High-Performance Computing Networks at BYU

Lloyd Brown

October 10, 2013

What makes a supercomputer, super?

HPC or High-Performance Computing, is characterized by workloads and hardware requirements

What makes a supercomputer, super?

HPC or High-Performance Computing, is characterized by workloads and hardware requirements

- Significantly larger compute capability than an average system

What makes a supercomputer, super?

HPC or High-Performance Computing, is characterized by workloads and hardware requirements

- Significantly larger compute capability than an average system
- Used to solve problems that are too large to easily be solved on a single, traditional system

What makes a supercomputer, super?

HPC or High-Performance Computing, is characterized by workloads and hardware requirements

- Significantly larger compute capability than an average system
- Used to solve problems that are too large to easily be solved on a single, traditional system
- May utilize specialty hardware and software

What makes a supercomputer, super?

HPC or High-Performance Computing, is characterized by workloads and hardware requirements

- Significantly larger compute capability than an average system
- Used to solve problems that are too large to easily be solved on a single, traditional system
- May utilize specialty hardware and software
- No specific threshold for capacity

Nature of HPC Computing

In HPC, speedup comes from one of two sources:

Nature of HPC Computing

In HPC, speedup comes from one of two sources:

- Using faster resources (eg. faster clock speeds)

Nature of HPC Computing

In HPC, speedup comes from one of two sources:

- Using faster resources (eg. faster clock speeds)
- Using more resources (eg. using more processors) or *Parallelism*

Nature of HPC Computing

In HPC, speedup comes from one of two sources:

- Using faster resources (eg. faster clock speeds)
- Using more resources (eg. using more processors) or *Parallelism*

Physics generally limits us on the faster resources, so we spend more time on parallelism.

Parallelism and Communication Needs

- When utilizing multiple resources (eg. multiple processors), the program must:

Parallelism and Communication Needs

- When utilizing multiple resources (eg. multiple processors), the program must:
  - Split up the workload

Parallelism and Communication Needs

- When utilizing multiple resources (eg. multiple processors), the program must:
  - Split up the workload
  - Provide necessary coordination among resources

Parallelism and Communication Needs

- When utilizing multiple resources (eg. multiple processors), the program must:
  - Split up the workload
  - Provide necessary coordination among resources
- The algorithm and data determine the nature of communication needs

Parallelism and Communication Needs

- When utilizing multiple resources (eg. multiple processors), the program must:
    - Split up the workload
    - Provide necessary coordination among resources
- The algorithm and data determine the nature of communication needs
- Therefore for HPC problems, communication is key.

Parallelism and Communication Needs

- When utilizing multiple resources (eg. multiple processors), the program must:
  - Split up the workload
  - Provide necessary coordination among resources
- The algorithm and data determine the nature of communication needs
- Therefore for HPC problems, communication is key.
  - For inter-process communication

Parallelism and Communication Needs

- When utilizing multiple resources (eg. multiple processors), the program must:
  - Split up the workload
  - Provide necessary coordination among resources
- The algorithm and data determine the nature of communication needs
- Therefore for HPC problems, communication is key.
  - For inter-process communication
  - For communicating with data storage

What kind of communication are we talking about?

What kind of communication are we talking about?

- Programs that utilize multiple processors to split up work, need to communicate between threads or processes, to coordinate efforts, report on results, etc.

What kind of communication are we talking about?

- Programs that utilize multiple processors to split up work, need to communicate between threads or processes, to coordinate efforts, report on results, etc.
- Communication between threads/processes on the same host ("*Intra*-node" communication) is extremely fast (usually via shared memory)

What kind of communication are we talking about?

- Programs that utilize multiple processors to split up work, need to communicate between threads or processes, to coordinate efforts, report on results, etc.
- Communication between threads/processes on the same host ("*Intra*-node" communication) is extremely fast (usually via shared memory)
- If the processes are on different hosts, we have to go out to some communication fabric ("*Inter*-node" communication)

What kind of communication are we talking about?

