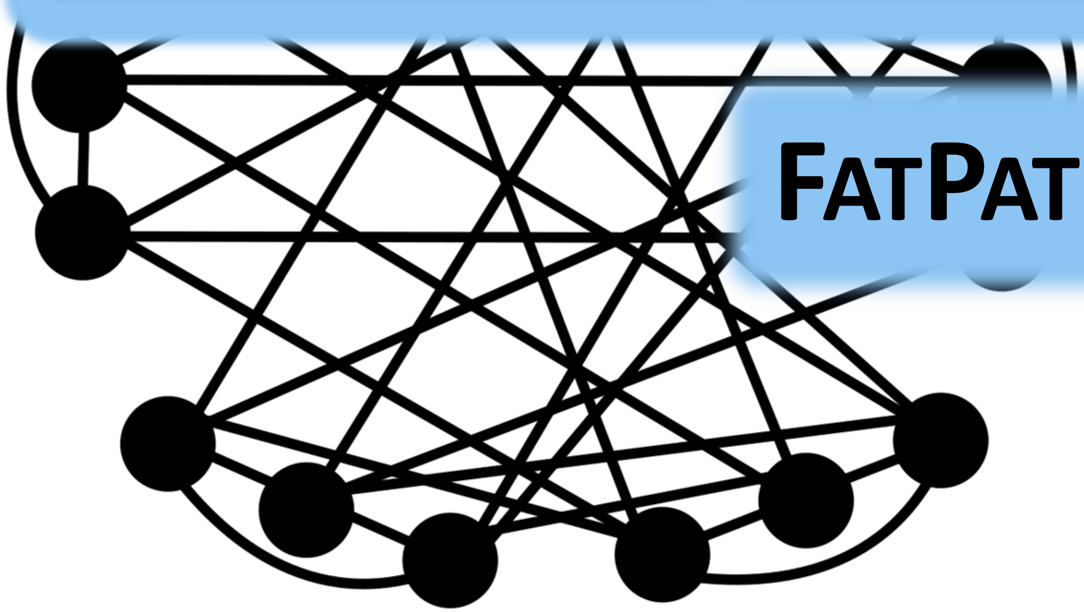


A ROUTING SCHEME FOCUSING ON LOW-DIAMETER TOPOLOGIES

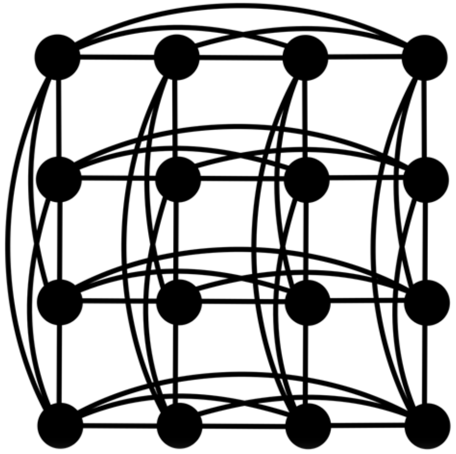


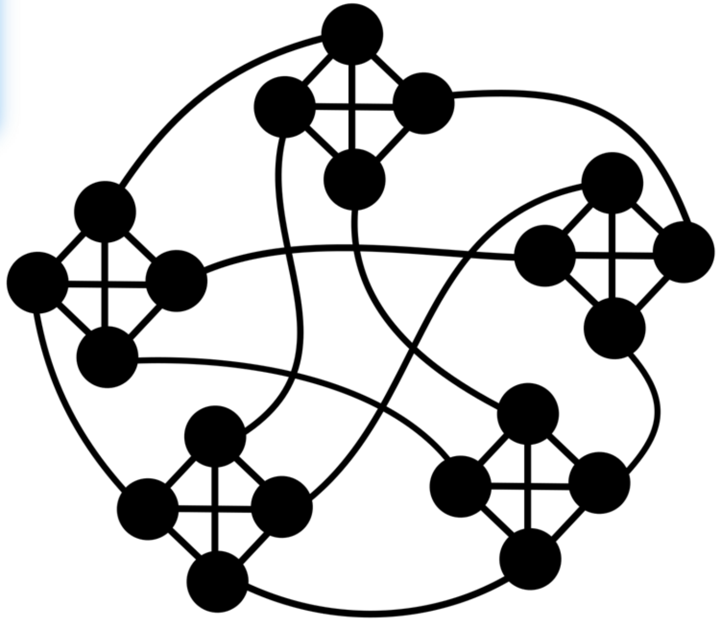




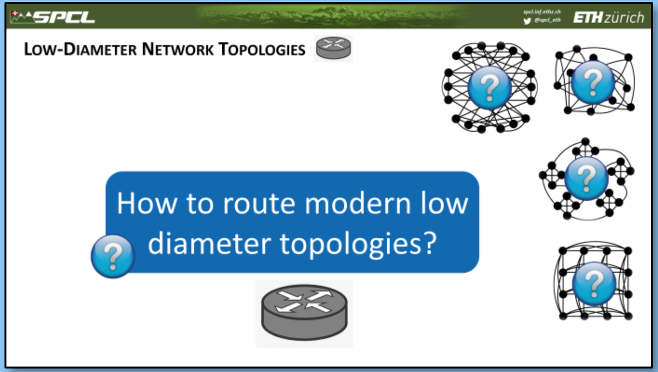


