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DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

19ECT301- COMMUNICATION NETWORKS

III YEAR/ V SEMESTER

UNIT V MULTILAYERING NETWORK

TOPIC 4–Data Center Networking

Data Center Networking

Major Theme:

What are new networking issues posed by large-scale data centers?

- Network Architecture?
- Topology design?
- Addressing?
- Routing?
- Forwarding?

Please do the required readings!

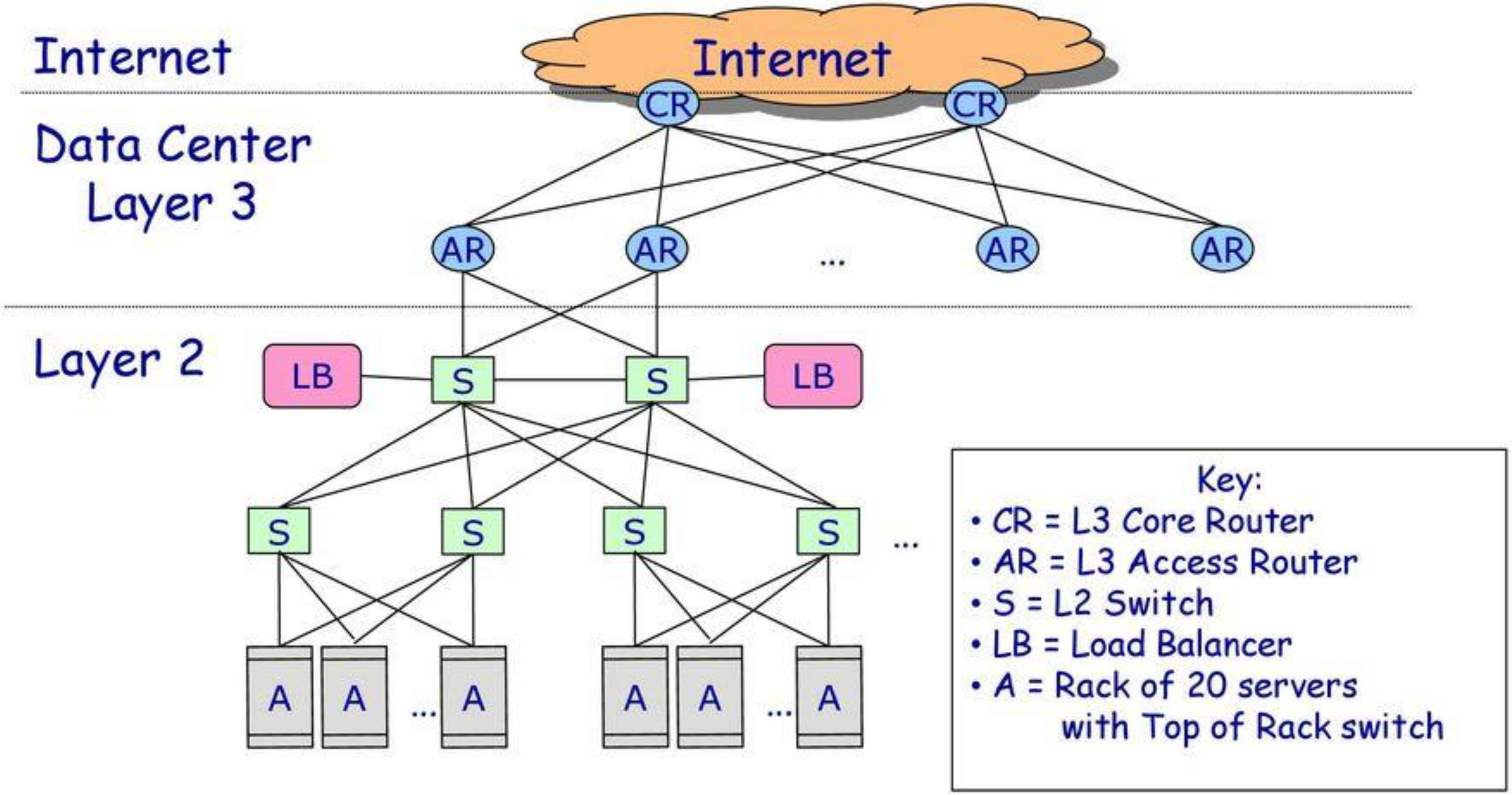
Data Center Interconnection Structure

- Nodes in the system: racks of servers
- How are the nodes (racks) inter-connected?
  - Typically a hierarchical inter-connection structure
- Today's typical data center structure

  Cisco recommended data center structure:

  starting from the bottom level
  - rack switches
  - 1-2 layers of (layer-2) aggregation switches
  - access routers
  - core routers
- Is such an architecture good enough?

Cisco Recommended DC Structure: Illustration



Data Center Design Requirements

- Data centers typically run two types of applications
  - outward facing (e.g., serving web pages to users)
  - internal computations (e.g., MapReduce for web indexing)
- Workloads often unpredictable:
  - Multiple services run concurrently within a DC
  - Demand for new services may spike unexpected
    - Spike of demands for new services mean success!
    - But this is when success spells trouble (if not prepared)!
- Failures of servers are the norm
  - Recall that GFS, MapReduce, etc., resort to dynamic re-assignment of chunkservers, jobs/tasks (worker servers) to deal with failures; data is often replicated across racks, …
  - "Traffic matrix" between servers are constantly changing

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

Source: the Cost of a Cloud: Research Problems in Data Center Networks. Sigcomm CCR 2009. Greenberg, Hamilton, Maltz, Patel.

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!

