Data Center Networking

Prof. Andrzej Duda

1

Cloud Computing – Data Centers

2

What's a Cloud Service Data Center?

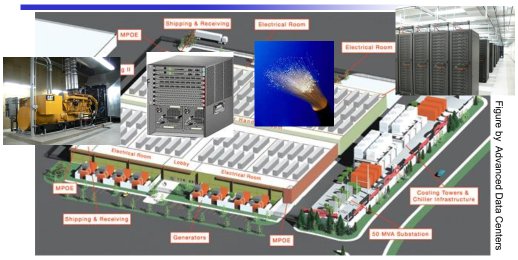


Figure by Advanced Data Centers

- Electrical power and economies of scale determine total data center size: 50,000 – 200,000 servers today
- Servers divided up among hundreds of different services
- Scale-out is paramount: some services have 10s of servers, some have 10s of 1000s

3

Data Center Costs

Amortized Cost*	Component	Sub-Components
~45%	Servers	CPU, memory, disk
~25%	Power infrastructure	UPS, cooling, power distribution
~15%	Power draw	Electrical utility costs
~15%	Network	Switches, links, transit

*3 yr amortization for servers, 15 yr for infrastructure; 5% cost of money

- Total cost varies
  - upwards of $1/4 B for mega data center
  - server costs dominate
  - network costs significant
- Long provisioning timescales:
  - new servers purchased quarterly at best

4

Overall Data Center Design Goal

Agility – Any service, Any Server

- Turn the servers into a single large fungible pool
  - Let services "breathe" : dynamically expand and contract their footprint as needed
    - We already see how this is done in terms of Google's GFS, BigTable, MapReduce
- Benefits
  - Increase service developer productivity
  - Lower cost
  - Achieve high performance and reliability

These are the three motivators for most data center infrastructure projects!

5

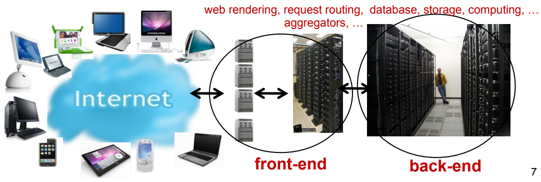
Cloud Computing

- Elastic resources
  - Expand and contract resources
  - Pay-per-use
  - Infrastructure on demand
- Multi-tenancy
  - Multiple independent users
  - Security and resource isolation
  - Amortize the cost of the (shared) infrastructure
- Flexibility service management
  - Resiliency: isolate failure of servers and storage
  - Workload movement: move work to other locations

6

Internet and Web …

- From "traditional" web to "web service" (or SOA)
  - – no longer simply "file" (or web page) downloads
    - pages often dynamically generated, more complicated "objects" (e.g., Flash videos used in YouTube)
  - – HTTP is used simply as a "transfer" protocol
    - many other "application protocols" layered on top of HTTP
  - – web services & SOA (service-oriented architecture)
- A schematic representation of "modern" web services



7

Data Center Network

8

Networking Objectives

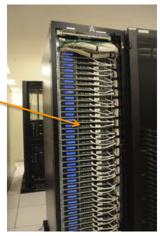
1. Uniform high capacity
   - Capacity between servers limited only by their NICs
   - No need to consider topology when adding servers

     => In other words, high capacity between two any servers no matter which racks they are located !
2. Performance isolation
   - Traffic of one service should be unaffected by others
3. Ease of management: "Plug-&-Play" (layer-2 semantics)
   - Flat addressing, so any server can have any IP address
   - Server configuration is the same as in a LAN
   - Legacy applications depending on broadcast must work

9

What goes into a datacenter (network)?

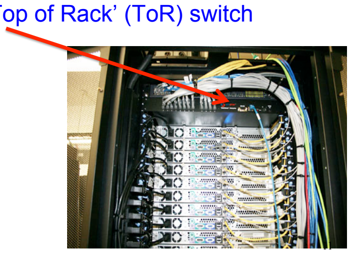
- Servers organized in racks



10

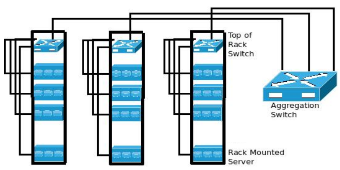
What goes into a datacenter (network)?

- Servers organized in racks
- Each rack has a `Top of Rack' (ToR) switch



What goes into a datacenter (network)?

