Parallel Computing Platforms

Routing, Network Embedding

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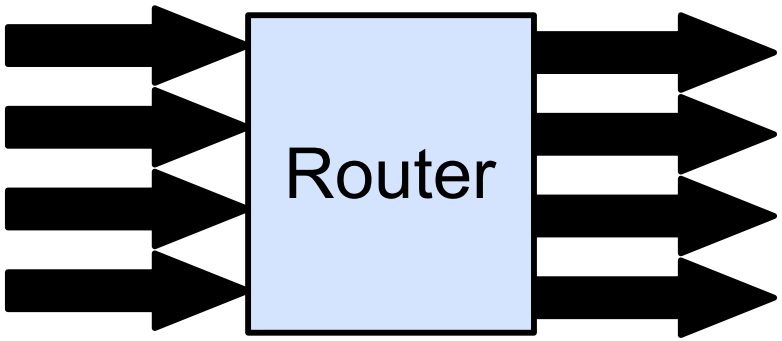
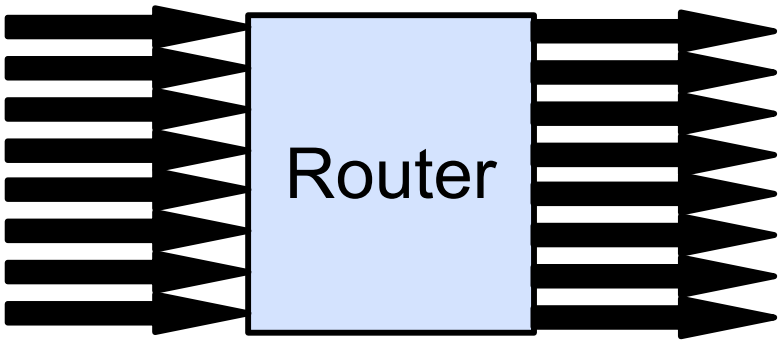
Topics for Today

- Dragonfly topology
- Routing
  - example network fabric: Infiniband
- Network embeddings

The Trend in Routers

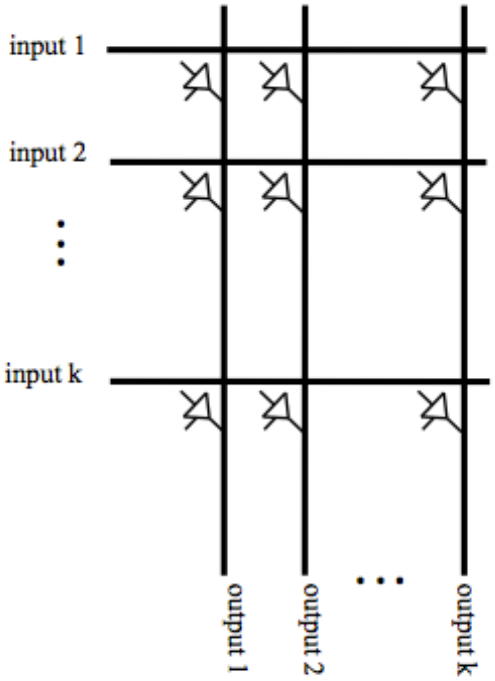


Low radix router
(small number of fat ports)



High radix router
(large number of skinny ports)

High Radix Routers



(a) Baseline design

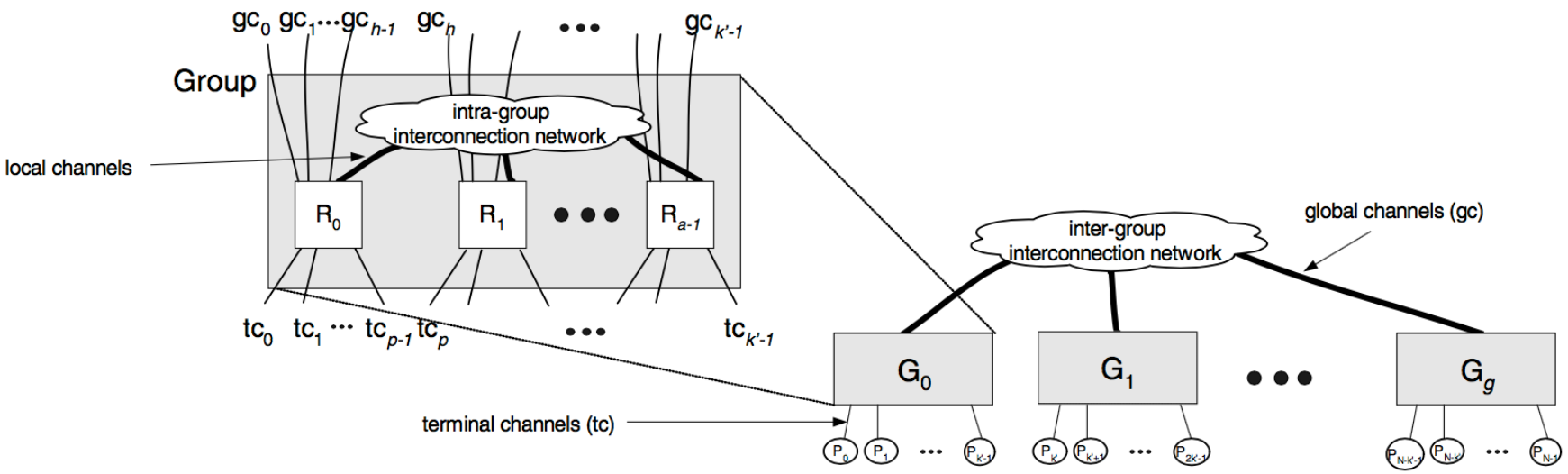
B. Dally. From Hypercubes to Dragonflies. IAA Workshop, 2008.

Dragonfly: Three Level Network

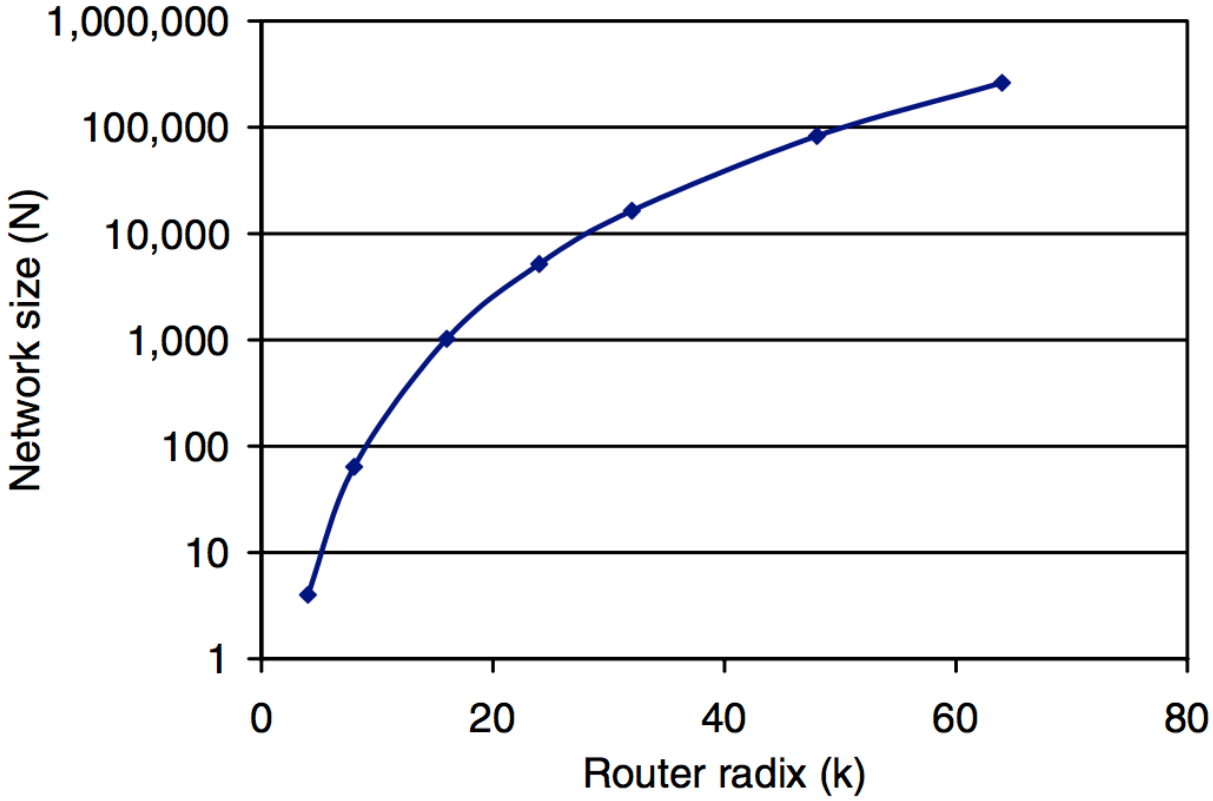
- **Levels**
  - **router**
  - **group**
  - **system**

router has to connect to
- p terminals
- a -1 routers within the same group
- h global channels to other groups

radix = p + a - 1 + h



Dragonfly Scalability



network scale vs.
router radix

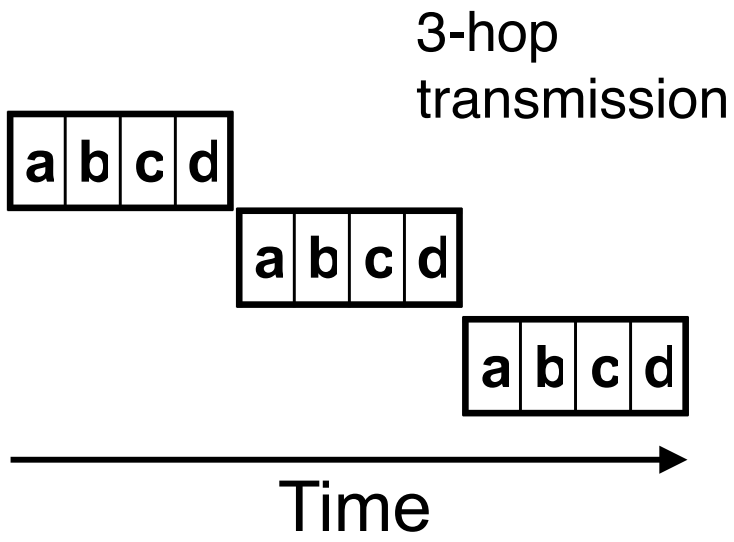
J. Kim, B. Dally, S. Scott, D. Abts. Technology-Driven, Highly-Scalable Dragonfly Topology. ISCA 2008.