Achieving Agility …

- Workload Management
  - means for rapidly installing a service's code on a server
  - *dynamical cluster scheduling and server assignment* ☑
    - *E.g., MapReduce, Bigtable, …*
  - *virtual machines, disk images* ☑
- Storage Management
  - means for a server to access persistent data
  - *distributed file systems (e.g., GFS)* ☑
- Network Management
  - Means for communicating with other servers, regardless of where they are in the data center
  - Achieve high performance and reliability

Networking Objectives

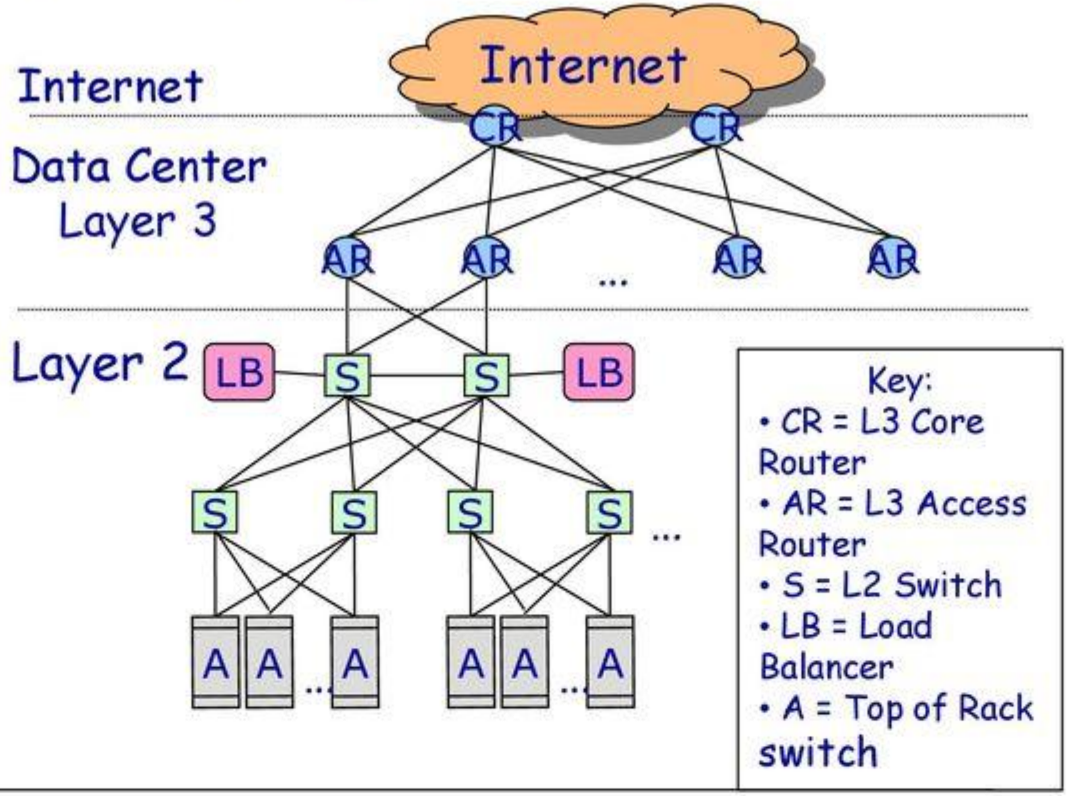
1. Uniform high capacity
   - Capacity between servers limited only by their NICs
   - No need to consider topology when adding servers

   => 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

Is Today's 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?



Case Studies

- A Scalable, Commodity Data Center Network Architecture
  - a new Fat-tree "inter-connection" structure (topology) to increases "bi-section" bandwidth
    - needs "new" addressing, forwarding/routing
- VL2: A Scalable and Flexible Data Center Network
  - consolidate layer-2/layer-3 into a "virtual layer 2"
  - separating "naming" and "addressing", also deal with dynamic load-balancing issues

Optional Materials

- PortLand: A Scalable Fault-Tolerant Layer 2 Data Center Network Fabric
- BCube: A High-Performance, Server-centric Network Architecture for Modular Data Centers

A Scalable, Commodity Data Center Network Architecture

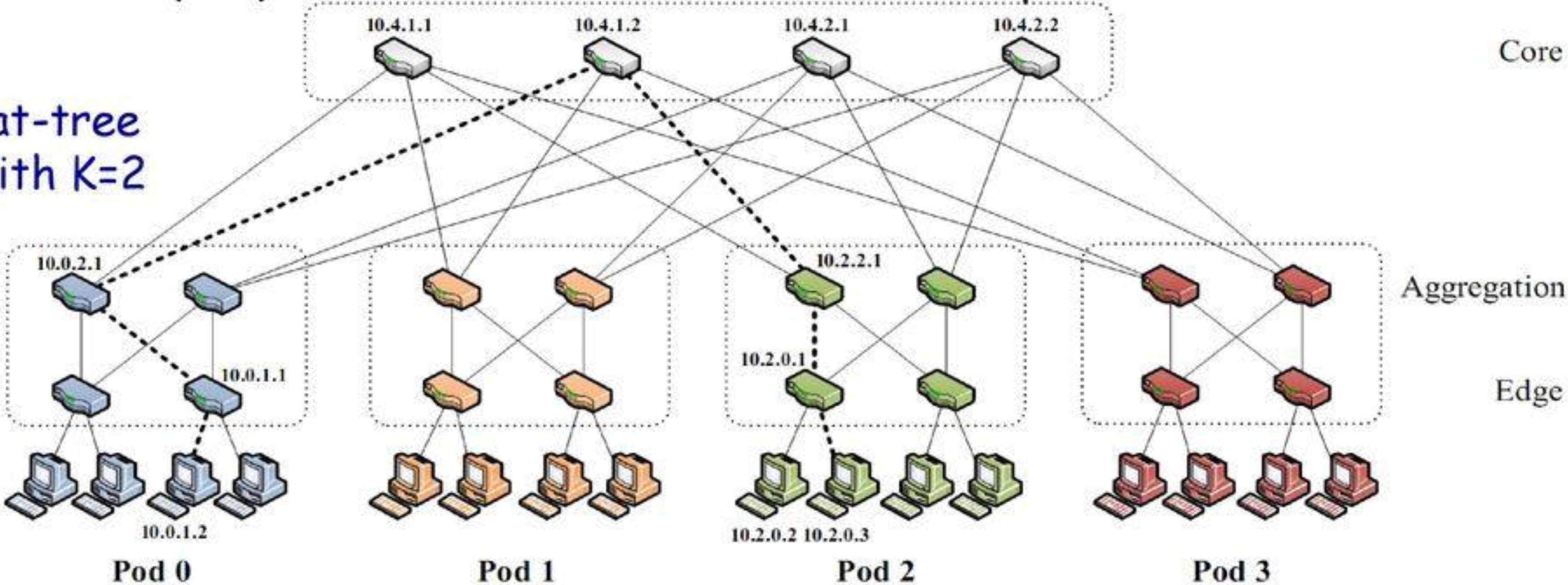
- Main Goal: addressing the limitations of today's data center network architecture
  - sing point of failure
  - over subscript of links higher up in the topology
    - trade-offs between cost and providing
- Key Design Considerations/Goals
  - Allows host communication at line speed
    - no matter where they are located!
  - Backwards compatible with existing infrastructure
    - no changes in application & support of layer 2 (Ethernet)
  - Cost effective
    - cheap infrastructure
    - and low power consumption & heat emission