- Programs that utilize multiple processors to split up work, need to communicate between threads or processes, to coordinate efforts, report on results, etc.
- Communication between threads/processes on the same host ("*Intra*-node" communication) is extremely fast (usually via shared memory)
- If the processes are on different hosts, we have to go out to some communication fabric ("*Inter*-node" communication)
    - There's a lot of research in speeding up *intra*-node communication, but that's more of a Computer Science or Electrical Engineering problem. We'll spend our time today on *inter*-node communication

What is Infiniband? And why do I care?

Infiniband is the most common high-performance interconnect used in HPC. It:

What is Infiniband? And why do I care?

Infiniband is the most common high-performance interconnect used in HPC. It:

- is switched-fabric architecture (more like Fibre Channel than like Ethernet)

What is Infiniband? And why do I care?

Infiniband is the most common high-performance interconnect used in HPC. It:

- is switched-fabric architecture (more like Fibre Channel than like Ethernet)
- utilizes multiple speeds, lanes, and links

What is Infiniband? And why do I care?

Infiniband is the most common high-performance interconnect used in HPC. It:

- is switched-fabric architecture (more like Fibre Channel than like Ethernet)
- utilizes multiple speeds, lanes, and links
- provides:
  - extremely high bandwidth

What is Infiniband? And why do I care?

Infiniband is the most common high-performance interconnect used in HPC. It:

- is switched-fabric architecture (more like Fibre Channel than like Ethernet)
- utilizes multiple speeds, lanes, and links
- provides:
  - extremely high bandwidth
  - extremely low latency (one-way < 5 μs, compared to approx. 22 μs for 1GbE)

What is Infiniband? And why do I care?

Infiniband is the most common high-performance interconnect used in HPC. It:

- is switched-fabric architecture (more like Fibre Channel than like Ethernet)
- utilizes multiple speeds, lanes, and links
- provides:
  - extremely high bandwidth
  - extremely low latency (one-way $< 5\ \mu$s, compared to approx. 22 μs for 1GbE)
- Speedup comes mostly from:
  - Short protocol stack (very little above layer 2)

What is Infiniband? And why do I care?

Infiniband is the most common high-performance interconnect used in HPC. It:

- is switched-fabric architecture (more like Fibre Channel than like Ethernet)
- utilizes multiple speeds, lanes, and links
- provides:
  - extremely high bandwidth
  - extremely low latency (one-way $< 5\ \mu$s, compared to approx. 22 μs for 1GbE)
- Speedup comes mostly from:
  - Short protocol stack (very little above layer 2)
  - Low-latency switching (very little decision making in the switch)

What is Infiniband? And why do I care?

Infiniband is the most common high-performance interconnect used in HPC. It:

- is switched-fabric architecture (more like Fibre Channel than like Ethernet)
- utilizes multiple speeds, lanes, and links
- provides:
  - extremely high bandwidth
  - extremely low latency (one-way $< 5\ \mu$s, compared to approx. 22 μs for 1GbE)
- Speedup comes mostly from:
  - Short protocol stack (very little above layer 2)
  - Low-latency switching (very little decision making in the switch)
  - Remote Direct Memory Access (RDMA)

Lanes/Links/Speeds

Infiniband utilizes multiple lanes per physical link. Each link has a certain speed based on the standard:

Lanes/Links/Speeds

Infiniband utilizes multiple lanes per physical link. Each link has a certain speed based on the standard:

	SDR	*DDR*	*QDR*	*FDR*
1x	2.5 Gb/s	5 Gb/s	10 Gb/s	14 Gb/s
4x	10 Gb/s	20 Gb/s	40 Gb/s	56 Gb/s
12x	30 Gb/s	60 Gb/s	120 Gb/s	168 Gb/s

Encoding Overhead

Infiniband uses bit-line encodings to guarantee bit transitions for clock synchronization:

- SDR, DDR, QDR - 8b/10b encoding (8 data bytes encoded in 10 bytes total; 20% overhead)
- FDR and beyond - 64b/66b encoding (64 data bytes encoded in 66 bytes total; 3% overhead)