Communication Performance

- Depends on a variety of features
  - —programming model semantics
    - synchronous or asynchronous communication
  - —associated software protocols
    - get/put, send/receive
  - —network topology
  - —embedding
  - —routing

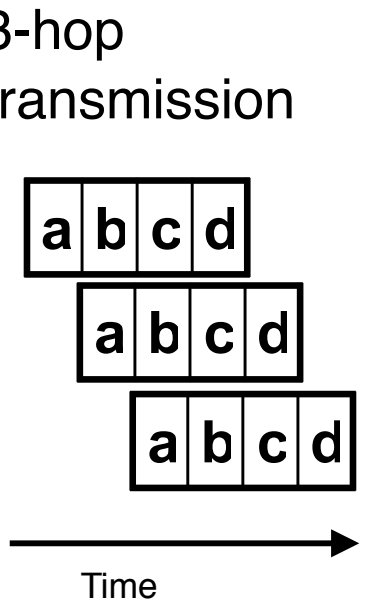
Store-and-Forward Routing

- **Definition**
  - —an intermediate hop completely receives a multi-hop message before forwarding it to the next hop
- **Total communication cost for**
  - —message of size m words
  - —cost for header + message to traverse l communication links



Packet Routing

- **Store-and-forward makes poor use of communication resources**
- **Packet routing**
  - **—breaks messages into packets**
  - **—pipelines them through the network**
- **Packets may take different paths, thus each packet must carry**
  - **—routing information**
  - **—error checking**
  - **—sequencing information**
- **Transmission time is much shorter, sum of**
  - **—time for the first packet through the whole path**
  - **—transmission time for the rest of the data**



Cut-through Routing

- Packet routing in the extreme
  - —divide messages into basic units called flits
  - —start forwarding flit before it is received in its entirety
    - typically, after seeing the destination address in the first few bytes
    - pass along even bad packets: requires end-to-end error checking
- Flits are typically small → header information must be small
- To enable small headers
  - —force all flits to take the same path, in sequence
    - tracer message first programs all intermediate routers
    - all flits then take same route
  - —perform error checks on the entire message
    - not separately on flits
    - no sequence numbers needed
- Used in today's Infiniband networks

Messaging Costs

- If a link serves multiple messages
  - —cost for transmission across the link must be scaled up by the number of messages traversing that link
- Network congestion varies by
  - —communication pattern
  - —match between pattern and network topology
- Communication cost models must account for congestion

Cost Models for Shared Memory Machines

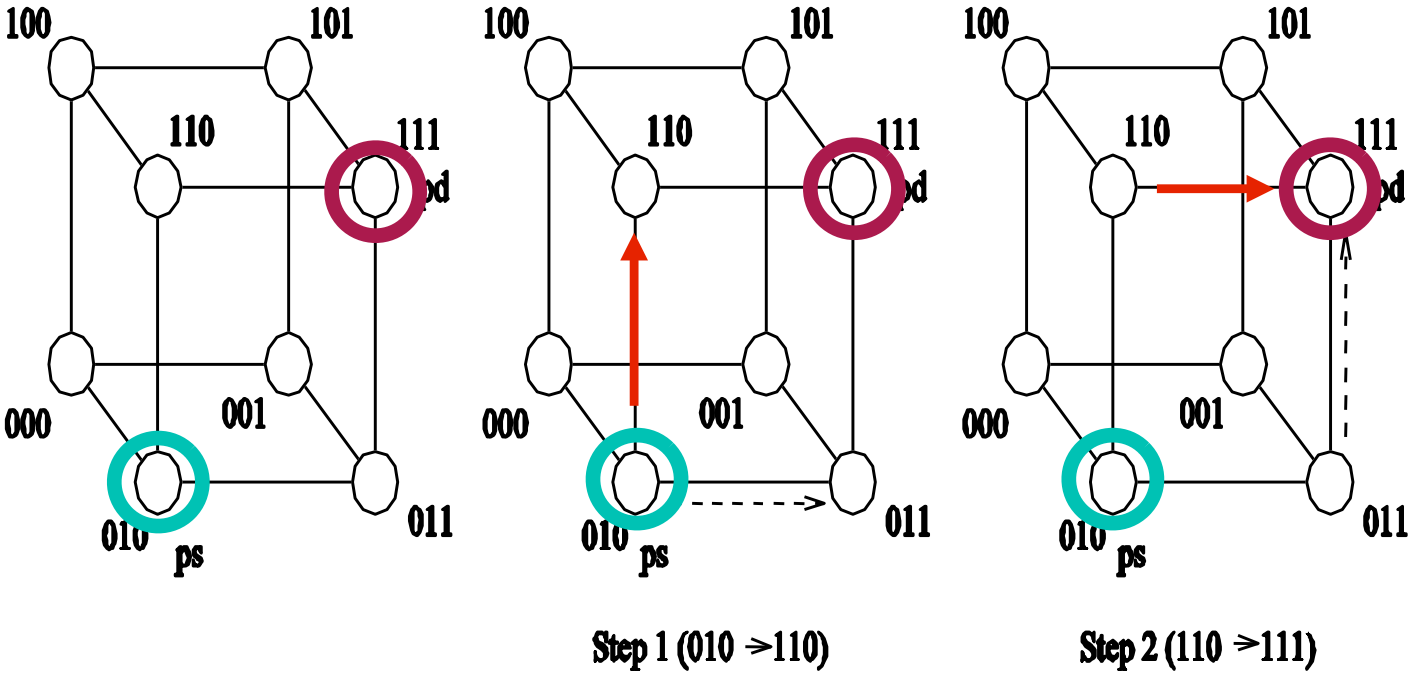
Modeling shared memory communication cost is difficult

- Memory layout is typically determined by the system
- Finite cache sizes can cause cache thrashing
  - additional traffic because of failure to exploit close reuse
- Difficult to quantify overheads for coherence traffic
  - especially for multi-level caches with some shared levels
- Difficult to model
  - spatial locality
  - false sharing and contention
- Prefetching and multithreading can reduce exposed latency for data accesses

Routing Variants

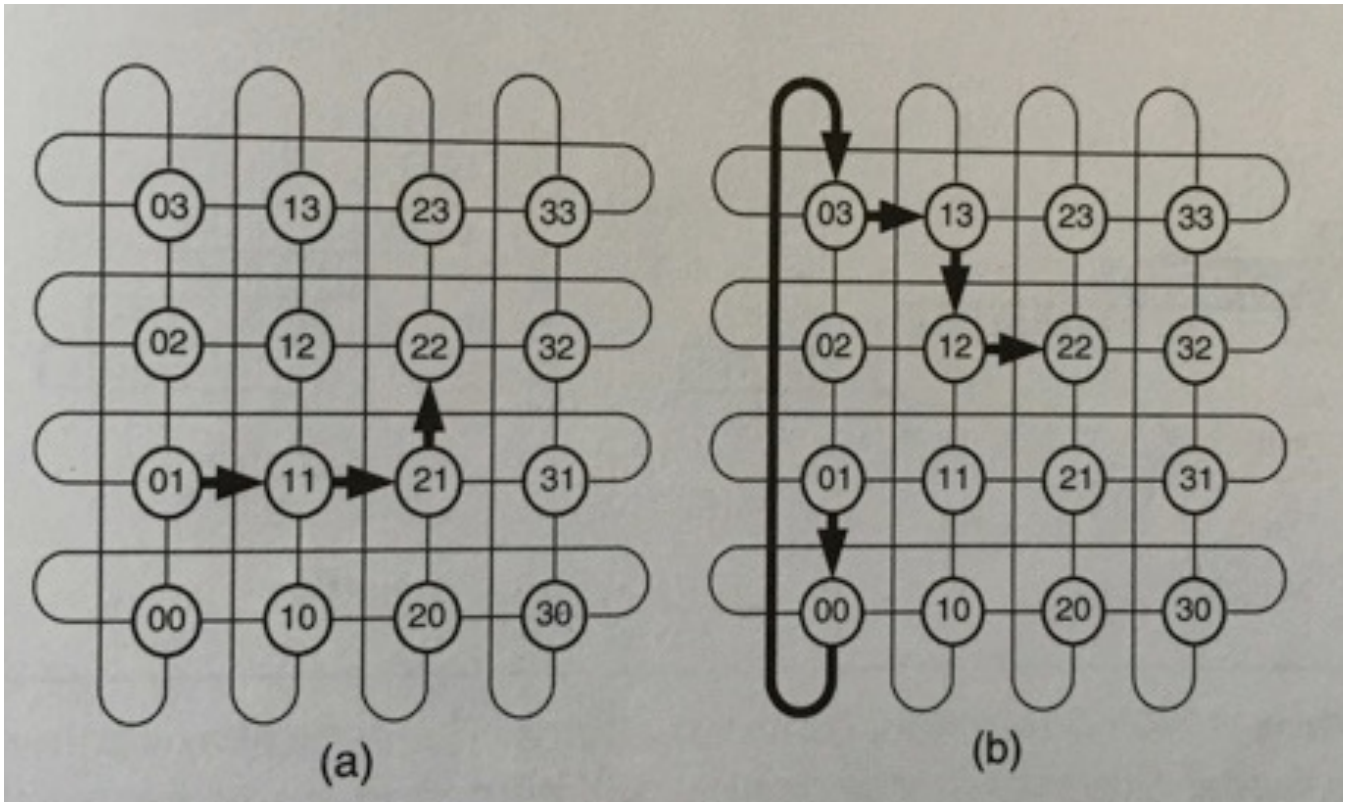
- **Method for choosing a path**
  - —oblivious: unique path between source and destination
    - determines route for each pair without considering traffic
    - appeal: can be computed in advance, even if they are computationally expensive
      - optimal deterministic routing (with a minimal edge-forwarding index) in arbitrary networks is NP-hard [Saad ’93]
  - —adaptive: use info about network state to determine path
    - must react quickly to changes in the global network
    - often constrained to fast suboptimal algorithms
- **Path characteristics**
  - —minimal: shortest path between source and destination
  - —non-minimal: may use longer path to avoid congestion

Dimension-ordered Routing



Routing a message from node P_s (010) to node P_d (111) in a 3D mesh using dimension-ordered routing

Minimal vs. Non-minimal Routes



- **(a) dimension ordered route: x then y**
- **(b) non-minimal route**

WJ Dally, BP Towles. Principles and practices of interconnection networks. Elsevier. 2004

Routing Challenges and Approaches

- **Routing must prevent deadlocks**
  - **use virtual channels with separate resources**
- **Routing must avoid hot-spots**
  - **can use two-step routing**
    - **message from *s* → *d***

      first sent to a randomly chosen intermediate processor i

      then forward from i to destination *d*

    - ***reduces a worst case permutation route to two randomized routing steps***

      source to a randomly picked intermediate

      the randomly picked intermediate to destination

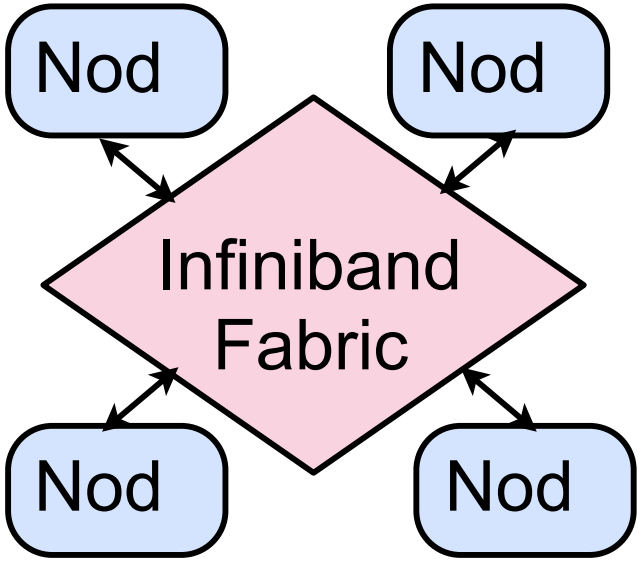
L. G. Valiant. A scheme for fast parallel communication. SIAM Journal on Computing, 11(2):350–361, 1982.