Fat-Tree Based DC Architecture

- Inter-connect racks (of servers) using a fat-tree topology
- Fat-Tree: a special type of Clos Networks (after C. Clos)

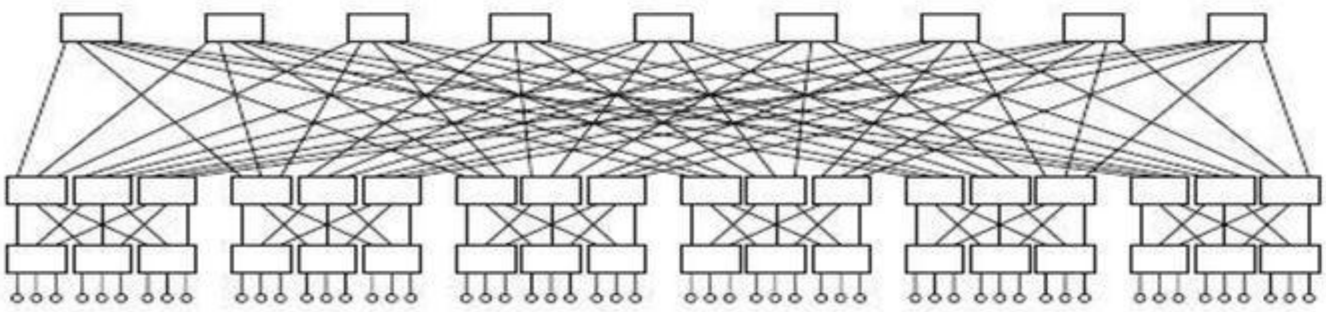
  K-ary fat tree: three-layer topology (edge, aggregation and core)
  - each pod consists of $(k/2)^2$ servers & 2 layers of k/2 k-port switches
  - each edge switch connects to k/2 servers & k/2 aggr. switches
  - each aggr. switch connects to k/2 edge & k/2 core switches
  - $(k/2)^2$ core switches: each connects to k pods

Fat-tree with K=2



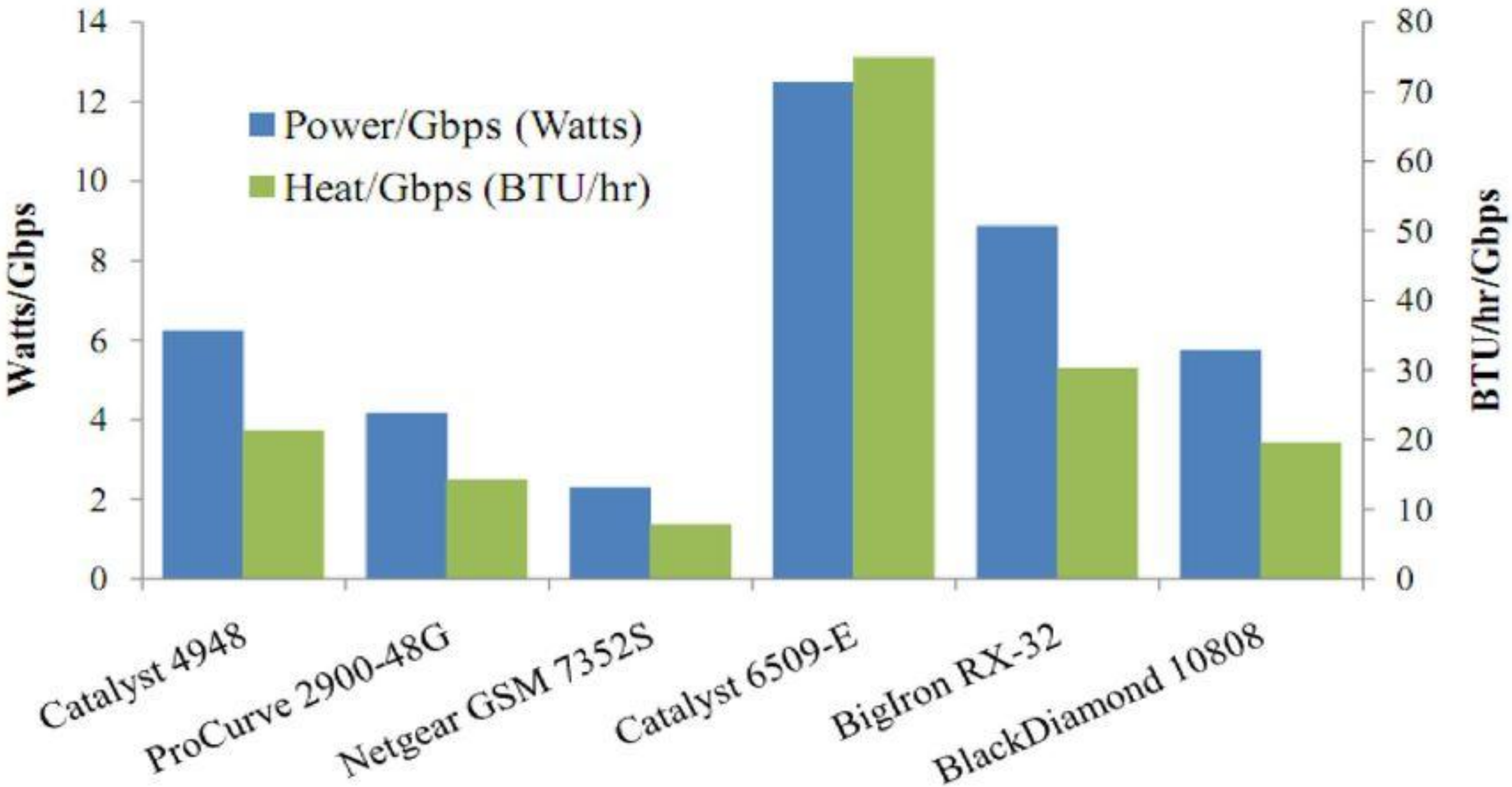
Fat-Tree Based Topology …

- Why Fat-Tree?
  - Fat tree has identical bandwidth at any bisections
  - Each layer has the same aggregated bandwidth
- Can be built using cheap devices with uniform capacity
  - Each port supports same speed as end host
  - All devices can transmit at line speed if packets are distributed uniform along available paths
- Great scalability: k-port switch supports $k^3/4$ servers



Fat tree network with K = 3 supporting 54 hosts

Cost of Maintaining Switches



Fat-tree Topology is Great, But ...