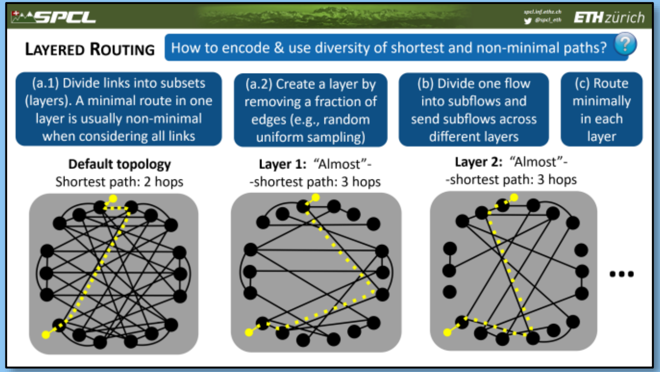
FatPaths Overview



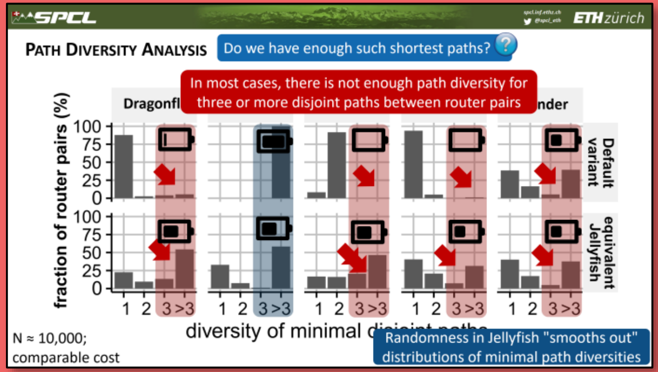


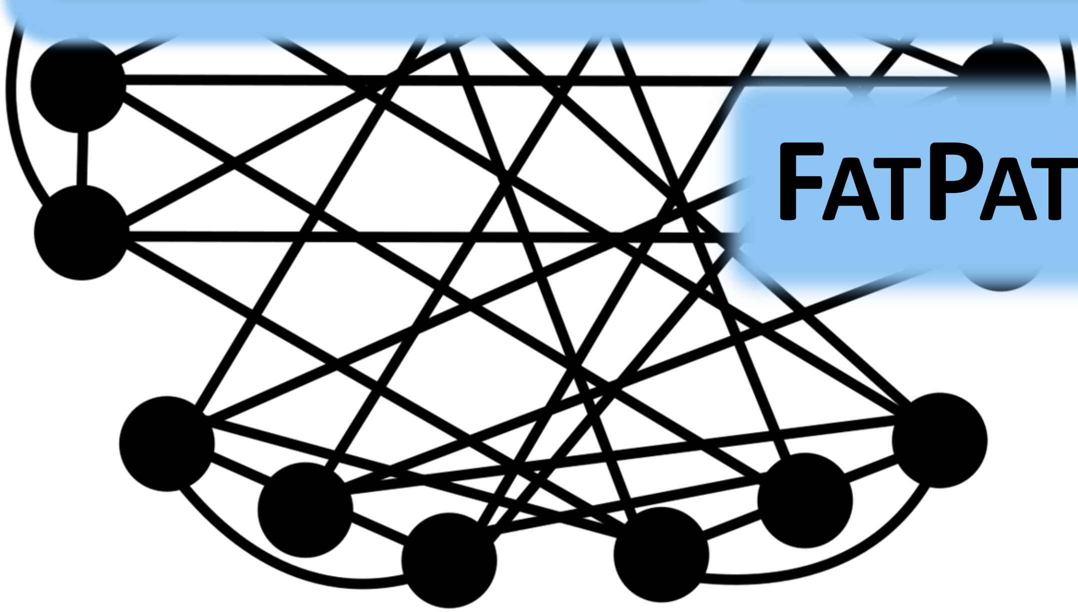
A routing scheme focusing on low-diameter topologies