Routing Costs: Theory vs. Practice

- Point-to-point metrics (bandwidth, latency) are not accurate predictors for average network bandwidth
- Widely-used aggregate theoretical metrics
  - edge-forwarding index: max # of paths through any edge
  - bisection bandwidth
- Practical techniques to increase performance
  - multiple virtual transmission channels
  - operating system bypass
  - adaptive routing
- Optimized routing offers substantial benefits
  - Infiniband: for some traffic patterns, congestion degrades bandwidth by 6.5x and increases latency 5x
  - can characterize routing algorithms by "effective bisection bandwidth"

Infiniband

- **Infiniband: a switched, high-performance interconnect fabric**
  - **serial connection**
  - **high bandwidth, low latency**
    - **basic link rate: 2.5Gb/s (SDR)**
      - **multipliers: 4x, 12x**
      - **double data rate (DDR)**
    - **cut through routing (< 200ns switching*)**
  - **quality of service, failover, scalability**



- **Typical switching elements**
  - **crossbar with 24 full-duplex links**
  - **support virtual lanes to break routing cycles & avoid deadlock**
- **Does not mandate any topology**
  - **deployed networks typically use a fat tree, mesh, or torus**
- **Scalable to thousands of ports**

*Mellanox Inifiniscale III

Infiniband Routing

- Oblivious destination-based distributed routing
- Each switch has a forwarding table (random or linear)
  - defines which port leads to which endpoint
  - on startup or after topology changes
    - Subnet Manager (SM) discovers the topology
    - computes forwarding table for each switch
    - uploads tables to the switches
- Credit-based flow control scheme in hardware
  - goal: avoid packet loss at congested switches
  - how: each output port can only send packets if it has credits at the destination input port

Infiniband OpenSM Routing Algorithms

- **MINHOP**
  - minimal paths among all endpoints; tries to balance the number of routes per link locally at each switch (under the constraint of minimal routes)
  - can be circular dependencies among switch buffers (admits deadlock)
- **UPDN**
  - uses the up*/down* routing algorithm to avoid circular buffer dependencies by restricting # of possible paths in the network
  - legal route must traverse zero or more links in “up” direction followed by zero or more links in “down” direction
- **FTREE**
  - a routing scheme optimized for fat trees; deadlock-free, but requires a fat tree network topology
- **DOR (Dimension Order Routing)**
  - routes along the dimensions of a k-ary n-cube to determine shortest paths and might create circular buffer dependencies
- **LASH (Layered Shortest Path)**
  - uses Virtual Lanes (VL) to break cyclic dependencies among channels of an underlying DOR scheme

P-SSSP Routing

- Single source shortest path based routing
- Algorithm iterates over all endpoints u $\in V_P$ and finds reverse shortest paths from u to all other endpoints v $\in V_P$

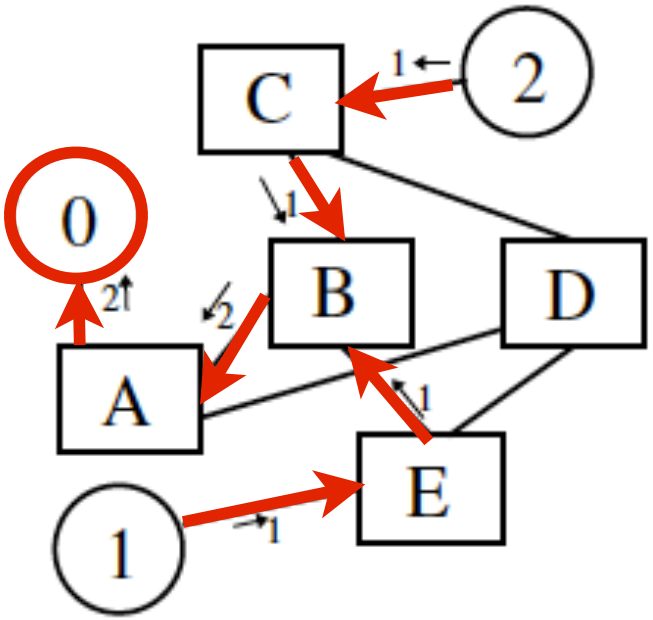
Input: Network $G = (V_p \cup V_c, E)$
Output: Routes R
1 **foreach** $u \in V_p$ **do**
2 comp. shortest paths from u to all $v \in V_p$
3 add reverse paths to forwarding tables (R)
4 update edge weights along paths

- Tree structure of the shortest path tree automatically generates valid destination-based routes
- After each endpoint, the algorithm updates edge weights with the number of routes that pass through each edge
- Difference between OpenSM's MINHOP and P-SSSP
  - P-SSSP performs a global optimization of the edge loads
  - MINHOP does it only locally at each switch

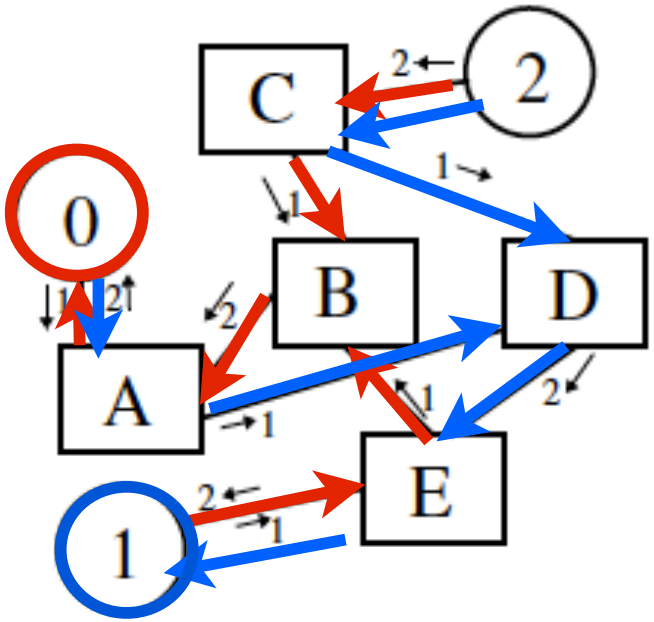
Computing Routes with P-SSSP

Input: Network $G = (V_p \cup V_c, E)$
Output: Routes R
1 **foreach** $u \in V_p$ **do**
2 comp. shortest paths from u to all $v \in V_p$
3 add reverse paths to forwarding tables (R)
4 update edge weights along paths

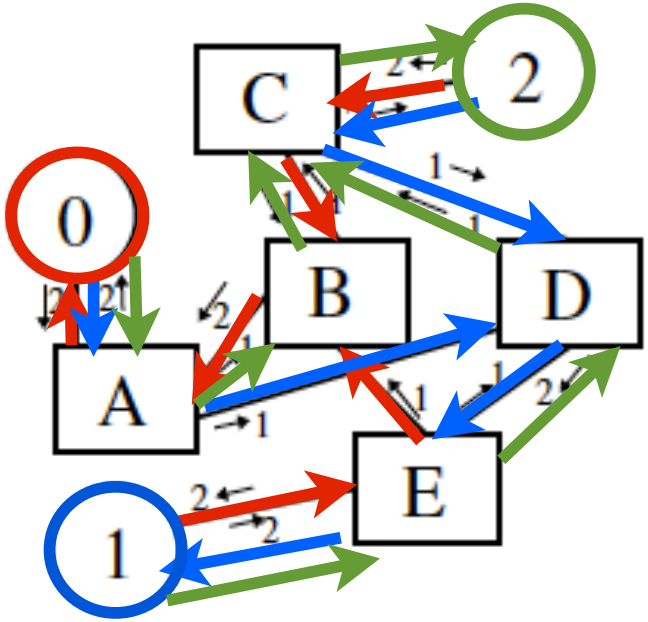
V_P set of endpoints
V_C set of crossbars



(b) From endpoint 0



(c) From endpoint 1

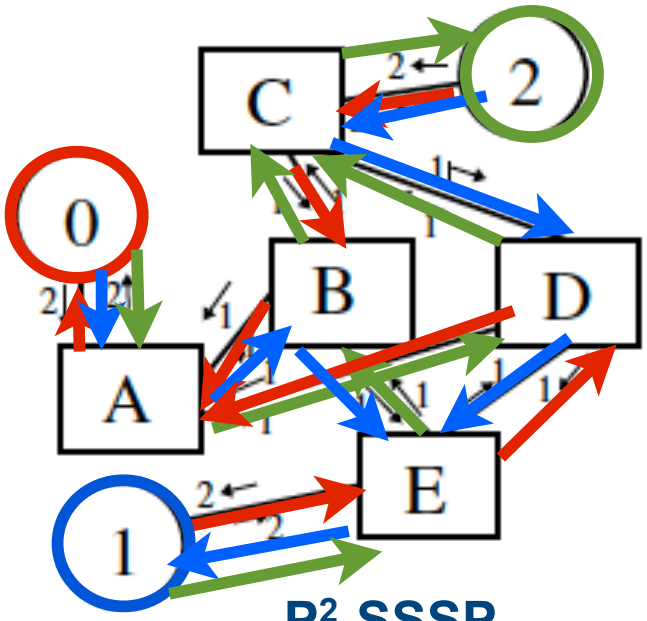


(d) From endpoint 2

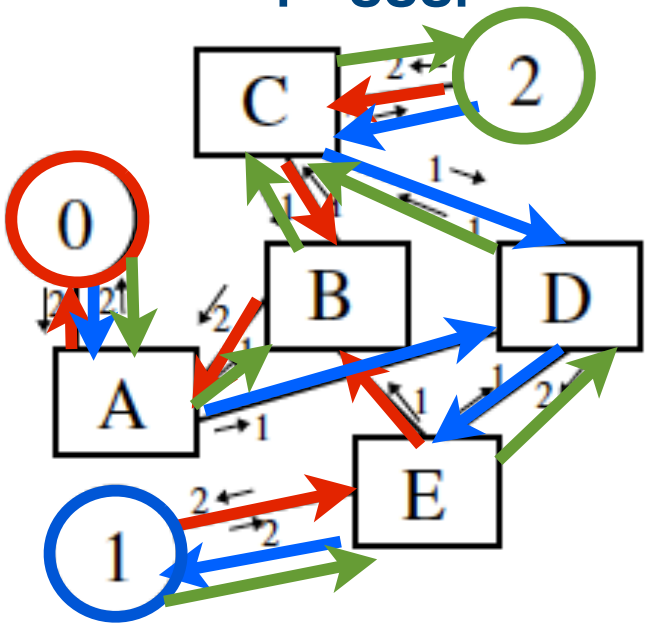
P²-SSSP

Input: Network $G = (V_p \cup V_c, E)$
Output: Routes R
1 **foreach** $u \in V_p$ **do**
2 **foreach** $v \in V_p$ **do**
3 comp. shortest path $u \rightarrow v$
4 */* the path is constrained by destination-based routing! */*
5 add path to forwarding tables (R)
6 update edge weights along path

(a) The P^2-SSSP Algorithm



P²-SSSP

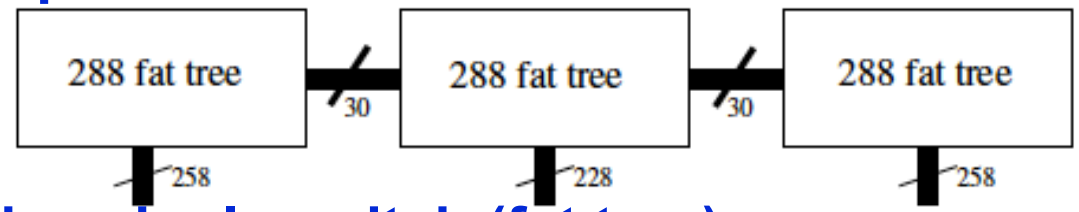


P-SSP: only updates weights P times
P²-SSSP: more accurate greedy heuristic to minimize the edge-forwarding index: perform the SSSP for each source-destination pair and updates the edge weights **P(P − 1)** times (one for each pair of endpoints)