Does using fat-tree topology to inter-connect racks of servers in itself sufficient?

- What routing protocols should we run on these switches?
- Layer 2 switch algorithm: data plane flooding!
- Layer 3 IP routing:
  - shortest path IP routing will typically use only one path despite the path diversity in the topology
  - if using equal-cost multi-path routing at each switch independently and blindly, packet re-ordering may occur; further load may not necessarily be well-balanced
  - Aside: control plane flooding!

FAT-Tree Modified

- Enforce a special (IP) addressing scheme in DC
  - unused.PodNumber.switchnumber.Endhost
  - Allows host attached to same switch to route only through switch
  - Allows inter-pod traffic to stay within pod
- Use two level look-ups to distribute traffic and maintain packet ordering

- First level is prefix lookup
  - used to route down the topology to servers
- Second level is a suffix lookup
  - used to route up towards core
  - maintain packet ordering by using same ports for same server

Prefix	Output port
10.2.0.0/24	0
10.2.1.0/24	1
0.0.0.0/0	

Suffix	Output port
0.0.0.2/8	2
0.0.0.3/8	3

More on Fat-Tree DC Architecture

Diffusion Optimizations

- Flow classification
  - Eliminates local congestion
  - Assign to traffic to ports on a per-flow basis instead of a per-host basis
- Flow scheduling
  - Eliminates global congestion
  - Prevent long lived flows from sharing the same links
  - Assign long lived flows to different links

What are potential drawbacks of this architecture?

VL2: A Scalable and Flexible Data Center Network

Main Goal: support agility & be cost-effective

- A virtual (logical) layer 2 architecture for connecting racks of servers (network as a big "virtual switch")
  - employs a 3-level Clos topology (full-mesh in top-2 levels) with non-uniform switch capacities
- Also provides identity and location separation
  - "application-specific" vs. "location-specific" addresses
  - employs a directory service for name resolution
  - but needs direct host participation (thus mods at servers)
- Explicitly accounts for DC traffic matrix dynamics
  - employs the Valiant load-balancing (VLB) technique
    - using randomization to cope with volatility

Specific Objectives and Solutions

Objective	Approach	Solution
1. Layer-2 semantics	Employ flat addressing	Name-location separation & resolution service
2. Uniform high capacity between servers	Guarantee bandwidth for hose-model traffic	Flow-based random traffic indirection (Valiant LB)
3. Performance Isolation	Enforce hose model using existing mechanisms only	TCP

VL2 Topology Design

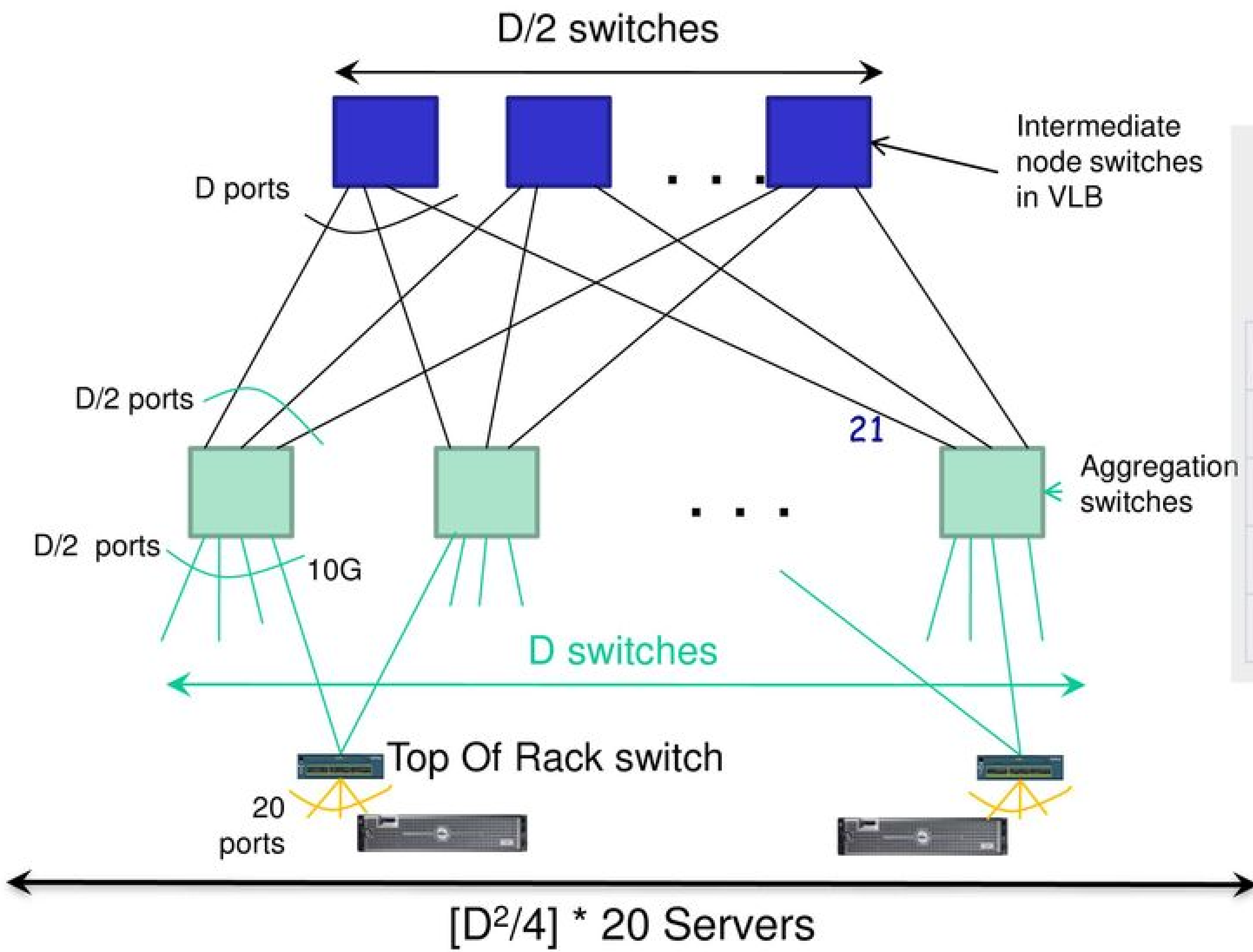
Scale-out vs. scale-up

- Argue for and exploit the gap in switch-to-switch capacity vs. switch-to-server capacities
  - current: 10Gbps vs. 1Gbps; future: 40 Gpbs vs. 10 Gbps
- A scale-out design with broad layers
  - E.g., a 3-level Clos topology with full-mesh in top-2 levels
    - ToR switches, aggregation switches & intermediate switches
    - less wiring complexity, and more path diversity
  - same bisection capacity at each layer