Encoding Overhead

Infiniband uses bit-line encodings to guarantee bit transitions for clock synchronization:

- SDR, DDR, QDR - 8b/10b encoding (8 data bytes encoded in 10 bytes total; 20% overhead)
- FDR and beyond - 64b/66b encoding (64 data bytes encoded in 66 bytes total; 3% overhead)

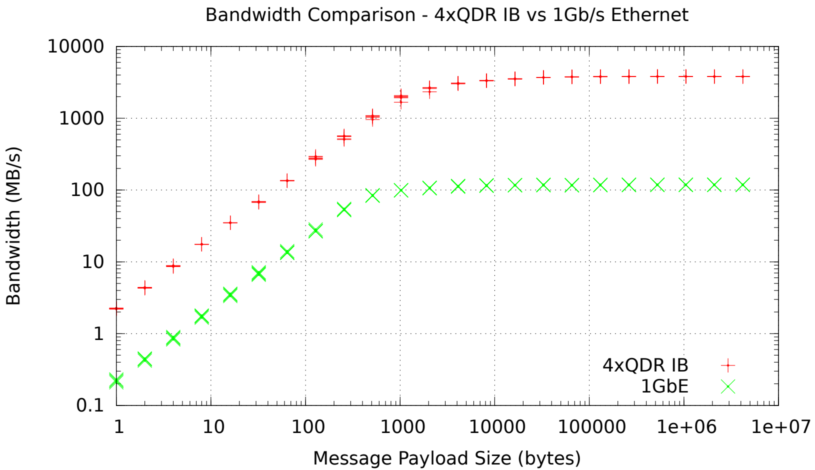
	SDR	*DDR*	*QDR*	*FDR*
1x	2.5 Gb/s raw 2 Gb/s net	5 Gb/s raw 4 Gb/s net	10 Gb/s raw 8 Gb/s net	14 Gb/s raw 13.6 Gb/s net
4x	10 Gb/s raw 8 Gb/s net	20 Gb/s raw 16 Gb/s net	40 Gb/s raw 32 Gb/s net	56 Gb/s raw 54.3 Gb/s net
12x	30 Gb/s raw 24 Gb/s net	60 Gb/s raw 48 Gb/s net	120 Gb/s raw 96 Gb/s net	168 Gb/s raw 162.9 Gb/s net

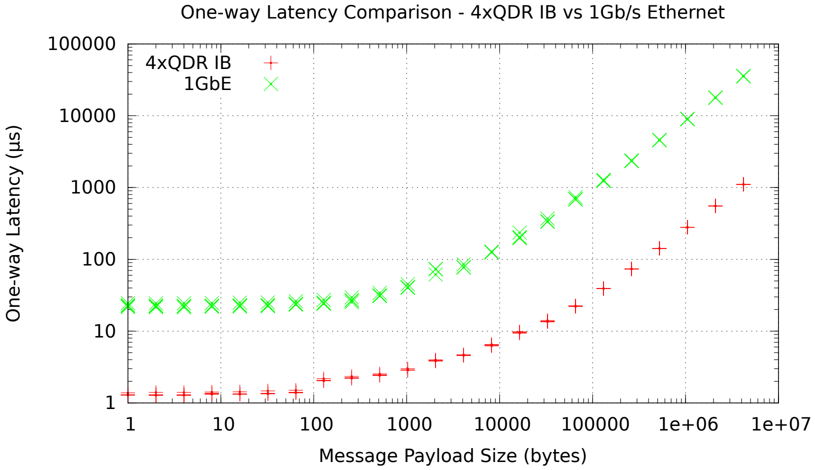
Performance at BYU's FSL

The graphs shown in the next couple of slides represent the bandwidth and latency performance of 4xQDR Infiniband vs 1Gb/s Ethernet at the Fulton Supercomputing Lab.