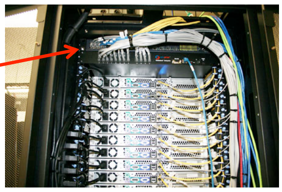
- Servers organized in racks
- Each rack has a `Top of Rack' (ToR) switch
- An `aggregation fabric' interconnects ToR switches

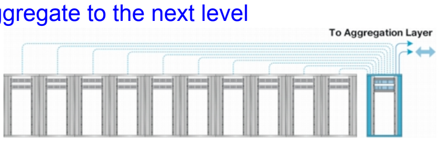


12

Top-of-Rack Architecture

- Rack of servers
  - Commodity servers
  - And top-of-rack switch
- Modular design
  - Preconfigured racks
  - Power, network, and storage cabling
- Aggregate to the next level





13

Top-of-Rack Architecture

- A rack has ~20-40 servers

Front of a rack

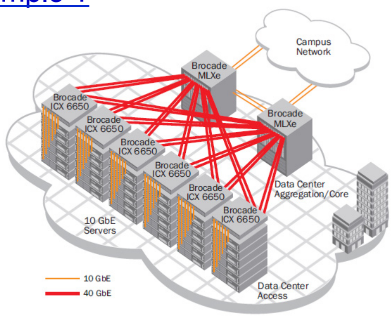
Rear of a rack

- Example of a TOR switch with 48 ports

"Top of Rack" switch

14

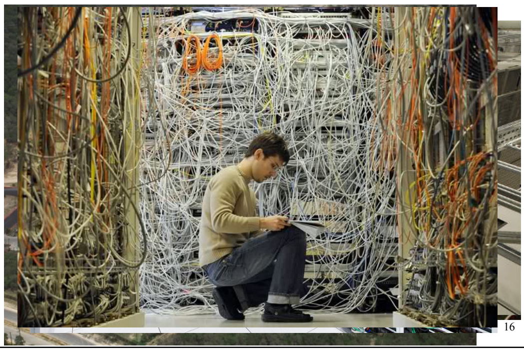
Example 1



Brocade reference design

15

SCALE!



16

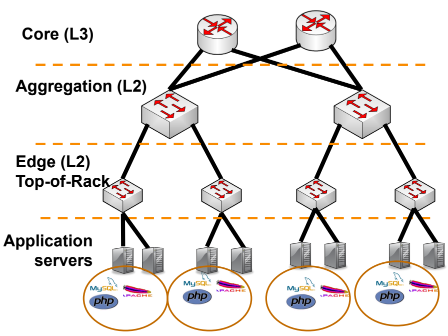
How big exactly?

- 1M servers [Microsoft]
  - less than Google, more than Amazon
- > $1B to build one site [Facebook]
- >$20M/month/site operational costs [Microsoft '09]

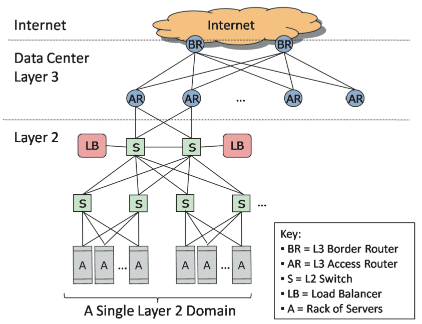
But only O(10-100) sites

17

Canonical Data Center Architecture



Data Center – Cisco Architecture



19

Example configuration

- Data center with 11'520 machines
- Machines organized in racks and rows
  - Data center with 24 rows
  - Each row with 12 racks
  - Each rack with 40 blades
- Machines in a rack interconnected with a ToR switch (access layer)
  - ToR Switch with 48 GbE ports and 4 10GbE uplinks
- ToR switches connect to End-of-Row (EoR) switches via 1-4 10GigE uplinks (aggregation layer)
  - For fault-tolerance ToR might be connected to EoR switches of different rows
- EoR switches typically 10GbE
  - To support 12 ToR switches EoR would have to have 96 ports (4*12*2)
- Core Switch layer
  - 12 10GigE switches with 96 ports each (24*48 ports)

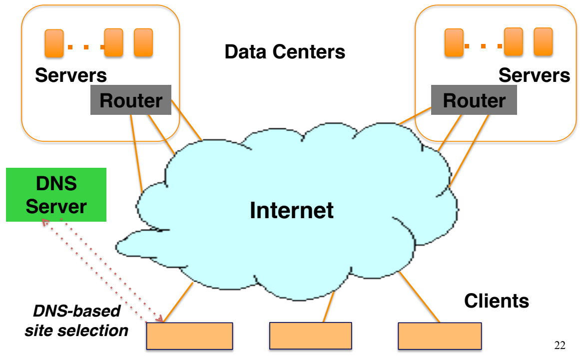
20

Componentization leads to different types of network traffic

- "North-South traffic"
  - Traffic between external clients and the datacenter
  - Handled by front-end (web) servers, mid-tier application servers, and back-end databases
  - Traffic patterns fairly stable, though diurnal variations