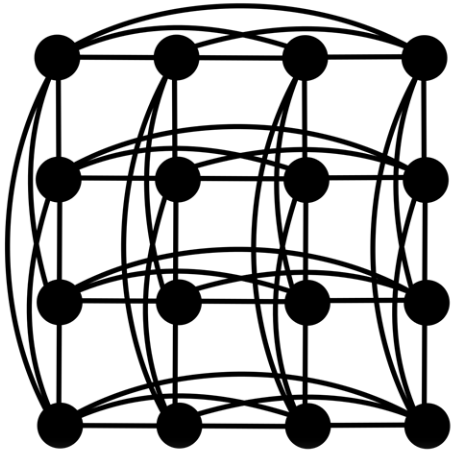


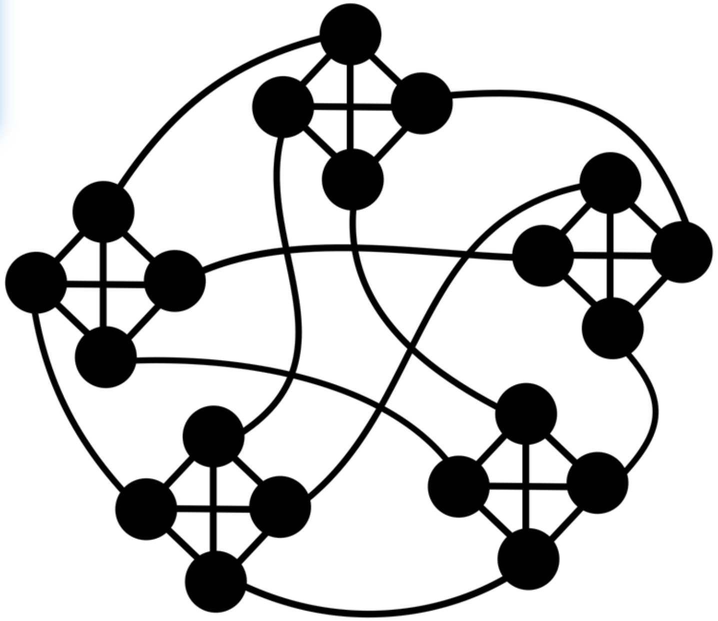
Broad analysis of path diversity





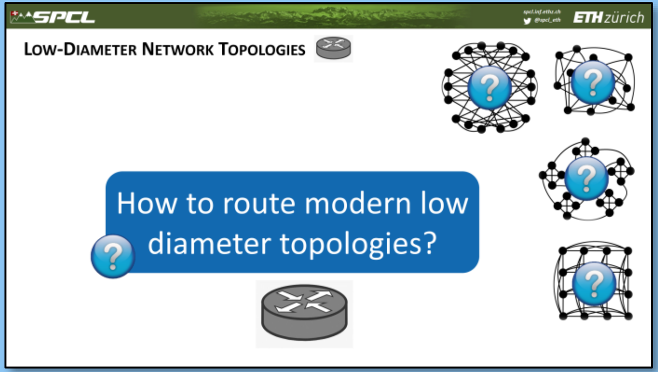
FatPaths Overview

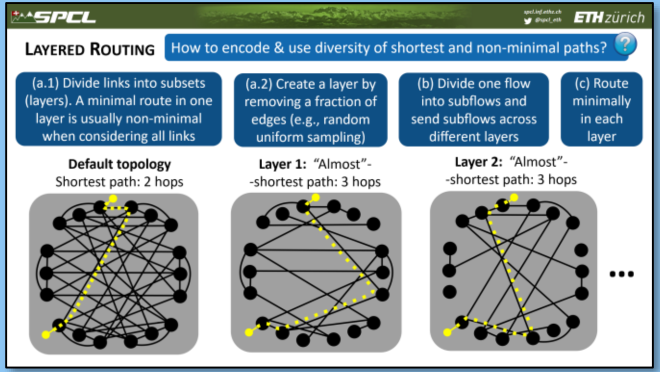




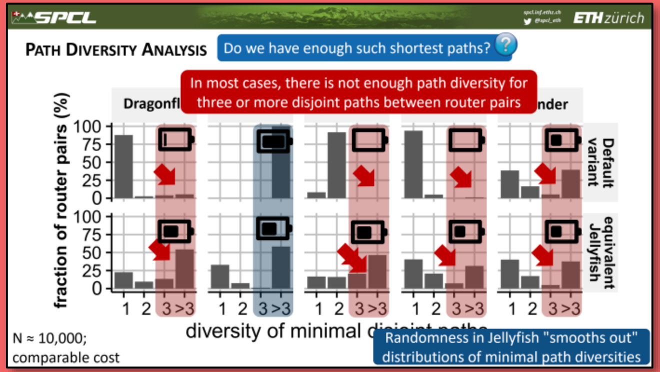
FatPaths Overview