- All tests were performed host-to-host with one intervening switch (eg. host-switch-host)
- All tests utilize increasing message sizes, to demonstrate where one effect ends and the other starts
- Tests were performed using the "osu_bw" and "osu_latency" binaries from the OSU Micro-Benchmarks for MPI (a.k.a. "OMB")[1]

[1] http://mvapich.cse.ohio-state.edu/benchmarks/


Bandwidth Comparison - 4xQDR IB vs 1Gb/s Ethernet
Bandwidth (MB/s)
10000
1000
100
10
1
0.1
1
10
100
1000
10000
100000
1e+06
1e+07
Message Payload Size (bytes)
4xQDR IB
1GbE


One-way Latency Comparison - 4xQDR IB vs 1Gb/s Ethernet
4xQDR IB
1GbE
One-way Latency (μs)
100000
10000
1000
100
10
1
1
10
100
1000
10000
100000
1e+06
1e+07
Message Payload Size (bytes)

How Infiniband is Managed

Infiniband is designed as a trusted network. The network is managed by a *subnet manager* which does the following:

How Infiniband is Managed

Infiniband is designed as a trusted network. The network is managed by a *subnet manager* which does the following:

- Periodically sweep the network, looking for topology changes, checking for errors, etc.

How Infiniband is Managed

Infiniband is designed as a trusted network. The network is managed by a *subnet manager* which does the following:

- Periodically sweep the network, looking for topology changes, checking for errors, etc.
- Build a cohesive model of the network topology

How Infiniband is Managed

Infiniband is designed as a trusted network. The network is managed by a *subnet manager* which does the following:

- Periodically sweep the network, looking for topology changes, checking for errors, etc.
- Build a cohesive model of the network topology
- Load the switch forwarding tables with the LID/Port mapping

Infiniband Topologies

Infiniband puts very little restriction on the physical topology of the network.

- The Subnet Manager loads all the forwarding tables into the switches

Infiniband Topologies

Infiniband puts very little restriction on the physical topology of the network.

- The Subnet Manager loads all the forwarding tables into the switches
  - as long as you can build an appropriate graph parsing algorithm, and implement it in a subnet manager, you can use a topology

Infiniband Topologies

Infiniband puts very little restriction on the physical topology of the network.

- The Subnet Manager loads all the forwarding tables into the switches
  - as long as you can build an appropriate graph parsing algorithm, and implement it in a subnet manager, you can use a topology
  - allows some much more interesting topologies than those commonly Ethernet and TCP/IP networks usually use.[2]

[2] Technically you can use any topology with Ethernet as well. It just takes a huge amount of very-messy work, for very little benefit. I don't recommend trying it.

Possible Topologies

Possible Topologies

- Tree/Fat-Tree

Possible Topologies

- Tree/Fat-Tree
- Fully-connected Mesh

Possible Topologies

- Tree/Fat-Tree
- Fully-connected Mesh
- Torus

Possible Topologies

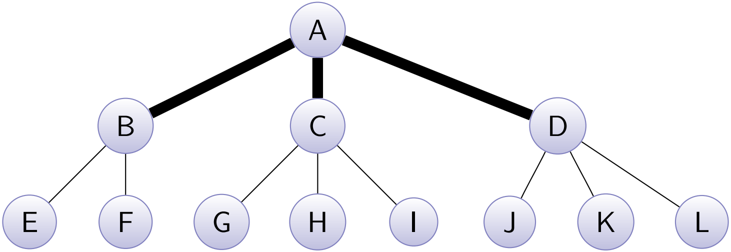
- Tree/Fat-Tree
- Fully-connected Mesh
- Torus
- Hypercube

Possible Topologies

- Tree/Fat-Tree
- Fully-connected Mesh
- Torus
- Hypercube
- Folded-Clos Network

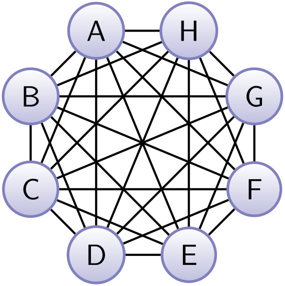
Fat Tree Example

A *Fat Tree* is basically a tree with increased bandwidth (faster links or more links) between upper tiers relative to lower tiers; Ethernet has no problems with this one, so it's not terribly exciting