    ➔ no oversubscription
  - extensive path diversity

    ➔ graceful degradation under failure

VL2 Topology: Example



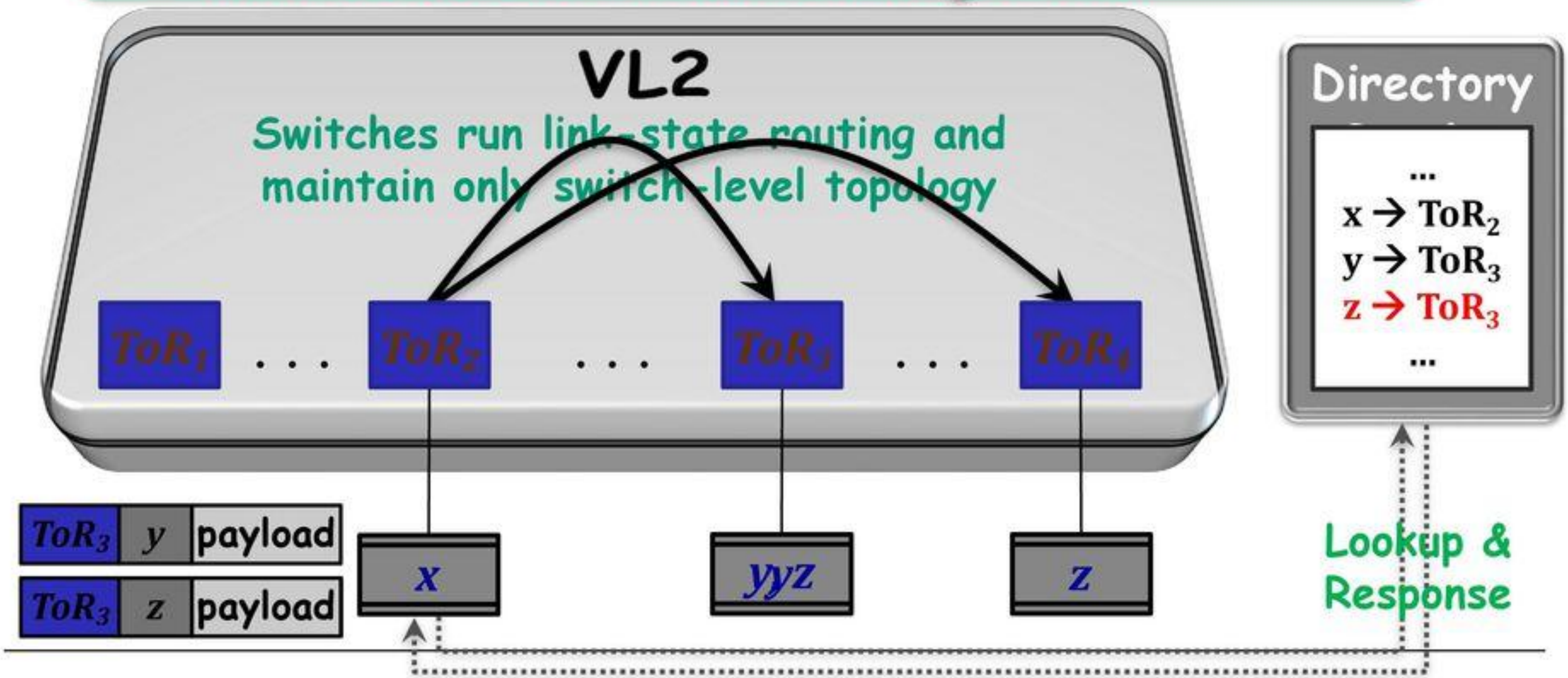
Node degree (D) of available switches & # servers supported

D	# Servers in pool
4	80
24	2,880
48	11,520
144	103,680

Addressing and Routing: Name-Location Separation

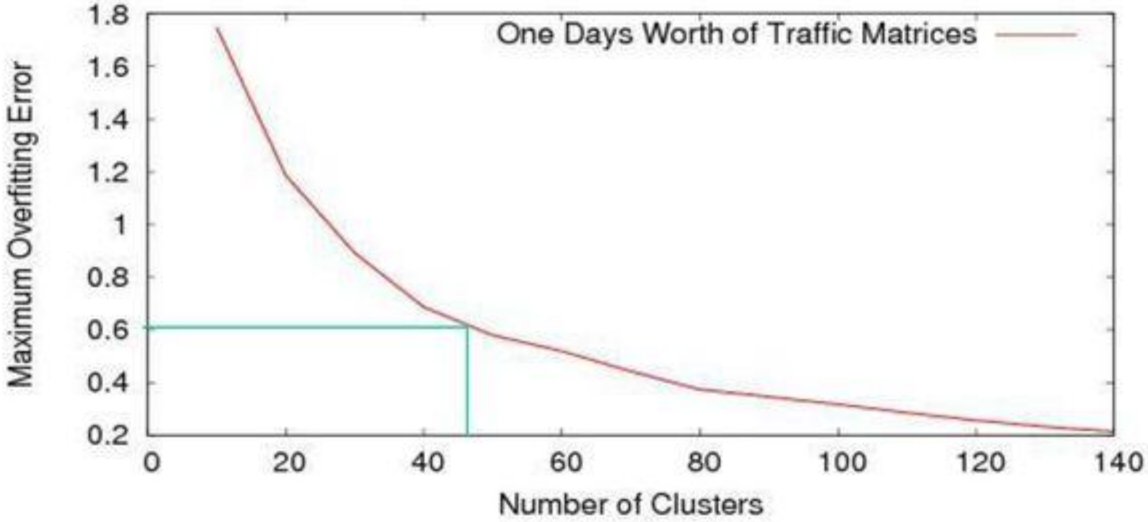
Cope with host churns with very little overhead