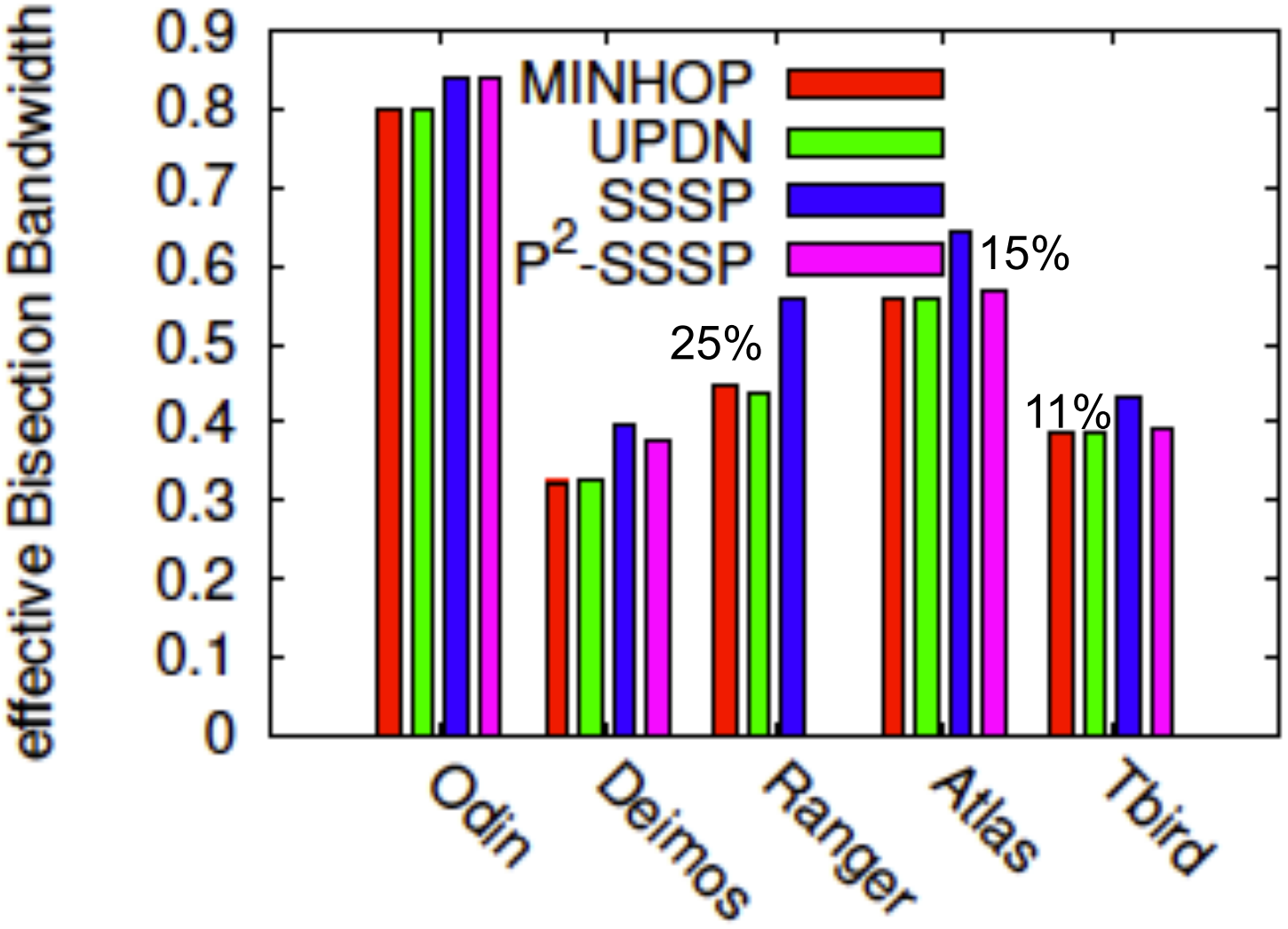
P-SSSP

Sample Infiniband Networks

- **Thunderbird (Sandia National Laboratories)**
  - 4390 endpoints, half-bisection bandwidth fat tree
- **Ranger (Texas Advanced Computing Center)**
  - 4080 endpoints, two Sun Magnum 3456 port switches, 5-stage full bisection bandwidth fat tree, 4 sockets (16 cores) / endpoint
- **Atlas (LLNL)**
  - 1142 endpoints, full bisection bandwidth fat tree
- **Deimos (Technical University of Dresden)**
  - 724 endpoints, three 288-port switches connected in a 30 link-wide chain
- **Odin (Indiana University)**
  - 128 endpoint cluster with a single switch (fat tree)



Routing Algorithm Performance Simulations



(a) $\Lambda(G, R)$ for different clusters

Routing vs. Infiniband B/W

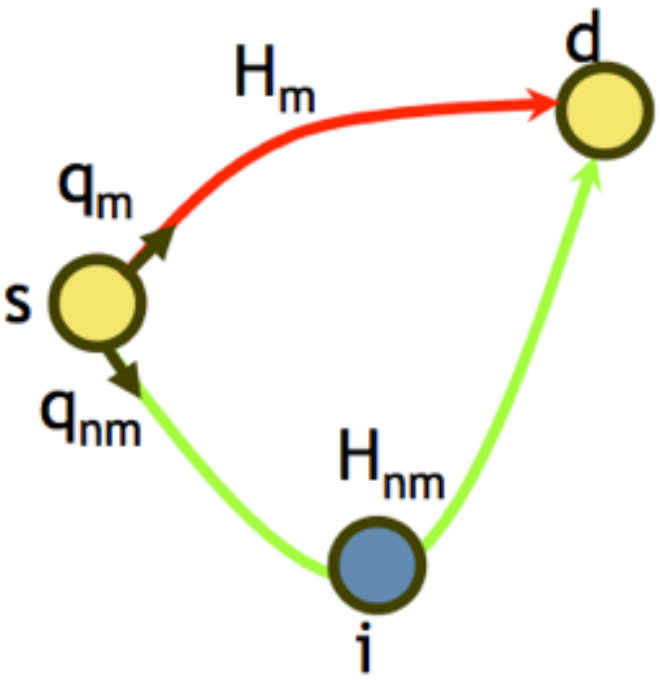
- P-SSSP algorithm globally balances routes and thus improves the effective bandwidth of the network
- Dramatically improves effective bisection bandwidth
  - 25% on the 4080 endpoint Ranger cluster @ TACC (simulated)
  - 40% on Deimos 724-endpoint InfiniBand cluster (measured)
- Why is P^2-SSSP not better?
  - edge forwarding index = theoretical lower bound to the minimal point-to-point bandwidth in the networks
    - not necessarily a good predictor for effective (avg) bisection BW

Global Adaptive Routing

- VAL gives optimal worst-case throughput
- MIN gives optimal benign traffic performance
- UGAL (Universal Globally Adaptive Load-balance)
  - [Singh '05]
  - Routes benign traffic minimally
  - Starts routing like VAL if load imbalance in channel queues
  - In the worst-case, degenerates into VAL, thus giving optimal worst-case throughput

B. Dally. From Hypercubes to Dragonflies. IAA Workshop, 2008.

UGAL



1. H_m= shortest path (SP) length
2. q_m= congestion of the outgoing channel for SP
3. Pick i, a random intermediate node
4. H_{nm}= non-min path (s→i→d) length
5. q_{nm}= congestion of the outgoing channel for s→i→d
6. Choose SP if $H_m q_m \leq H_{nm} q_{nm}$; else route via i, minimally in each phase

B. Dally. From Hypercubes to Dragonflies. IAA Workshop, 2008.

UGAL report card

64 node topology	Throughput (frac of capacity)			
	Algo	Θ benign	Θ adv	Θ avg
K_{64}	VAL	0.5	0.5	0.5
	MIN	1.0	0.02	0.02
	UGAL	1.0	0.5	0.5
8 x 8 torus	VAL	0.5	0.5	0.5
	MIN	1.0	0.33	0.63
	UGAL	1.0	0.5	0.7
64 node CCC	VAL	0.5	0.5	0.5
	MIN	1.0	0.2	0.52
	UGAL	1.0	0.5	0.63

B. Dally. From Hypercubes to Dragonflies. IAA Workshop, 2008.

Dragonfly Performance

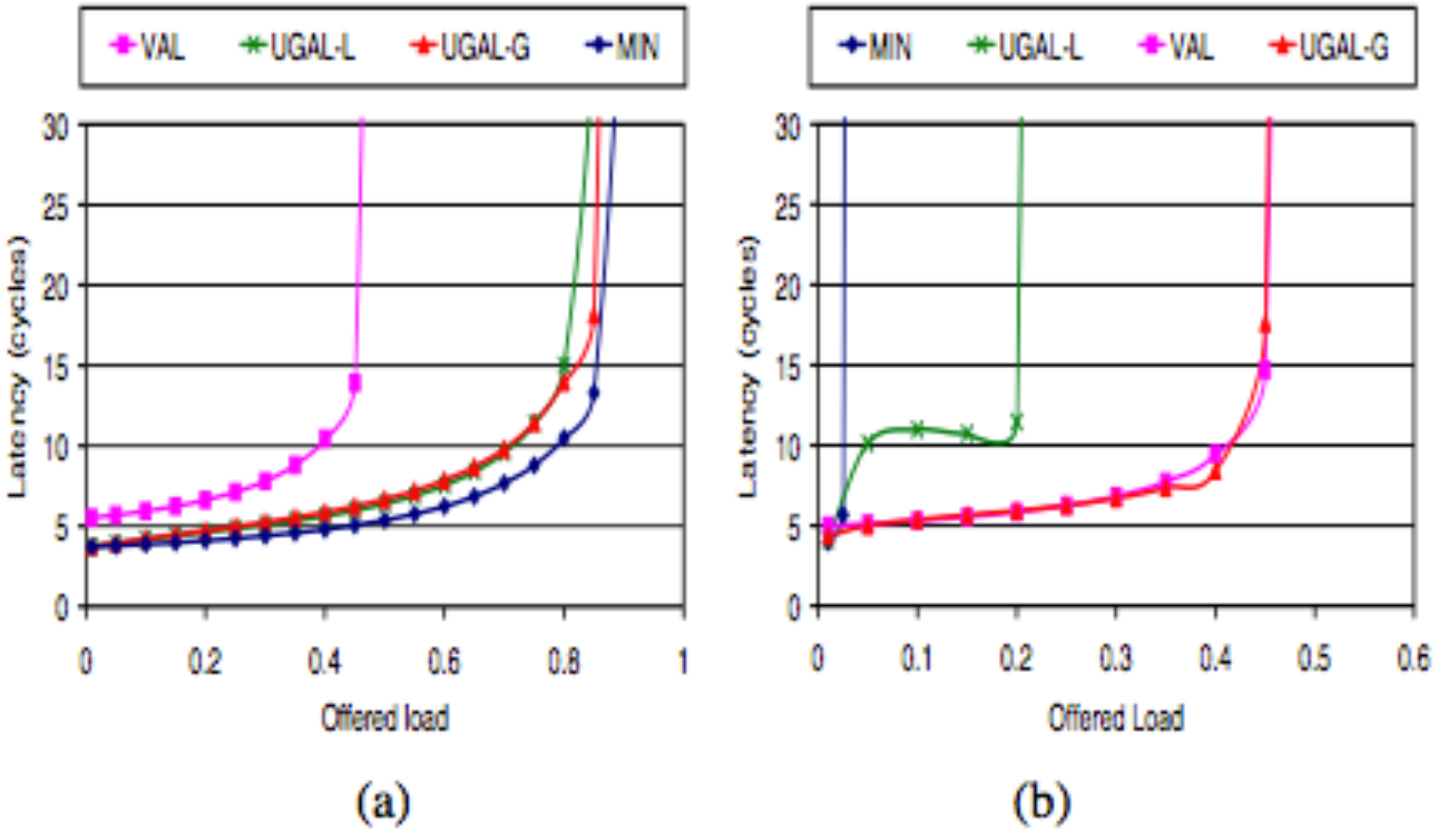


Figure 8. Routing algorithm comparison on the dragonfly for (a) uniform random traffic and (b) adversarial traffic pattern.