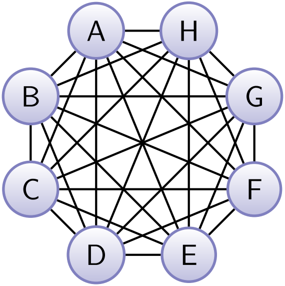
Fully-connected Mesh Example

- Pro: Shortest hop-count (1 hop) from any point to any other point



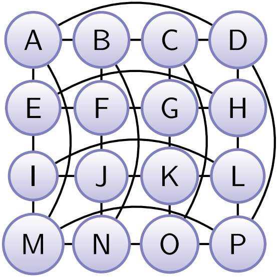
Fully-connected Mesh Example

- Pro: Shortest hop-count (1 hop) from any point to any other point
- Con: takes a huge amount of cables, and the cable count increases very, very quickly.



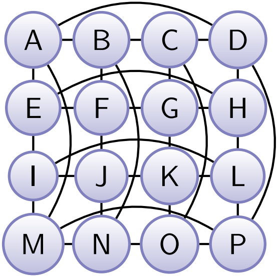
Torus example

- Pro: Excellent for large topologies (no core switches to buy)



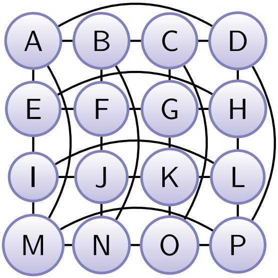
Torus example

- Pro: Excellent for large topologies (no core switches to buy)
- Con: Higher hop count than other options, depending on size and shape



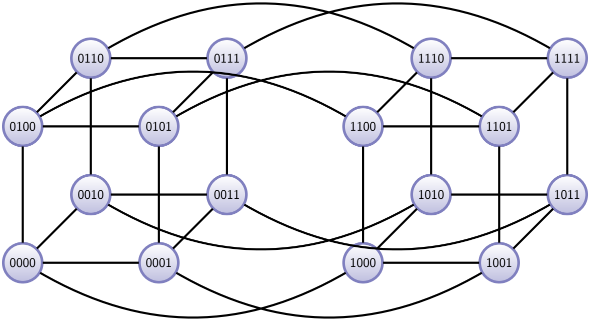
Torus example

- Pro: Excellent for large topologies (no core switches to buy)
- Con: Higher hop count than other options, depending on size and shape
- Con: Less desirable bandwidth ratios (MBB to Client BW; discussed later)



Hypercube example (4-dimensional)[3]

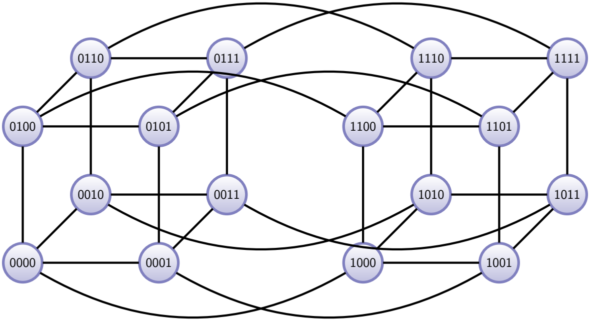
- Pro: for *d* dimensions, no more than *d* hops from any other point in the topology



[3]Note that this is really just a special case of a Torus.

Hypercube example (4-dimensional)[3]

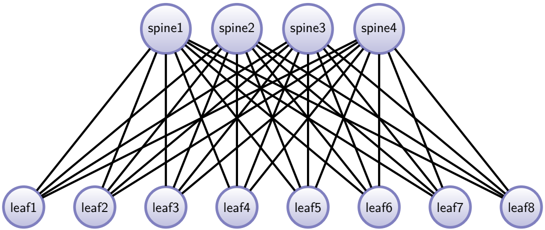
- Pro: for *d* dimensions, no more than *d* hops from any other point in the topology
- Con: cables/ports at each endpoint increase linearly with the dimension



[3] Note that this is really just a special case of a Torus.