A routing scheme focusing on low-diameter topologies

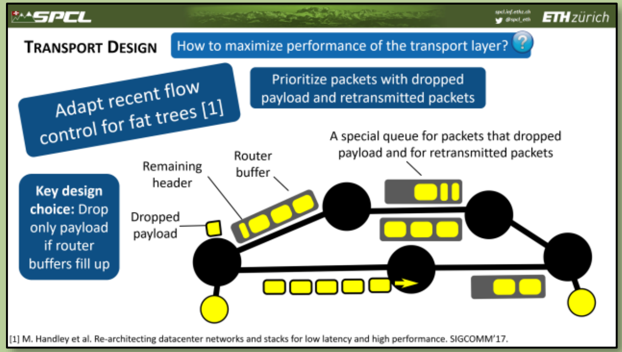


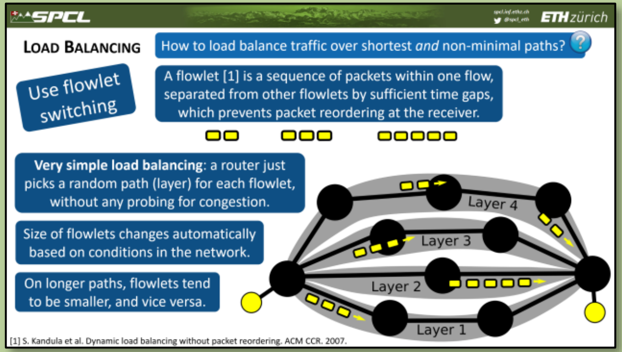


Broad analysis of path diversity



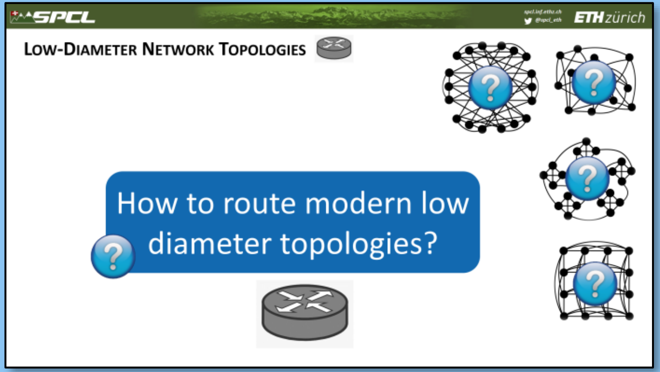
High-performance networking architecture

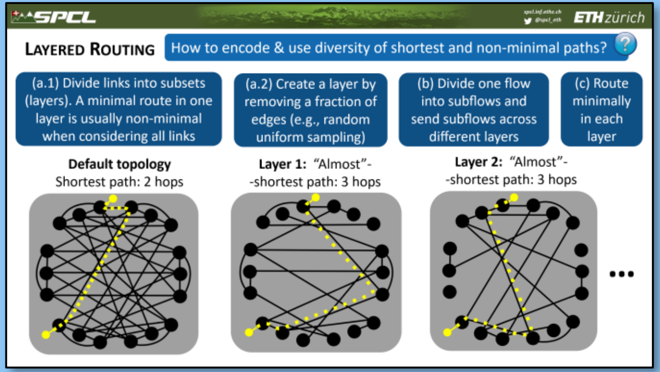




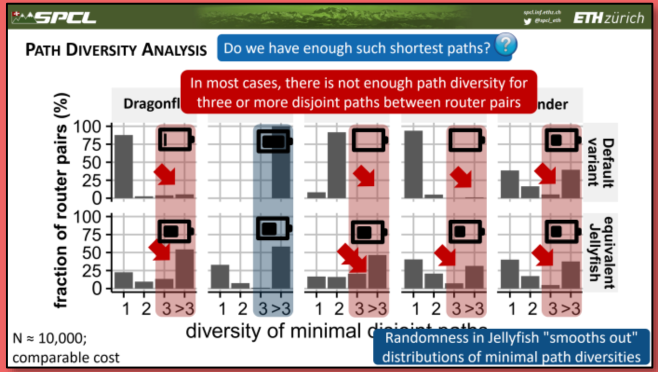