- Allows to use low-cost switches
- Protects network and hosts from host-state churn
- Obviates host and switch reconfiguration



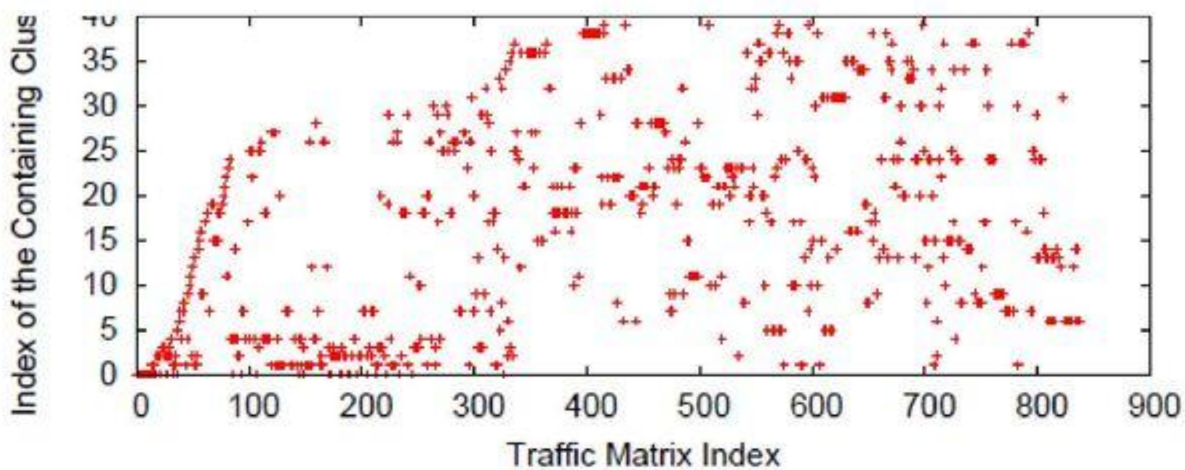
Servers use flat names

Traffic Matrix Volatility



- Collapse similar traffic matrices (over 100sec) into "clusters"

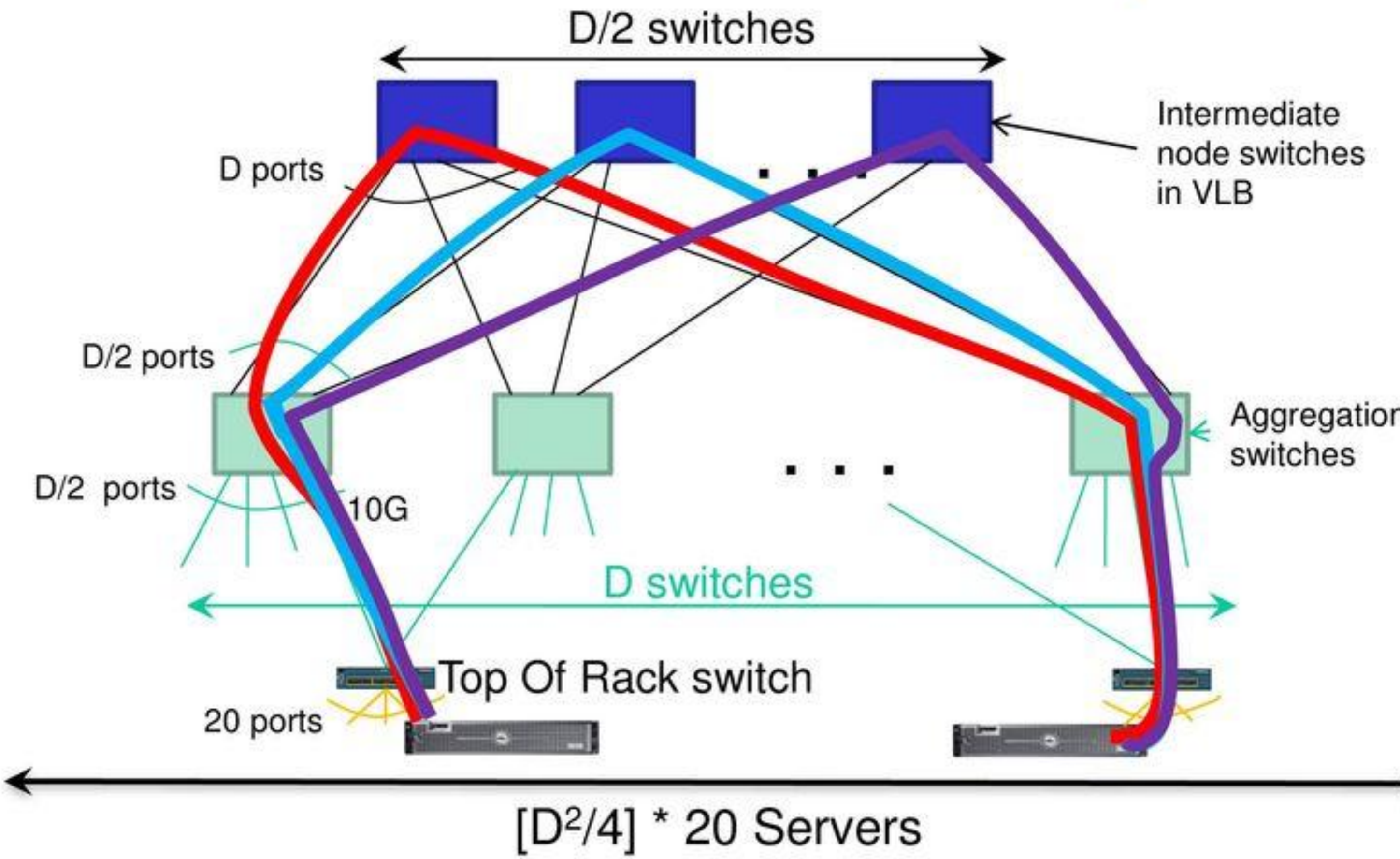
- Need 50-60 clusters to cover a day's traffic



- Traffic pattern changes nearly constantly

- Run length is 100s to 80% percentile; 99th is 800s

Use Randomization to Cope with Volatility



Node degree (D) of available switches & # servers supported

D	# Servers in pool
4	80
24	2,880
48	11,520
144	103,680

- Valiant Load Balancing
  - Every flow “bounced” off a random intermediate switch
  - Provably hotspot free for any admissible traffic matrix
  - Servers could randomize flow-lets if needed