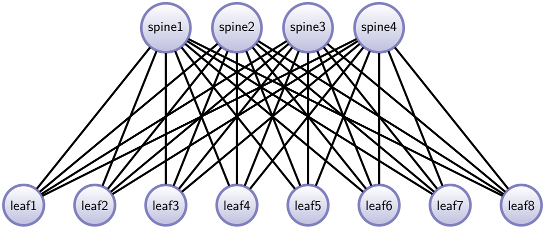
Folded Clos Network Example

- Pros:
    - Most common approach for small or medium-scale Infiniband fabrics



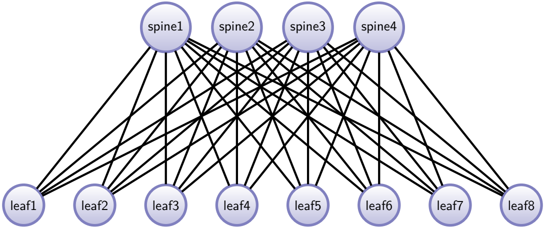
Folded Clos Network Example

- Pros:
  - Most common approach for small or medium-scale Infiniband fabrics
  - Well understood (how larger IB switches are designed internally)



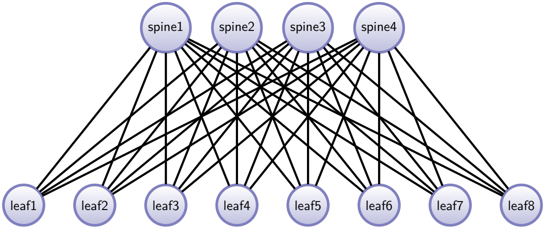
Folded Clos Network Example

- Pros:
  - Most common approach for small or medium-scale Infiniband fabrics
  - Well understood (how larger IB switches are designed internally)
  - Redundant; 1 link from each leaf to each spine



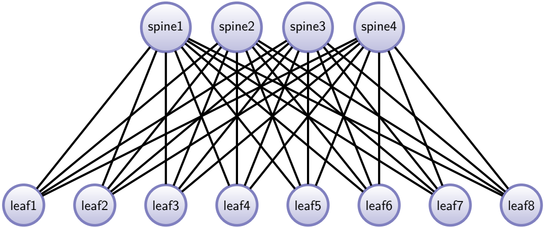
Folded Clos Network Example

- Pros:
  - Most common approach for small or medium-scale Infiniband fabrics
  - Well understood (how larger IB switches are designed internally)
  - Redundant; 1 link from each leaf to each spine
  - Easy to expand (up to the port count of the switches)



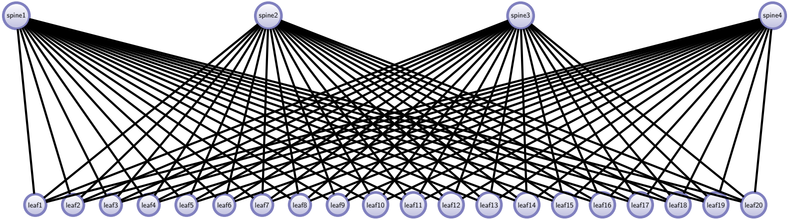
Folded Clos Network Example

- Pros:
  - Most common approach for small or medium-scale Infiniband fabrics
  - Well understood (how larger IB switches are designed internally)
  - Redundant; 1 link from each leaf to each spine
  - Easy to expand (up to the port count of the switches)
- Con: Scalability limited by the port count of spine & leaf switches



BYU Supercomputing's Clos Network

Note that this only shows the switches involved; there are 16 hosts attached to each leaf switch.



What are some important characteristics for evaluating networks and topologies?

What are some important characteristics for evaluating networks and topologies?

- Total host bandwidth

What are some important characteristics for evaluating networks and topologies?

- Total host bandwidth
- Latency/hop-count

What are some important characteristics for evaluating networks and topologies?

- Total host bandwidth
- Latency/hop-count
- Cost

What are some important characteristics for evaluating networks and topologies?