FatPaths Overview

A routing scheme focusing on low-diameter topologies





Broad analysis of path diversity



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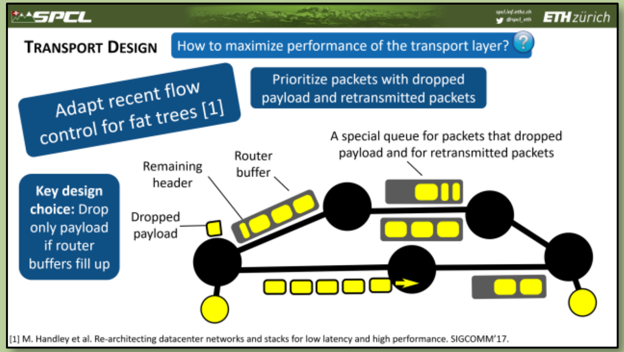

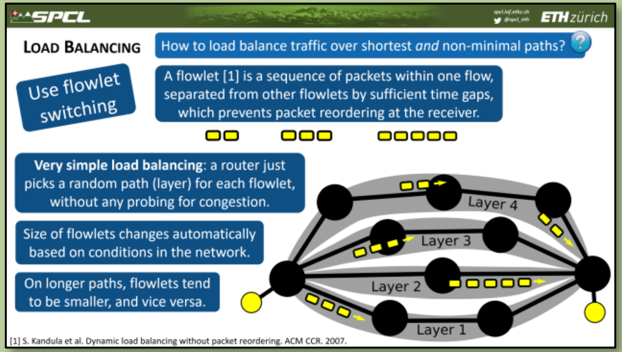

Rich evaluation, theoretical analysis, taxonomy