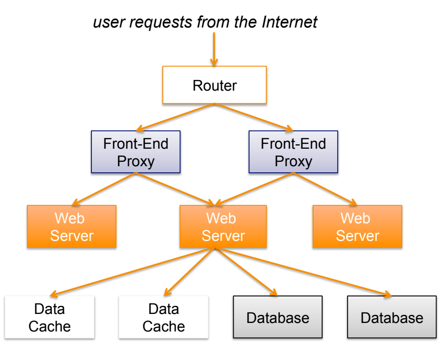
21

Wide-Area Network



22

North-South Traffic



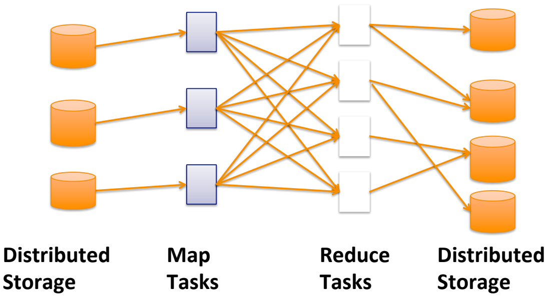
23

Componentization leads to different types of network traffic

- "North-South traffic"
  - Traffic between external clients and the datacenter
  - Handled by front-end (web) servers, mid-tier application servers, and back-end databases
  - Traffic patterns fairly stable, though diurnal variations
- "East-West traffic"
  - Traffic between machines in the datacenter
  - Comm *within* "big data" computations (e.g. Map Reduce)
  - Traffic may shift on small timescales (e.g., minutes)

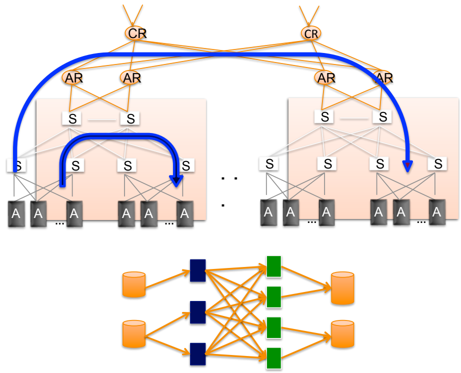
24

East-West Traffic

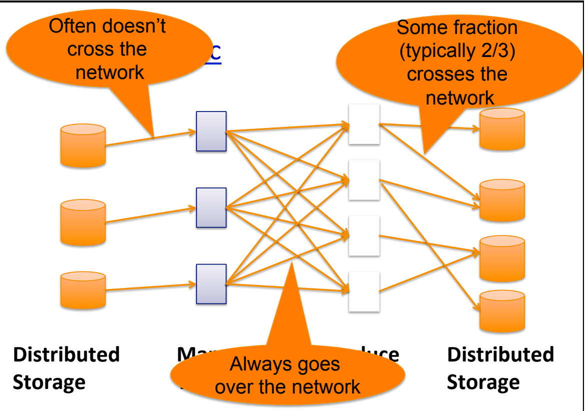


25

East-West Traffic



26



27

What's different about DC networks?

Characteristics

- Huge scale:
  - ~20,000 switches/routers
  - *contrast: AT&T ~500 routers*

What's different about DC networks?

Characteristics

- Huge scale:
- Limited geographic scope:
  - High bandwidth: 10/40/100G
  - *Contrast: Cable/aDSL/WiFi*
  - Very low RTT: 10s of microseconds
  - *Contrast: 100s of milliseconds in the WAN*

29

What's different about DC networks?

Characteristics

- Huge scale
- Limited geographic scope
- Single administrative domain
  - Can deviate from standards, invent your own, *etc.*
  - "Green field" deployment is still feasible

30

What's different about DC networks?

Characteristics

- Huge scale
- Limited geographic scope
- Single administrative domain
- Control over one/both endpoints
  - can change (say) addressing, congestion control, *etc.*
  - can add mechanisms for security/policy/etc. at the endpoints (typically in the hypervisor)

31

What's different about DC networks?

Characteristics

- Huge scale
- Limited geographic scope
- Single administrative domain
- Control over one/both endpoints
- Control over the *placement* of traffic source/sink
  - e.g., map-reduce scheduler chooses where tasks run
  - alters traffic pattern (what traffic crosses which links)

32

What's different about DC networks?

Characteristics

- Huge scale
- Limited geographic scope
- Single administrative domain
- Control over one/both endpoints
- Control over the *placement* of traffic source/sink
- Regular/planned topologies (e.g., trees/fat-trees)
  - Contrast: ad-hoc WAN topologies (dictated by real-world geography and facilities)

33

What's different about DC networks?