adversarial traffic pattern: each node in a group sends to randomly selected node in another group

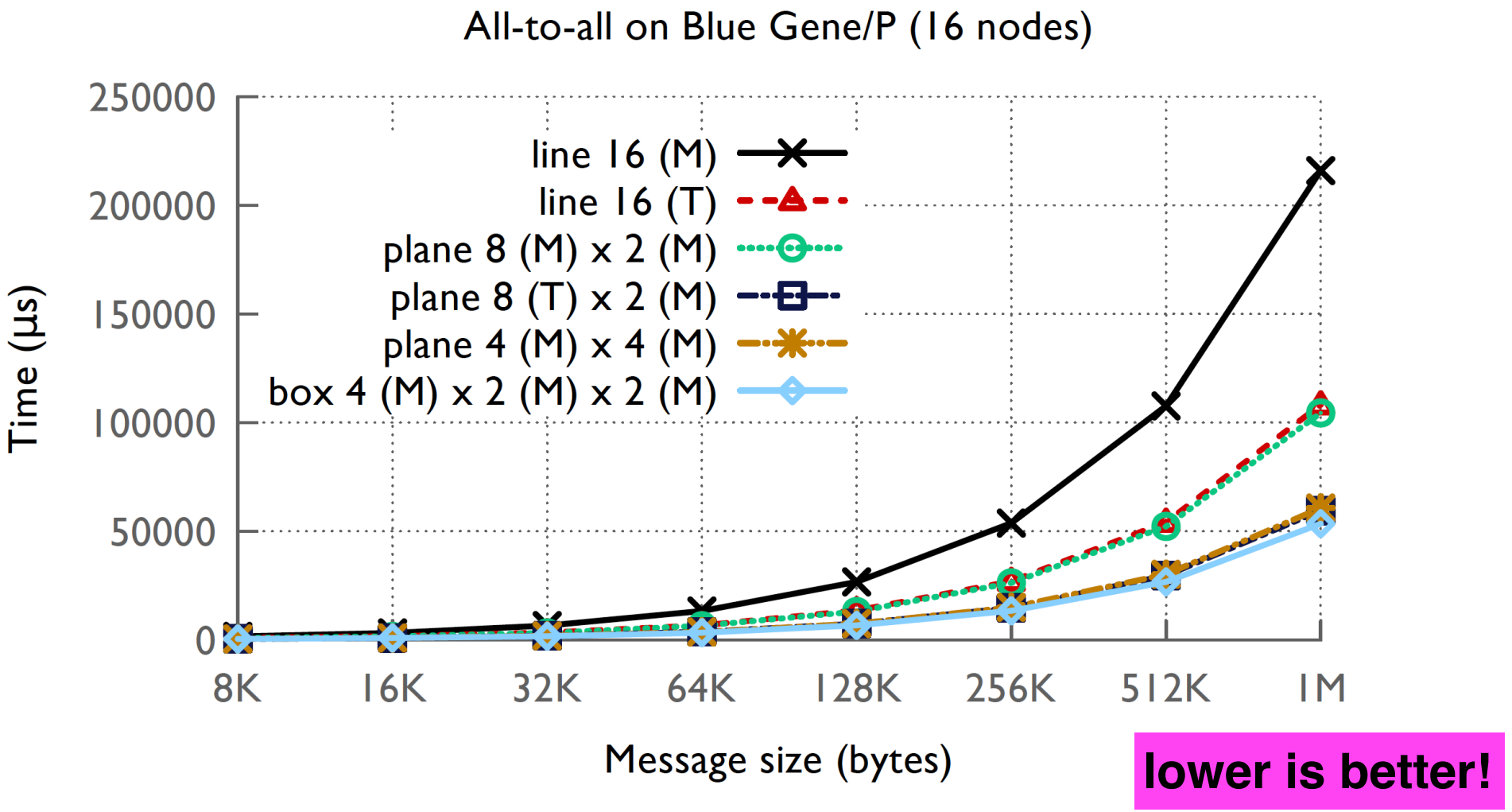
J. Kim, B. Dally, S. Scott, D. Abts. Technology-Driven, Highly-Scalable Dragonfly Topology. ISCA 2008.

Embeddings

Often need to embed a known communication pattern into a given interconnection topology

- **Why?**
  - **may have an algorithm based on a particular logical topology**
  - **how should we use it on a machine with a different topology**
- **Thus, it is useful to understand mapping between graphs**

Embeddings Matter!

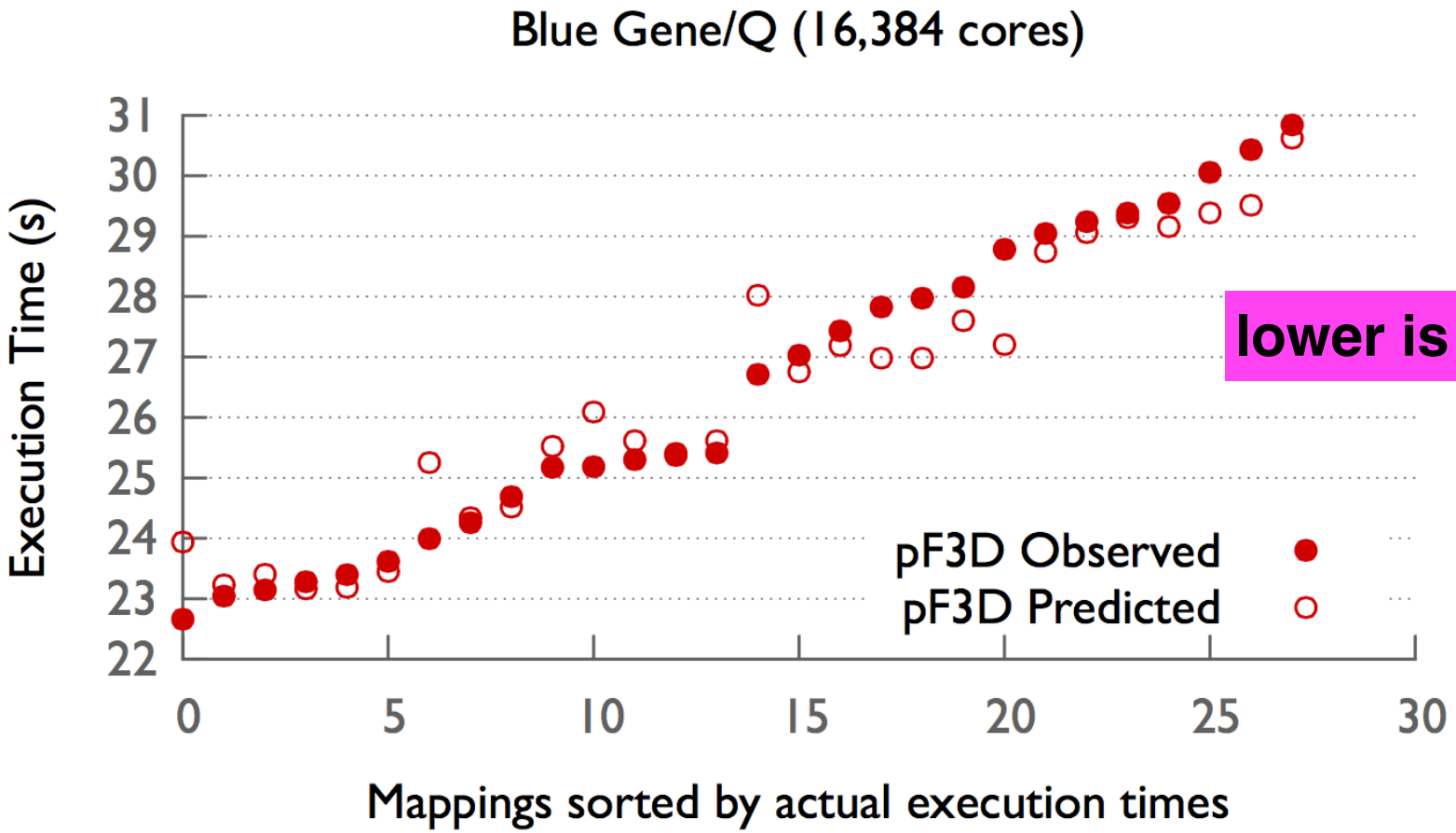


lower is better!

A. Bhatele et al. Mapping applications with collectives over sub-communicators on torus networks. In Proceedings SC '12. IEEE Computer Society, 2012.

Embeddings Matter!

pF3D: a laser-plasma interaction code

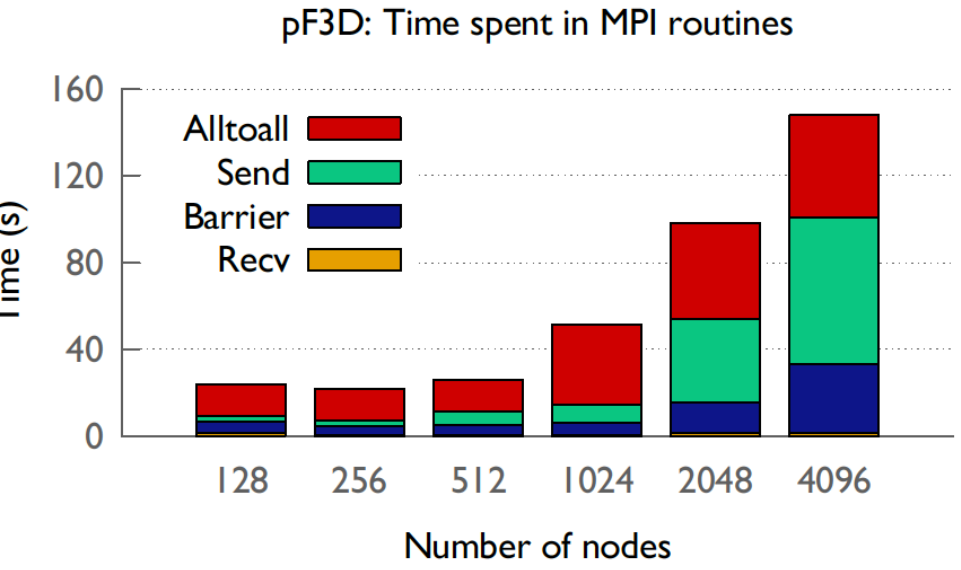


lower is better!