VL2 Summary

VL2 achieves **agility at scale** via

1. L2 semantics
2. Uniform high capacity between servers
3. Performance isolation between services

Lessons

- **Randomization can tame volatility**
- **Add functionality where you have control**
- **There's no need to wait!**

Additional Case Studies

Optional Material

- PortLand: A Scalable Fault-Tolerant Layer 2 Data Center Network Fabric
  - Main idea: new "hierarchical" addressing scheme to facilitate dynamic and fault-tolerant routing/forwarding
- BCube: A High-Performance, Server-centric Network Architecture for Modular Data Centers
  - Special network architecture for "shipping-container"-based DCs (will not discuss in details)

PortLand: A Scalable Fault-Tolerant Layer 2 Data Center Network Fabric

In a nutshell:

- PortLand is a single "logical layer 2" data center network fabric that scales to millions of endpoints
- PortLand internally separates host identity from host location
  - uses IP address as host identifier
  - introduces "Pseudo MAC" (PMAC) addresses internally to encode endpoint location
- PortLand runs on commodity switch hardware with unmodified hosts

Design Goals for Network Fabric

Support for Agility!

- Easy configuration and management: plug-&-play
- Fault tolerance, routing and addressing: scalability
- Commodity switch hardware: small switch state
- Virtualization support: seamless VM migration

What are the limitations of current layer-2 and layer-3?

- layer-2 (Ethernet w/ flat-addressing) vs.
- layer-3 (IP w/ prefix-based addressing):
  - plug-&-play?
  - scalability?
  - small switch state?
  - seamless VM migration?

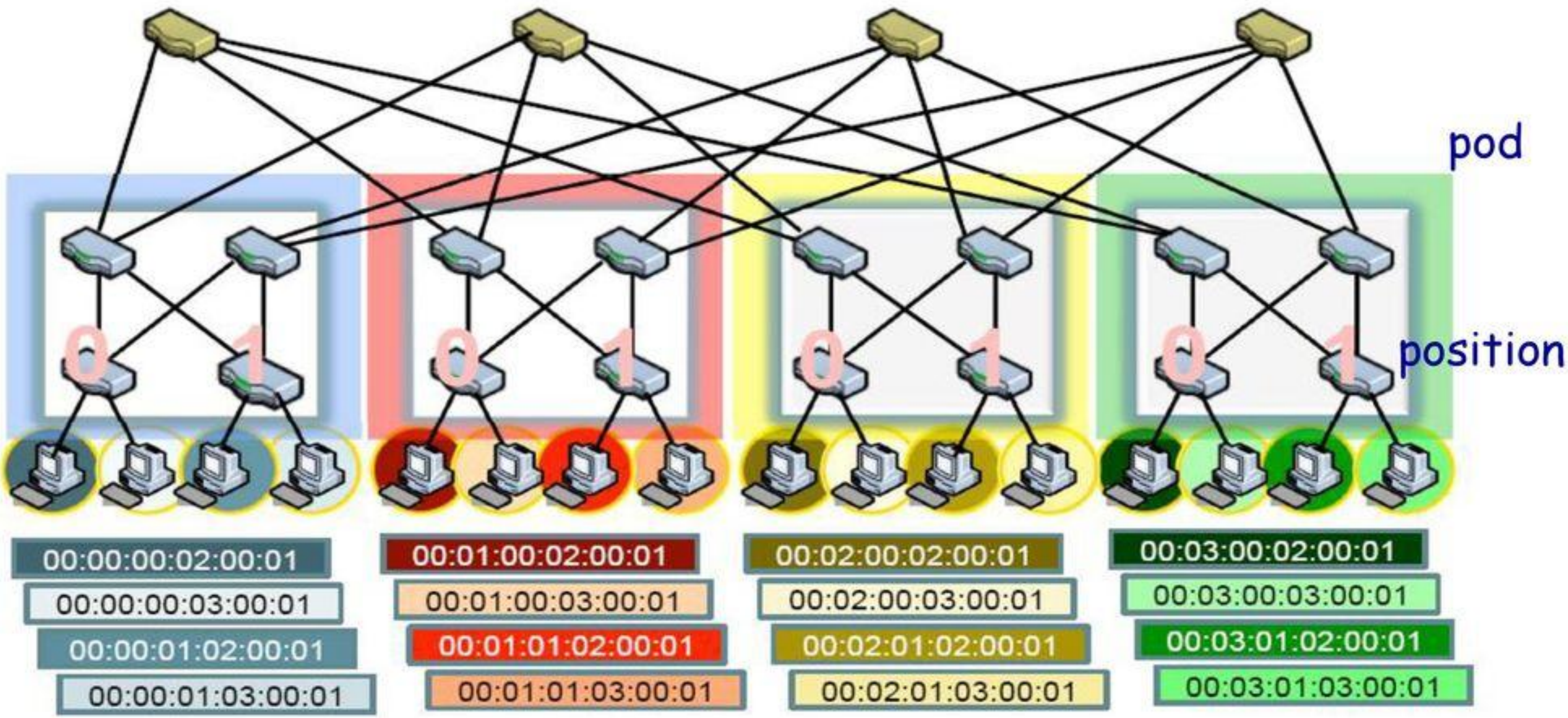
PortLand Solution

Assuming: a Fat-tree network topology for DC

- Introduce "pseudo MAC addresses" to balance the pros and cons of flat- vs. topology-dependent addressing
- PMACs are "topology-dependent," hierarchical addresses
  - But used only as "host locators," not "host identities"
  - IP addresses used as "host identities" (for compatibility w/ apps)
- Pros: small switch state & Seamless VM migration
- Pros: "eliminate" flooding in both data & control planes
- But requires a IP-to-PMAC mapping and name resolution
  - a location directory service
- And location discovery protocol & fabric manager
  - for support of "plug-&-play"