Characteristics

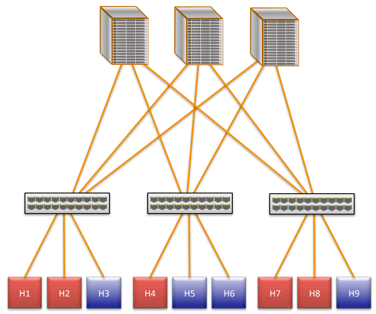
- Huge scale
- Limited geographic scope
- Single administrative domain
- Control over one/both endpoints
- Control over the *placement* of traffic source/sink
- Regular/planned topologies (e.g., trees/fat-trees)
- Limited heterogeneity
  - link speeds, technologies, latencies, …

34

High Bandwidth

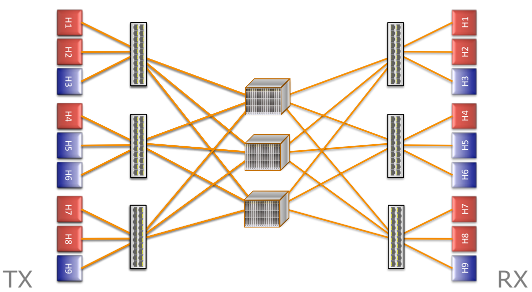
- Ideal: Each server can talk to any other server at its full access link rate
- Conceptually: DC network as one giant switch

DC Network: Just a Giant Switch!



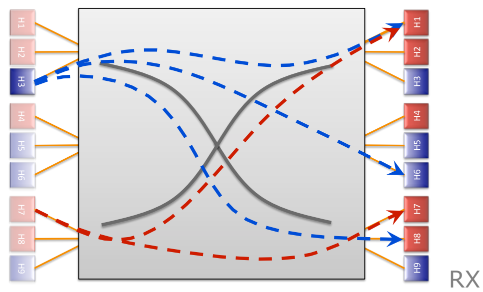
Slides from: Alizadeh, HotNets 2012

DC Network: Just a Giant Switch!



Slides from: Alizadeh, HotNets 2012

DC Network: Just a Giant Switch!



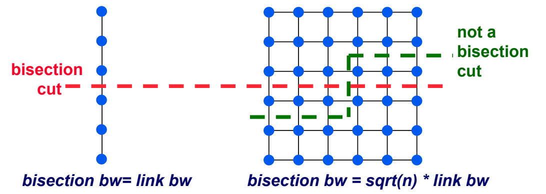
Slides from: Alizadeh, HotNets 2012

High Bandwidth

- Ideal: Each server can talk to any other server at its full access link rate
- Conceptually: DC network as one giant switch
  - Would require a 10 Pbits/sec switch!
    - 1M ports (one port/server)
    - 10Gbps per port
- Practical approach: build a network of switches ("fabric") with high "bisection bandwidth"
  - Each switch has practical #ports and link speeds

Performance Properties of a Network: Bisection Bandwidth

- Bisection bandwidth: bandwidth across smallest cut that divides network into two equal halves
- Bandwidth across "narrowest" part of the network



- Why is it relevant: if traffic is completely random, the probability of a message going across the two halves is 1/2 – if all nodes send a message, the bisection bandwidth will have to be N/2

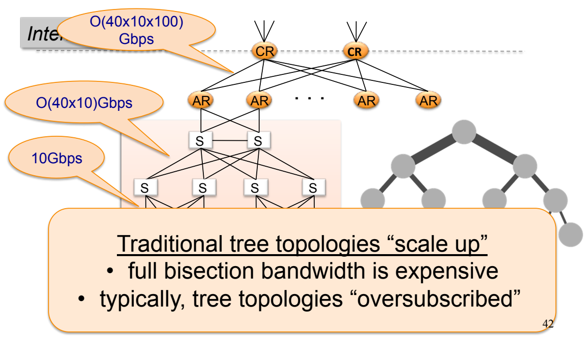
What's different about DC networks?

Goals

- Extreme bisection bandwidth requirements
  - recall: all that east-west traffic
  - target: any server can communicate at its full link speed
  - problem: server's access link is 10Gbps!

41

Full Bisection Bandwidth

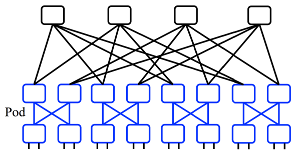


42

A “Scale Out” Design

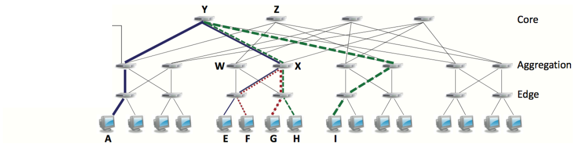
- Build multi-stage `Fat Trees' out of k-port switches
  - k/2 ports up, k/2 down
  - Supports $k^3/4$ hosts:
    - 48 ports, 27,648 hosts

All links are the same speed (e.g. 10Gps)



43

Full Bisection Bandwidth Not Sufficient



- To realize full bisectional throughput, routing must spread traffic across paths
- Enter load-balanced routing
  - How? (1) Let the network split traffic/flows at random (e.g., ECMP protocol -- RFC 2991/2992)
  - How? (2) Centralized flow scheduling?
  - Many more research proposals

44

What’s different about DC networks?