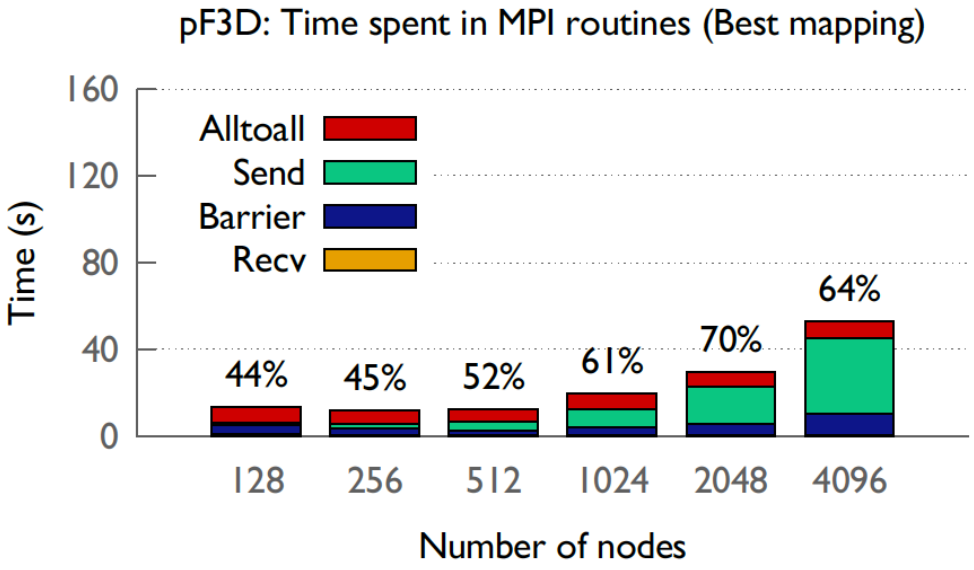
Abhinav Bhatele Task Mapping on Complex Computer Network Topologies for Improved Performance. LLNL-TR-678732 (FY2015 LDRD Final Report) http://charm.cs.uiuc.edu/~bhatele/pubs/pdf/2015/ldrd2015.pdf

Embeddings Matter!

pF3D: a laser-plasma interaction code



default mapping on BG/Q



best discovered mapping on BG/Q

lower is better!

Abhinav Bhatele Task Mapping on Complex Computer Network Topologies for Improved Performance. LLNL-TR-678732 (FY2015 LDRD Final Report) http://charm.cs.uiuc.edu/~bhatele/pubs/pdf/2015/ldrd2015.pdf

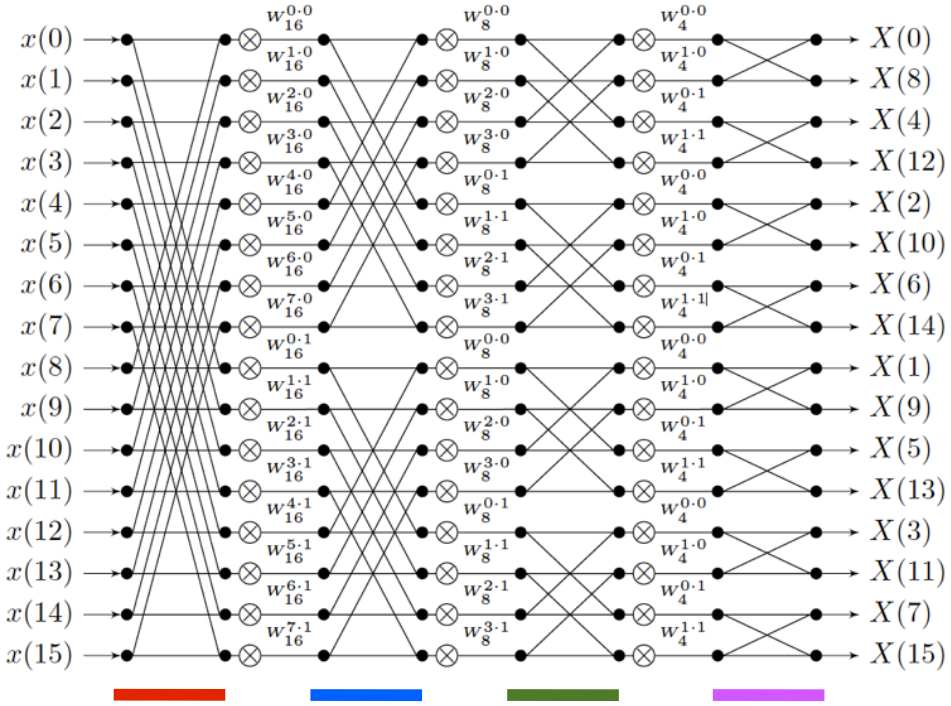
Metrics for Graph Mappings

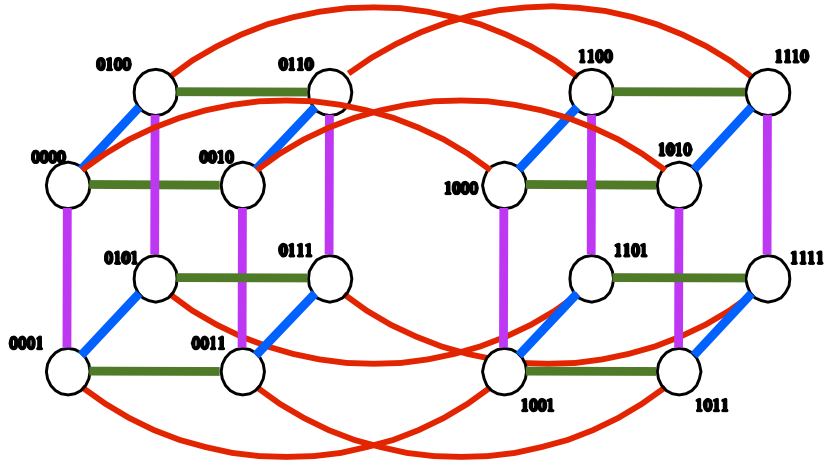
Mapping a graph G(V,E) into G'(V',E')

- **Congestion** = maximum # edges in E mapped onto edge in E'
- **Dilation** = maximum # edges in E' mapped onto 1 edge in E
- **Expansion** = (# nodes in V')/(# nodes in V)

A Motivating Problem

HPC Challenge Benchmark: 1D FFT





logical communication topology: 4D hypercube

Figure credit: http://media.texample.net/tikz/examples/PDF/radix2fft.pdf

Why FFT?

Often used in spectral methods - a class of techniques for numerically solving partial differential equations.

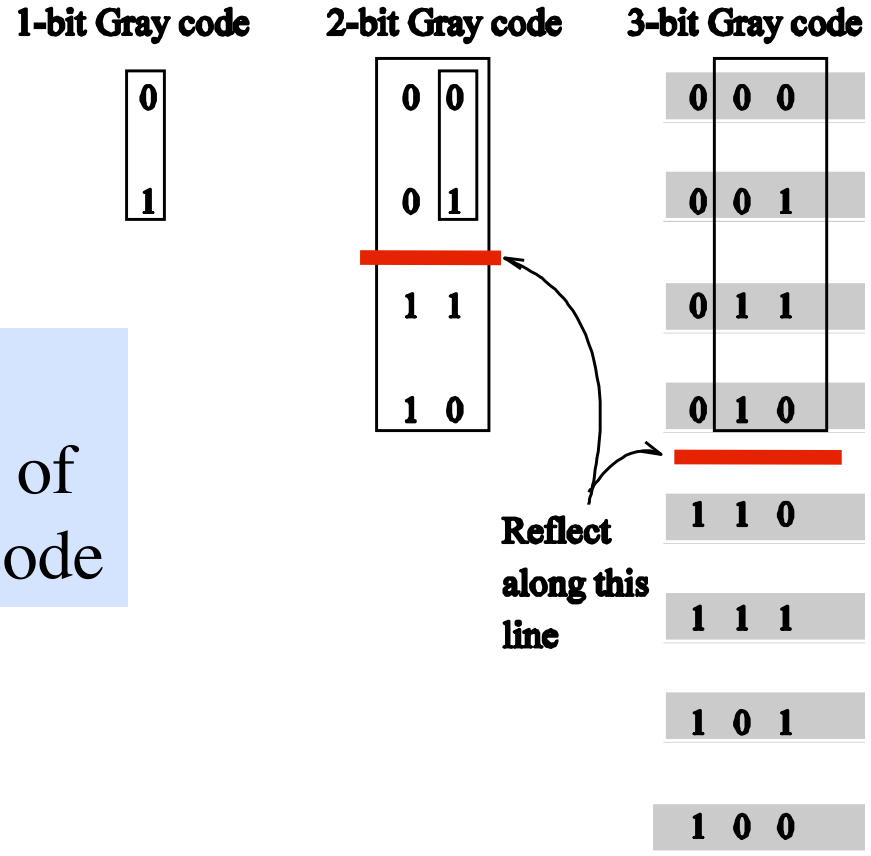
Binary Reflected Gray Code (RGC)

Adjacent entries *G(i, d)*, *G(i + 1, d)* differ in only 1 bit

G(i, x):

$$G(0,1) = 0 \qquad G(1,1) = 1$$

$$G(i,x+1) = \begin{cases} G(i,x), & i < 2^x \\ 2^x + G(2^{x+1} - 1 - i, x), & i \geq 2^x \end{cases}$$

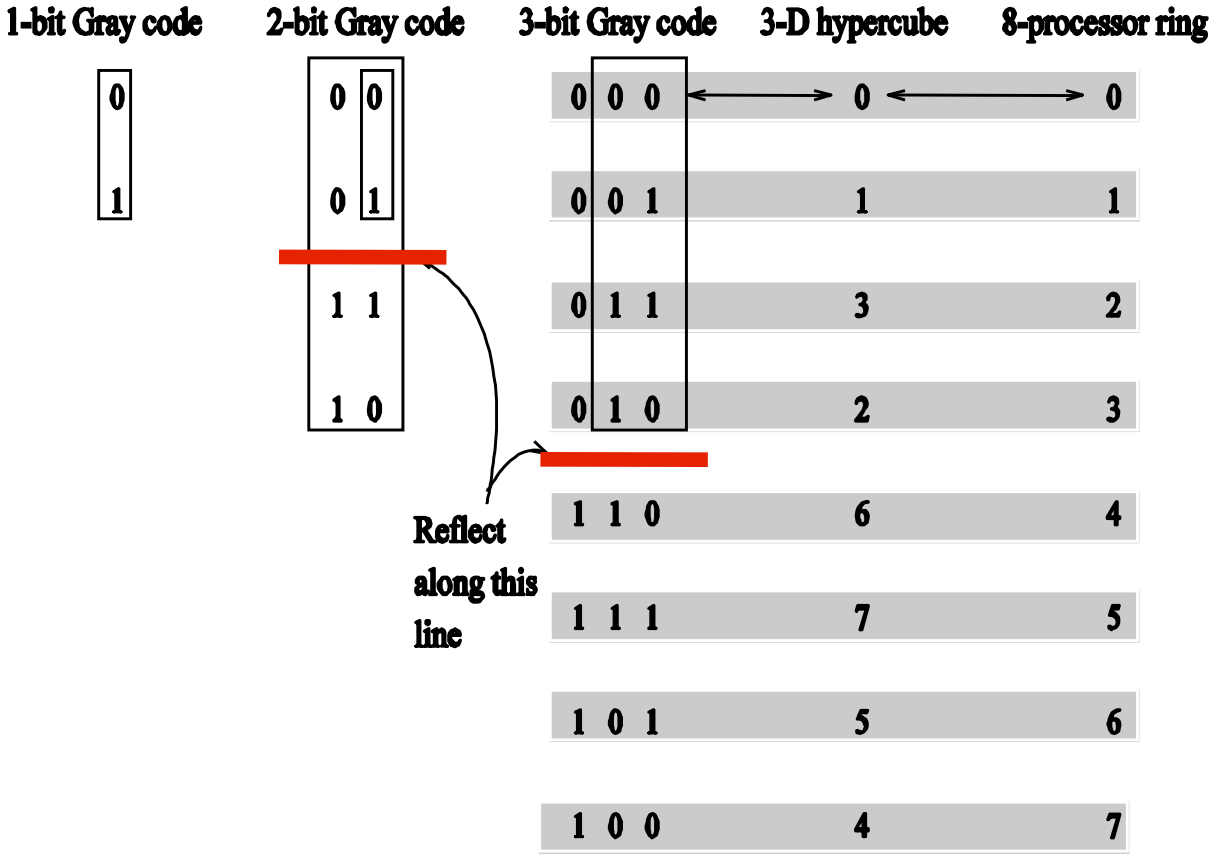


G(i,d)
d = number of bits in code

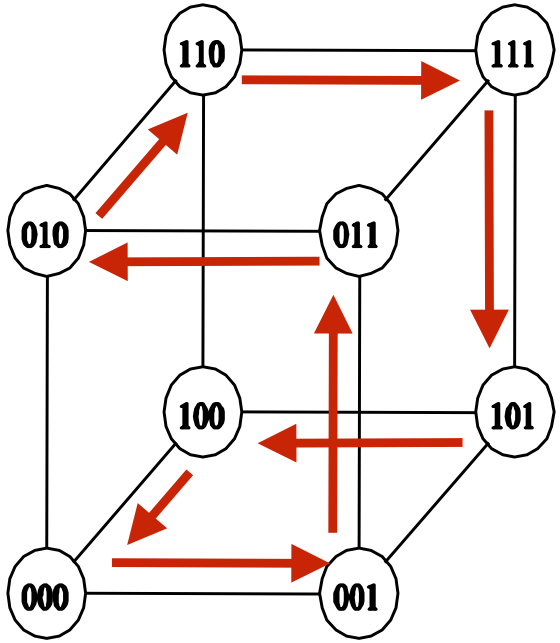
Embedding a Ring into a Hypercube

- **Given**
  - —ring of 2d nodes
  - —d-dimensional hypercube
- **Map**
  - —node i of the ring → node G(i, d) of the hypercube