- Total host bandwidth
- Latency/hop-count
- Cost
- Ease of expansion

What are some important characteristics for evaluating networks and topologies?

- Total host bandwidth
- Latency/hop-count
- Cost
- Ease of expansion
- Minimum Bisection Bandwidth

What are some important characteristics for evaluating networks and topologies?

- Total host bandwidth
- Latency/hop-count
- Cost
- Ease of expansion
- Minimum Bisection Bandwidth
- MBB to Client BW Ratio

What's "Minimum Bisection Bandwidth"?

What's "Minimum Bisection Bandwidth"?

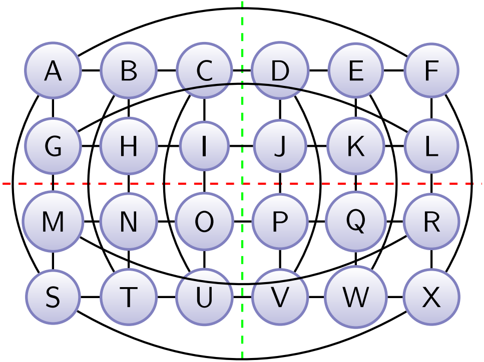
- If you were to draw a line across a topology, such that half the clients/switches/whatever are on each side of the line, the total bandwidth of all the links "cut" by that line is the *bisection bandwidth*

What's "Minimum Bisection Bandwidth"?

- If you were to draw a line across a topology, such that half the clients/switches/whatever are on each side of the line, the total bandwidth of all the links "cut" by that line is the *bisection bandwidth*
- Of all the possible *bisection bandwidth* lines, the one with the minimum bandwidth is called the *minimum bisection bandwidth*

MBB Example - Torus

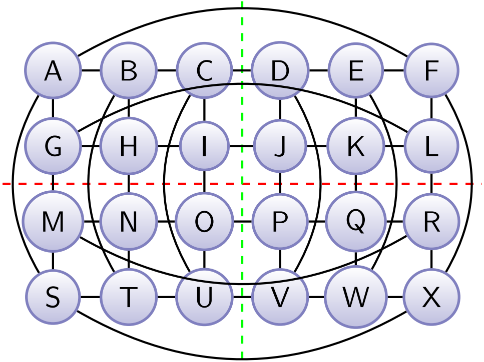
Which bisection line represents the minimum bandwidth bisection (assume all links are the same speed)?



MBB Example - Torus

Which bisection line represents the minimum bandwidth bisection (assume all links are the same speed)?

- Green line cuts 8 links; red line cuts 12 links; Green is the *minimum*



Why is MBB important?

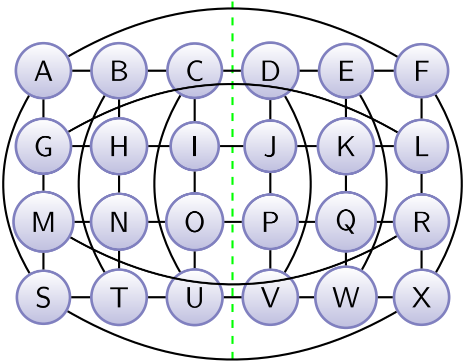
Why is MBB important?

- MBB represents the available bandwidth during a worst-case scenario:

Why is MBB important?

- MBB represents the available bandwidth during a worst-case scenario:
  - All the clients on one side of the MBB line are trying to communicate with someone on the other side of the line, as fast as possible

MBB Example - Torus



MBB vs Client BW - Torus

MBB vs Client BW - Torus

- Frequently we compare MBB to total Client Bandwidth on one side of the MBB line

MBB vs Client BW - Torus

- Frequently we compare MBB to total Client Bandwidth on one side of the MBB line
- Generally the smaller the ratio of MBB:Half-client-bandwidth, the better

MBB vs Client BW - Torus

- Frequently we compare MBB to total Client Bandwidth on one side of the MBB line
- Generally the smaller the ratio of MBB:Half-client-bandwidth, the better
- For example, using the diagram on the Torus slide:

MBB vs Client BW - Torus

- Frequently we compare MBB to total Client Bandwidth on one side of the MBB line
- Generally the smaller the ratio of MBB:Half-client-bandwidth, the better
- For example, using the diagram on the Torus slide:
  - Assuming each node is a switch, with 16 hosts hanging off it, what is the MBB:HalfClientBW ratio for the Green (MBB) line?
    - assume host-switch and switch-switch links are the same BW

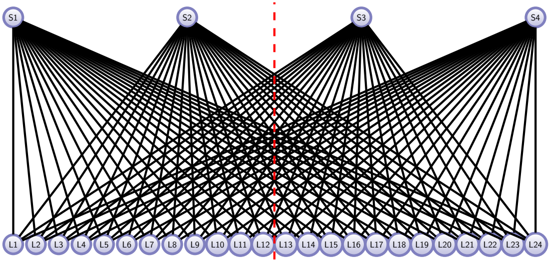
MBB vs Client BW - Torus

- Frequently we compare MBB to total Client Bandwidth on one side of the MBB line
- Generally the smaller the ratio of MBB:Half-client-bandwidth, the better
- For example, using the diagram on the Torus slide:
  - Assuming each node is a switch, with 16 hosts hanging off it, what is the MBB:HalfClientBW ratio for the Green (MBB) line?
    - assume host-switch and switch-switch links are the same BW
  - Each half has 12 switches, or 12*16=192 hosts, and the green line bisects 8 links, for a ratio of 24:1

MBB vs Client BW - Clos

Anyone want to try this one?

- Assume that 16 hosts are attached to each of the 24 switches at the bottom, and none to the 4 on the top
- 4 links coming out of each of the 24 switches on the bottom (1 to each of 4 core switch)



MBB vs Client BW - Clos

- Bisection line cuts 2 of 4 links per leaf switch (48 total links cut)

MBB vs Client BW - Clos

- Bisection line cuts 2 of 4 links per leaf switch (48 total links cut)
- 12 switches per half * 16 clients = 192 clients

MBB vs Client BW - Clos

- Bisection line cuts 2 of 4 links per leaf switch (48 total links cut)
- 12 switches per half * 16 clients = 192 clients
- 192:48 => 4:1

Multi-path Ethernet and TCP/IP

- Current efforts are underway to create multi-path options for more-common Ethernet and TCP/IP networks

Multi-path Ethernet and TCP/IP

- Current efforts are underway to create multi-path options for more-common Ethernet and TCP/IP networks
- Some approaches:
  - ECMP - Equal Cost Multi-Path Routing (layer 3)
    - Several layer 3 routing protocols support ECMP, including OSPF, IS-IS, and EIGRP

Multi-path Ethernet and TCP/IP

- Current efforts are underway to create multi-path options for more-common Ethernet and TCP/IP networks
- Some approaches:
  - ECMP - Equal Cost Multi-Path Routing (layer 3)
    - Several layer 3 routing protocols support ECMP, including OSPF, IS-IS, and EIGRP
  - TRILL - Transparent Interconnection of Lots of Links - Multi-path layer-2 Ethernet[4]

[4] The best reference I'm aware of is *Introduction to Trill* by Radia Perlman and Donald Eastlake, available at `http://www.ipjforum.org/?p=582`

What do I need to learn from this?

What do I need to learn from this?

- Not everything is Ethernet and TCP/IP

What do I need to learn from this?

- Not everything is Ethernet and TCP/IP
- A Tree-like topology may not be the best arrangement for a specific application, especially in data centers

What do I need to learn from this?

- Not everything is Ethernet and TCP/IP
- A Tree-like topology may not be the best arrangement for a specific application, especially in data centers
- You absolutely *must* understand the communication patterns of your application, in order to select the correct technology and topology

What do I need to learn from this?

- Not everything is Ethernet and TCP/IP
- A Tree-like topology may not be the best arrangement for a specific application, especially in data centers
- You absolutely *must* understand the communication patterns of your application, in order to select the correct technology and topology
- What you're used to doing now, may change in the future

Questions?

Any questions?