Goals

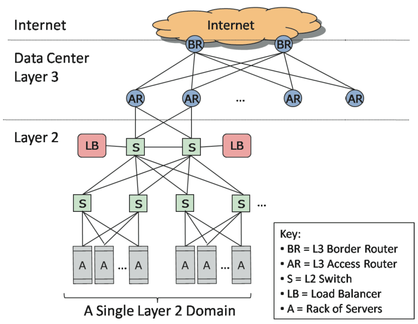
- Extreme bisection bandwidth requirements
- Extreme latency requirements
  - real money on the line
  - current target: 1μs RTTs
  - how? cut-through switches making a comeback
  - how? avoid congestion
  - how? fix TCP timers (e.g., default timeout is 500ms!)
  - how? fix/replace TCP to more rapidly fill the pipe

45

Advanced Data Center Architectures

46

Data Center – Cisco Architecture

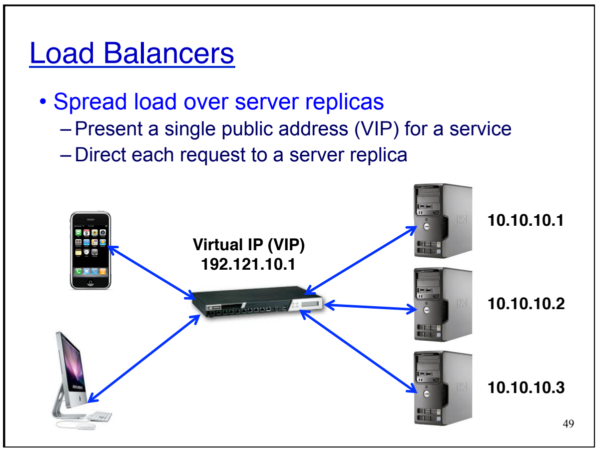


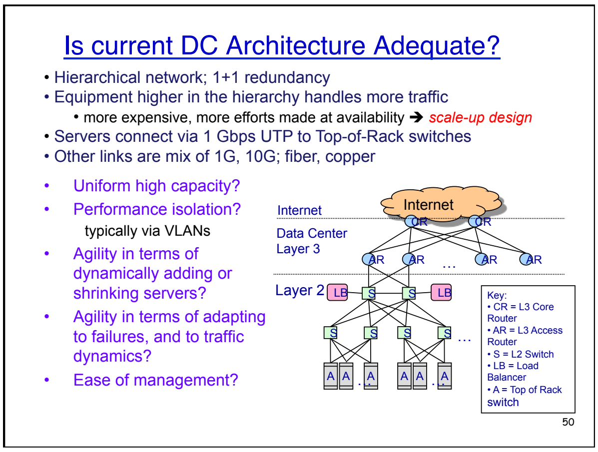
47

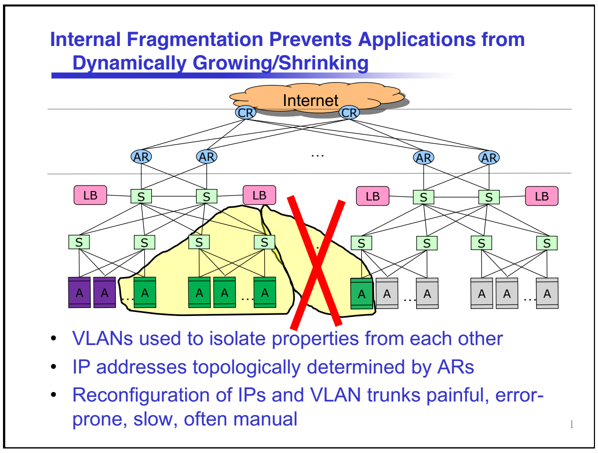
Reminder: Layer 2 vs. Layer 3

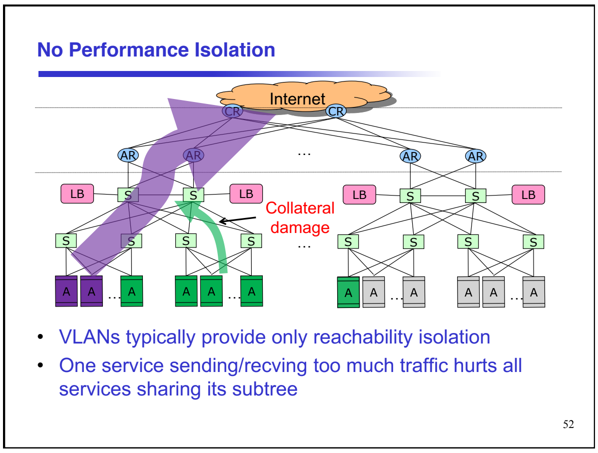
- Ethernet switching (layer 2)
  - Cheaper switch equipment
  - Fixed addresses and auto-configuration
  - Seamless mobility, migration, and failover
- IP routing (layer 3)
  - Scalability through hierarchical addressing
  - Efficiency through shortest-path routing
  - Multipath routing through Equal-Cost MultiPath (ECMP)
- So, like in enterprises…
  - Data centers often connect layer-2 islands by IP routers