Embedding a Ring in a Hypercube



3-bit reflected
Gray code ring



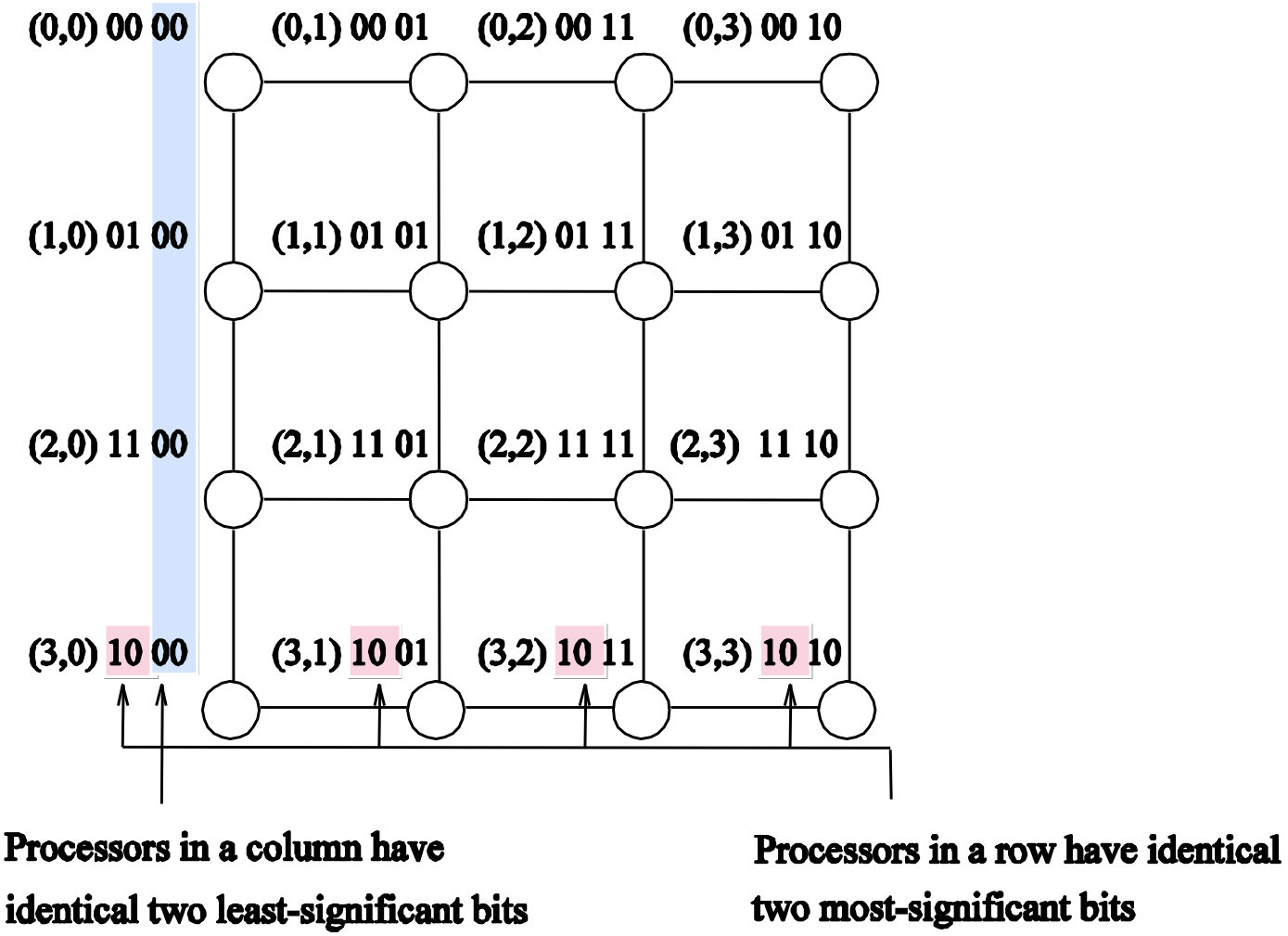
embedding into
a 3D hypercube

Embedding a Mesh into a Hypercube

Map $2^r \times 2^s$ wraparound mesh into a 2^{r+s}-node hypercube

- **G(k,d) = k^{th} element of Gray code of d bits**
- **Let || denote concatenation**
- **Map mesh node *(i, j)* → hypercube node *G(i, r)* || *G(j, s)***

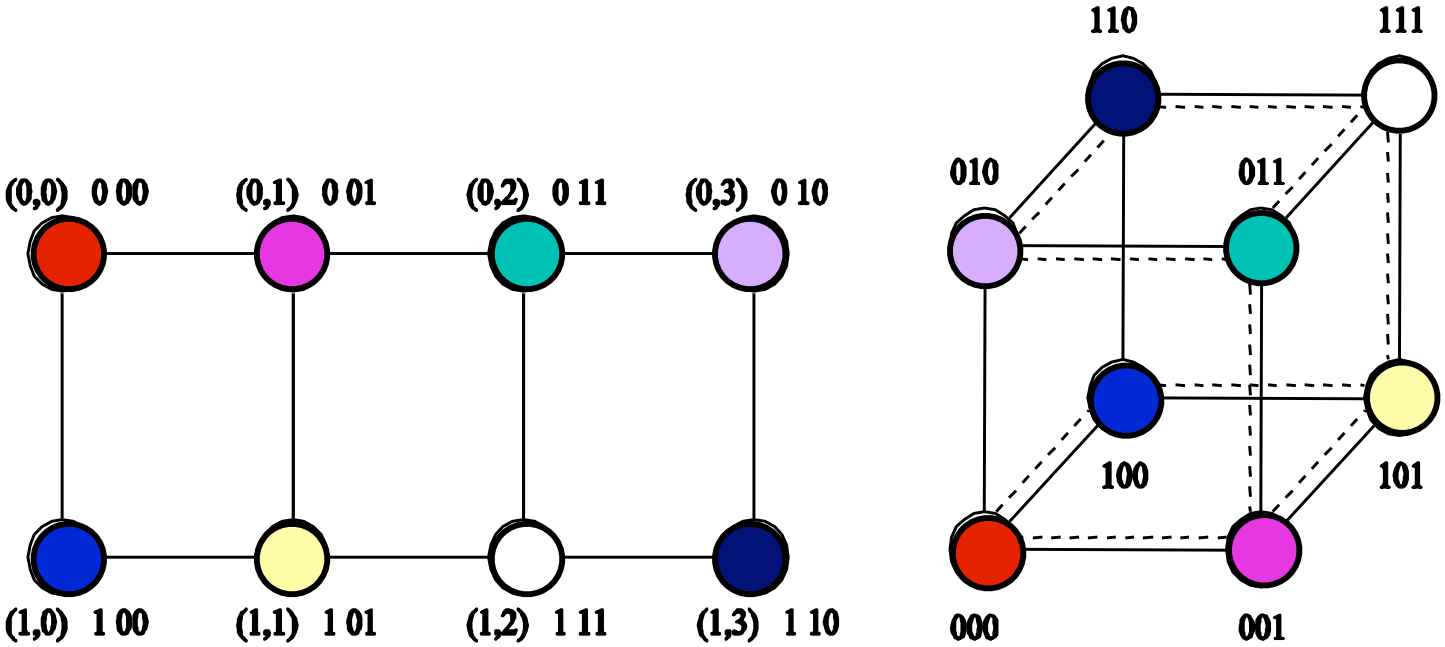
Embedding a Mesh into a Hypercube



Mapping nodes in 4 x 4 mesh to nodes in a 4D hypercube

Congestion, dilation, and expansion of the mapping is 1

Embedding a Mesh into a Hypercube



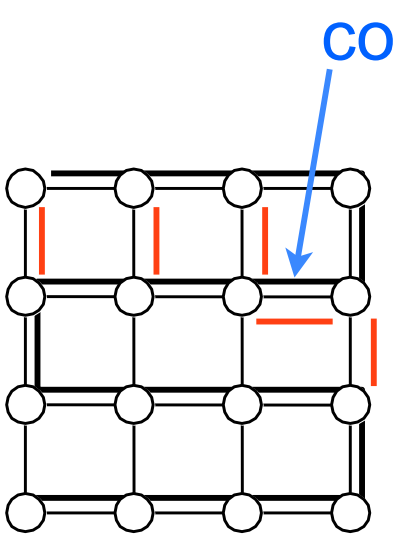
Embedding a 2 × 4 mesh into a 3D hypercube

Congestion, dilation, and expansion of the mapping is 1

Embedding a Mesh into a Linear Array

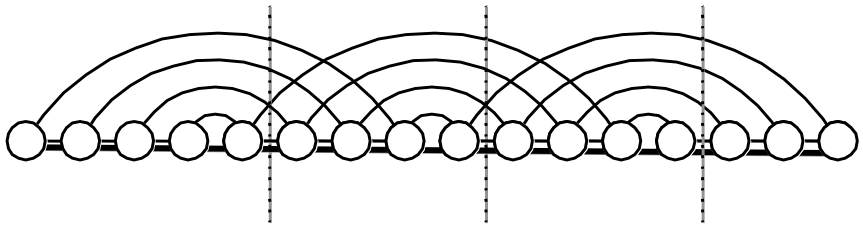
- Mesh has more edges than a linear array
- No possible mapping with congestion = 1, dilation = 1
- Approach
  - —first examine the mapping of a linear array into a mesh
  - —invert above mapping
    - yields optimal mapping in terms of congestion

Embedding a Mesh into a Linear Array



Mapping a linear array into a 2D mesh (congestion 1).

Embedding a 16 node linear array into a 2-D mesh



Inverting the mapping - mapping a 2D mesh into a linear array (congestion 5)

Inverse of the mapping:
2D mesh to 16-node linear array

Key:

dark lines: links in the linear array
normal lines: links in the mesh.