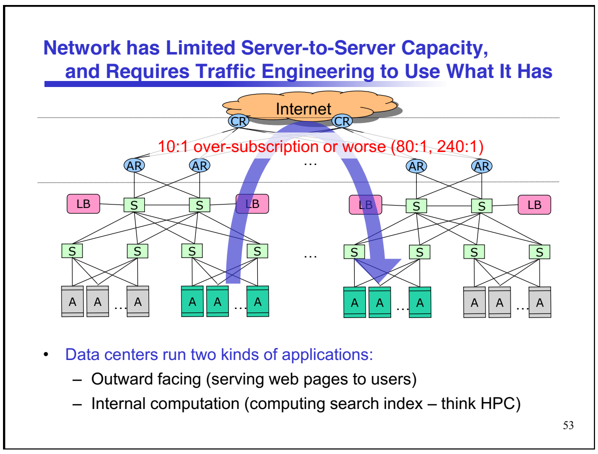
48

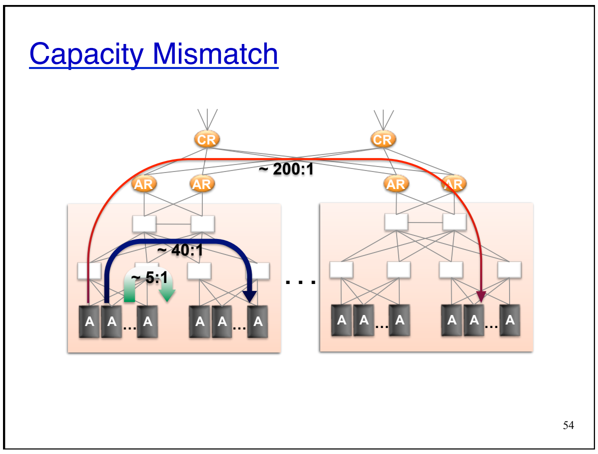

Load Balancers
• Spread load over server replicas
– Present a single public address (VIP) for a service
– Direct each request to a server replica
Virtual IP (VIP)
192.121.10.1
10.10.10.1
10.10.10.2
10.10.10.3
49


Is current DC Architecture Adequate?
• Hierarchical network; 1+1 redundancy
• Equipment higher in the hierarchy handles more traffic
• more expensive, more efforts made at availability → scale-up design
• Servers connect via 1 Gbps UTP to Top-of-Rack switches
• Other links are mix of 1G, 10G; fiber, copper
• Uniform high capacity?
• Performance isolation?
typically via VLANs
• Agility in terms of dynamically adding or shrinking servers?
• Agility in terms of adapting to failures, and to traffic dynamics?
• Ease of management?
Internet
Data Center
Layer 3
Layer 2
Key:
• CR = L3 Core Router
• AR = L3 Access Router
• S = L2 Switch
• LB = Load Balancer
• A = Top of Rack switch
50

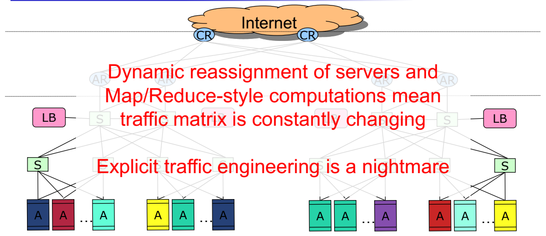

Internal Fragmentation Prevents Applications from Dynamically Growing/Shrinking
Internet
• VLANs used to isolate properties from each other
• IP addresses topologically determined by ARs
• Reconfiguration of IPs and VLAN trunks painful, error-prone, slow, often manual


No Performance Isolation
Internet
Collateral damage
• VLANs typically provide only reachability isolation
• One service sending/recving too much traffic hurts all services sharing its subtree
52


Network has Limited Server-to-Server Capacity, and Requires Traffic Engineering to Use What It Has
Internet
10:1 over-subscription or worse (80:1, 240:1)
• Data centers run two kinds of applications:
– Outward facing (serving web pages to users)
– Internal computation (computing search index – think HPC)
53


Capacity Mismatch
~ 200:1
~ 40:1
~ 5:1
54

Network Needs Greater Bisection BW, and Requires Traffic Engineering to Use What It Has



- Data centers run two kinds of applications:
  - Outward facing (serving web pages to users)
  - Internal computation (computing search index – think HPC)

55

Objectives for the Network of Single Data Center

Developers want ***network virtualization***: a mental model where all their servers, and only their servers, are plugged into an Ethernet switch

- Uniform high capacity
  - Capacity between two servers limited only by their NICs
  - No need to consider topology when adding servers
- Performance isolation
  - Traffic of one service should be unaffected by others
- Layer-2 semantics
  - Flat addressing, so any server can have any IP address
  - Server configuration is the same as in a LAN
  - Legacy applications depending on broadcast must work

56

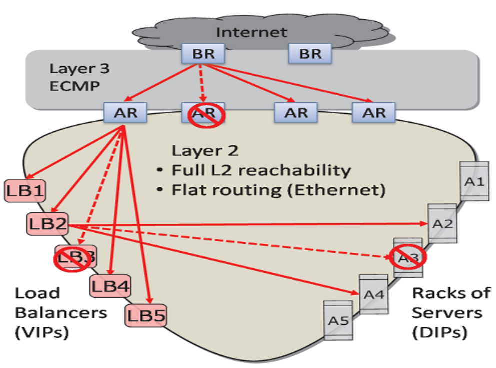
Monsoon

57

Monsoon approach

- Layer 2 based using commodity switches
- Hierarchy has 2 types of switches:
  - access switches (top of rack)
  - load balancing switches
- Eliminate spanning tree
  - Flat routing
  - Allows network to take advantage of path diversity
- Prevent MAC address learning
  - Monsoon Agent distribute data plane information
  - TOR: Only need to learn address for the intermediate switches
  - Core: learn for TOR switches
- Support efficient grouping of hosts (VLAN replacement)

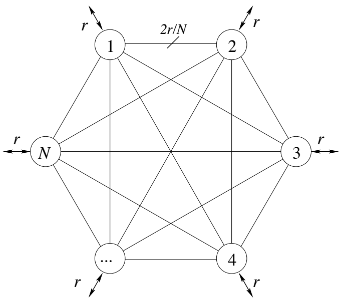
Moonson



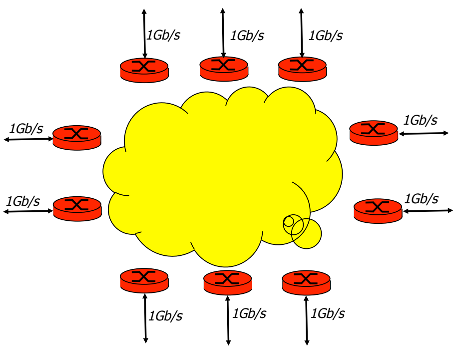
Monsoon Components

- Top-of-Rack switch:
  - Aggregate traffic from 20 end host in a rack
  - Performs IP to MAC translation
- Intermediate Switch
  - Disperses traffic
  - Balances traffic among switches
  - Used for Valiant load balancing
- Decision Element
  - Places routes in switches
  - Maintain a directory services of IP to MAC
- Endhost
  - Performs IP to MAC lookup

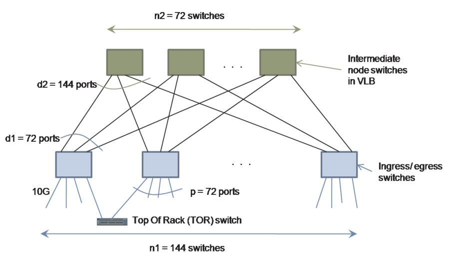
Valiant Load Balancing



61



Switch Topology



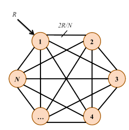
- Example topology for layer 2 switches connecting 103,680 servers. Uses Valiant Load Balancing to support any feasible traffic matrix.

Interconnection structure

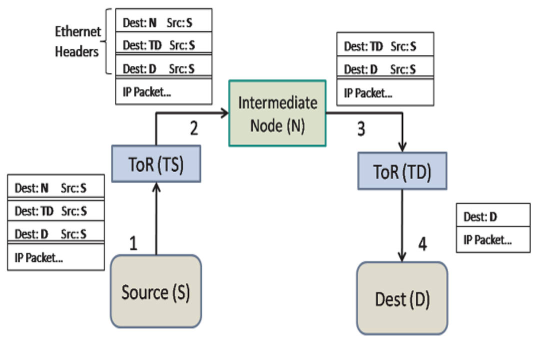
- You must set up a network peering N x N, N = 10, where each connected source can generate traffic up to 1 Gb/s.
- What would be an interconnection structure based Ethernet switches that have the following characteristics:
  - 1 port of 1 Gb/s, 10 ports of 200 Mb/s

Interconnection structure

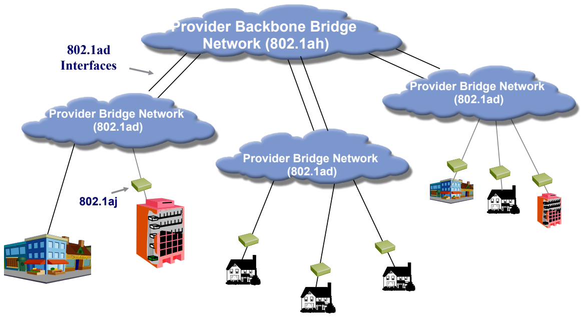
- You have N Ethernet switches with 100 ports of 1 Gb/s.
- You need to design an interconnection structure that can support any traffic matrix.
- What is the largest single network you can build (maximum number of server-facing ports R)? How many switches N are required to build the largest possible network?