Embeddings can Help Route Diversity

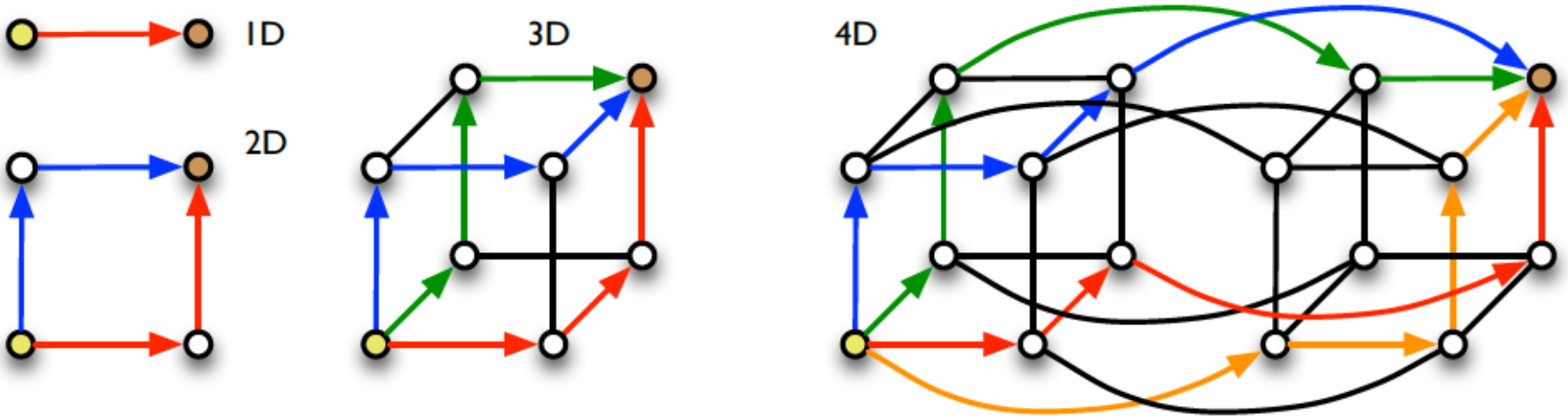


Fig. 2: Disjoint (non-overlapping) paths and "spare" links between a pair of nodes on n-dimensional topologies

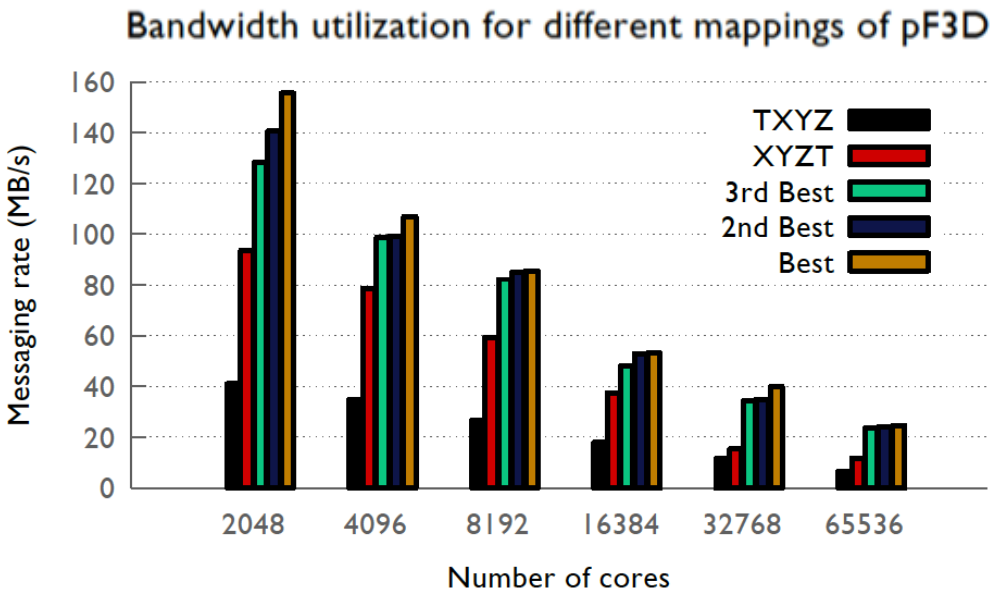
Large messages may be routed adaptively to minimize hot-spots or congestion on the network. A careful mapping of communicating tasks to the physical network can assist the system software and hardware in achieving this goal. Consider a message sent between two nodes on an **n** D Cartesian network. Depending on where these tasks are located, there are one, two, or more routes that the message can take. If tasks are placed on a line, there is a single shortest path route between them. If we place the tasks on the diagonally opposite corners of a **2 x 2** plane, there exist two shortest paths between them, and twice the available bandwidth. Also, when one of these paths is being used by other messages, the other path can be used to avoid congested links.

A. Bhatele et al. Mapping applications with collectives over sub-communicators on torus networks. In Proceedings SC '12. IEEE Computer Society, 2012.

RUBIK Results with PF3D

# Cores	Application	Torus	Best mapping
2048	$16 \times 8 \times 16$	$8 \times 8 \times 8 \times 4$	torus.tile([8, 8, 2, 1]) tilt(Z, X, 1) tilt(Z, Y, 1)
4096	$16 \times 8 \times 32$	$8 \times 8 \times 16 \times 4$	torus.tile([1, 8, 16, 1]) tilt(X, Y, 1) tilt(X, Z, 1)
8192	$16 \times 8 \times 64$	$8 \times 8 \times 32 \times 4$	torus.tile([8, 8, 2, 1]) tilt(X, Y, 1)
16384	$16 \times 8 \times 128$	$8 \times 16 \times 32 \times 4$	torus.tile([8, 16, 1, 1])
32768	$16 \times 8 \times 256$	$8 \times 32 \times 32 \times 4$	torus.tile([2, 8, 8, 1]) tilt(X, Y, 1) tilt(X, Z, 1)
65536	$16 \times 8 \times 512$	$16 \times 32 \times 32 \times 4$	torus.tile([1, 8, 16, 1]) tilt(X, Y, 1) tilt(X, Z, 1)

TABLE II: Rubik operations corresponding to the best mappings (out of the ones tried) for running pF3D on different core counts



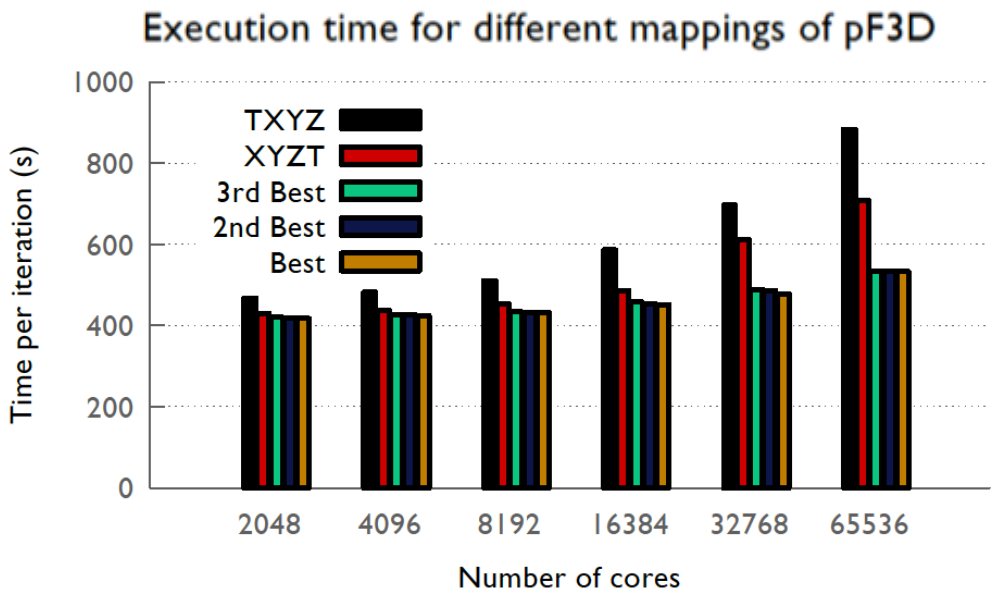


Fig. 14: Weak scaling performance of pF3D for the two default mappings as well as the three best mappings for each core count.

A. Bhatele et al. Mapping applications with collectives over sub-communicators on torus networks. In Proceedings SC '12. IEEE Computer Society, 2012.

Sharing Machines

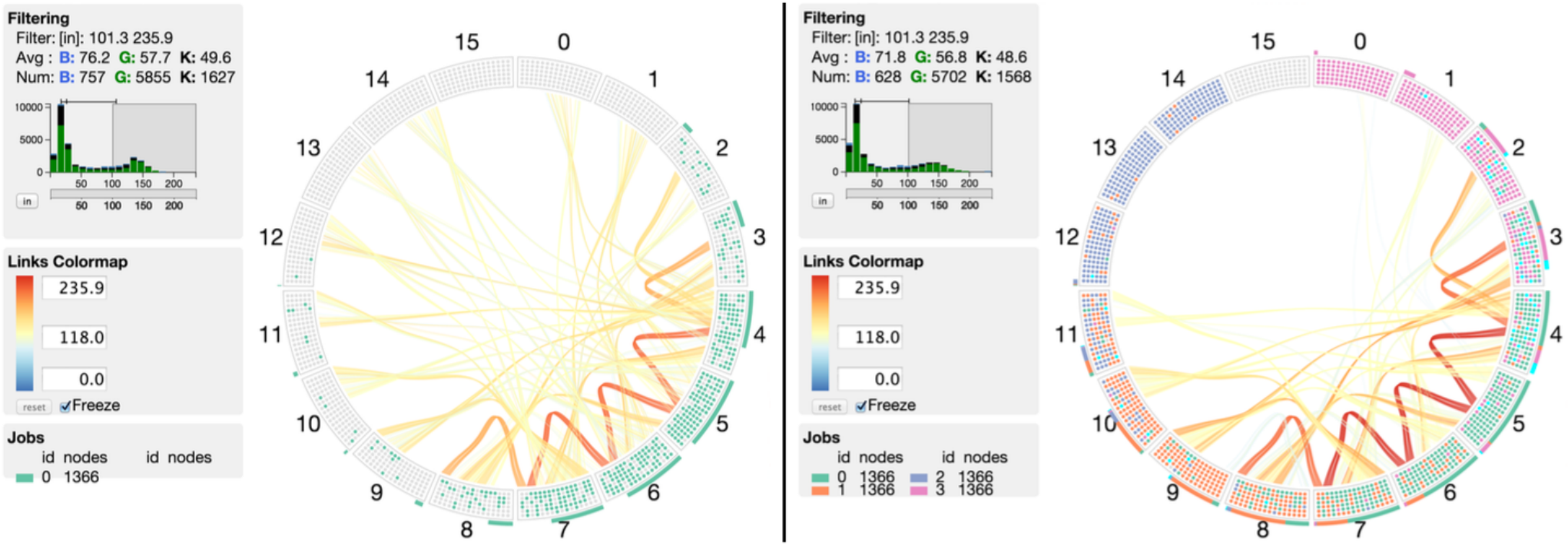


Figure 5: Visualizations of the network traffic on a dragonfly system for two different job workloads/scenarios (traffic output obtained using Damselfly). Comparing with a scenario in which Job 0 (4D Stencil) runs alone (left), when it is run in a workload along side other jobs (right), the number of links with traffic above a certain threshold decreases and overall maximum traffic on inter-group links increases (231 MB as opposed to 191 MB when run alone). In the parallel workload run, Job 0's traffic is confined to fewer inter-group links in order to share bandwidth with other jobs.

Abhinav Bhatele Task Mapping on Complex Computer Network Topologies for Improved Performance. LLNL-TR-678732 (FY2015 LDRD Final Report) http://charm.cs.uiuc.edu/~bhatele/pubs/pdf/2015/ldrd2015.pdf

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