Forwarding



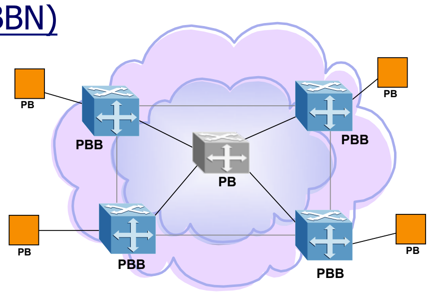
IEEE 802.1ah (Provider Backbone Bridge) Context



CFM - Connectivity Fault Management (802.1ag) runs end-to-end

69

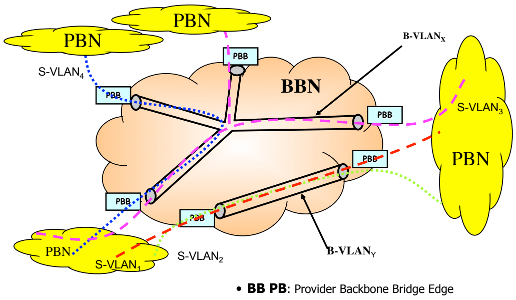
Provider Backbone Bridge Network (PBBN)



- **PB**: Provider Bridge (as defined by 802.1ad)
- **PBB**: Provider Backbone Bridge Edge (as defined by 802.1ah)

70

PBBN: tunnels between PBNs



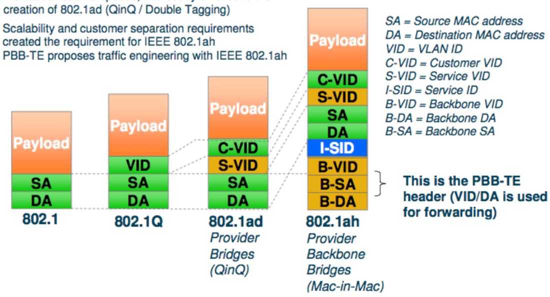
- **BB PB**: Provider Backbone Bridge Edge

- Each B-VLAN carries many S-VLANs
- S-VLANs may be carried on a subset of a B-VLAN (i.e. all P-P S-VLANs could be carried on a single MP B-VLAN providing connection to all end points.

71

Encapsulation

- Increased reach & speeds, interest by SPs led to the creation of 802.1ad (QinQ / Double Tagging)
- Scalability and customer separation requirements created the requirement for IEEE 802.1ah
- PBB-TE proposes traffic engineering with IEEE 802.1ah



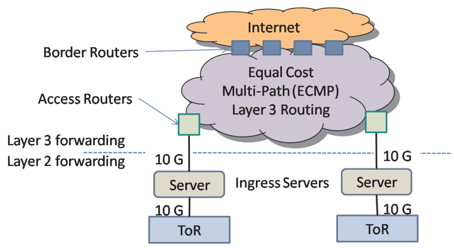
72

Agreed Terminology

- IEEE 802.1ad Terminology
  - C-TAG Customer VLAN TAG
  - C-VLAN Customer VLAN
  - C-VID Customer VLAN ID
  - S-TAG Service VLAN TAG
  - S-VLAN Service VLAN
  - S-VID Service VLAN ID
- Additional Provider Backbone Bridge Terminology
  - I-TAG Extended Service TAG
  - I-SID Extended Service ID
  - C-MAC Customer MAC Address
  - B-MAC Backbone MAC Address
  - B-VLAN Backbone VLAN (tunnel)
  - B-TAG Backbone TAG Field
  - B-VID Backbone VLAN ID (tunnel)

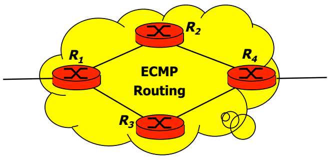
73

External Connections



- Network path for connections across the Internet. ECMP provides resiliency at Layer 3 for Access Router failures. Traffic is routed to nodes inside the data center with the help of Ingress Servers.

Equal Cost Multi-Path



- Three packets arrive at R_1 for destination R_4
- P_1: IP dst=R_4, TCP dst port=22
- P_2: IP dst=R_4, TCP dst port=80
- P_1: IP dst=R_4, TCP dst port=80

How routing works

- End-host checks flow cache for MAC of flow
  - If not found ask monsoon agent to resolve
  - Agent returns list of MACs for server and MACs for intermediate routers
- Send traffic to Top of Router
  - Traffic is triple encapsulated
- Traffic is sent to intermediate destination
- Traffic is sent to Top of Rack switch of destination

Monsoon Agent Lookup