PMAC Addressing Scheme

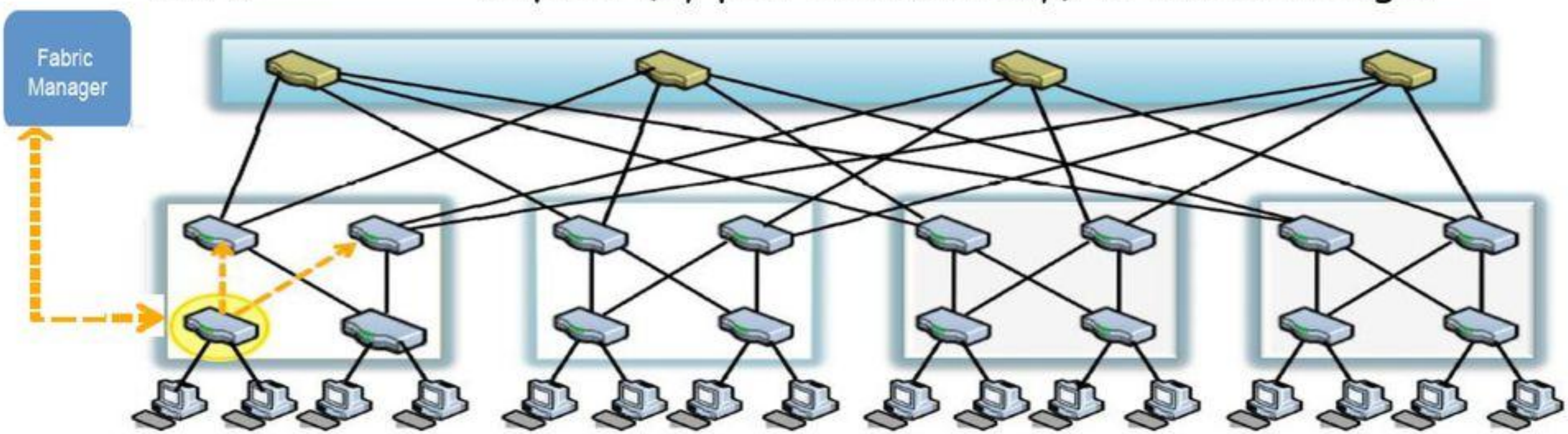
- PMAC (48 bits): pod.position.port.vmid
  - Pod: 16 bits; position and port (8 bits); vmid: 16 bits
- Assign only to servers (end-hosts) – by switches



Location Discovery Protocol

- Location Discovery Messages (LDMs) exchanged between neighboring switches
- Switches self-discover location on boot up

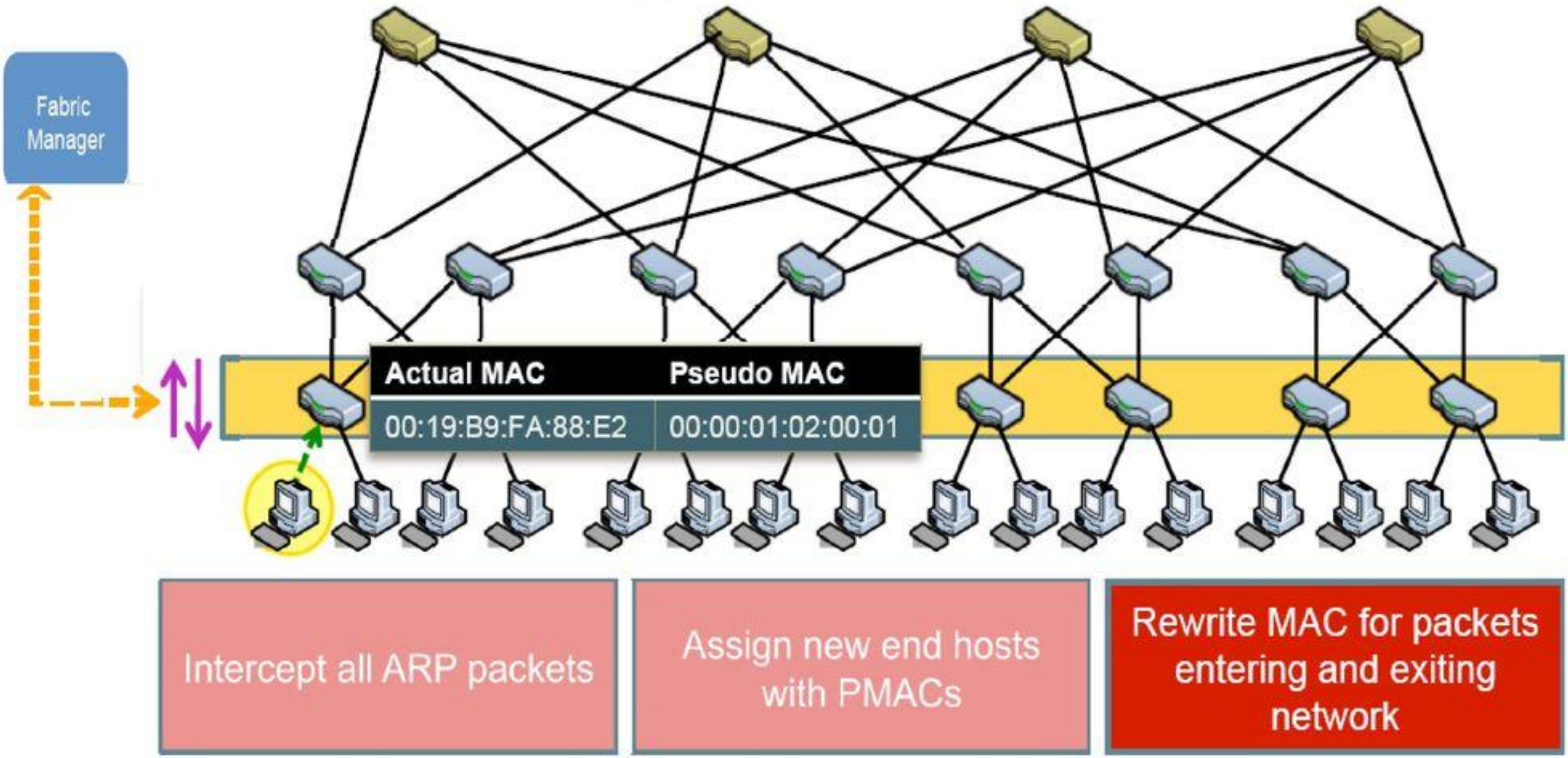
Location Characteristics	Technique
Tree-level (edge, aggr. , core)	auto-discovery via neighbor connectivity
Position #	aggregation switch help edge switches decide
Pod #	request (by pos. 0 switch only) to fabric manager



Switch Identifier	Pod Number	Position	Tree Level
A0:B1:FD:56:32:01	??	??	??

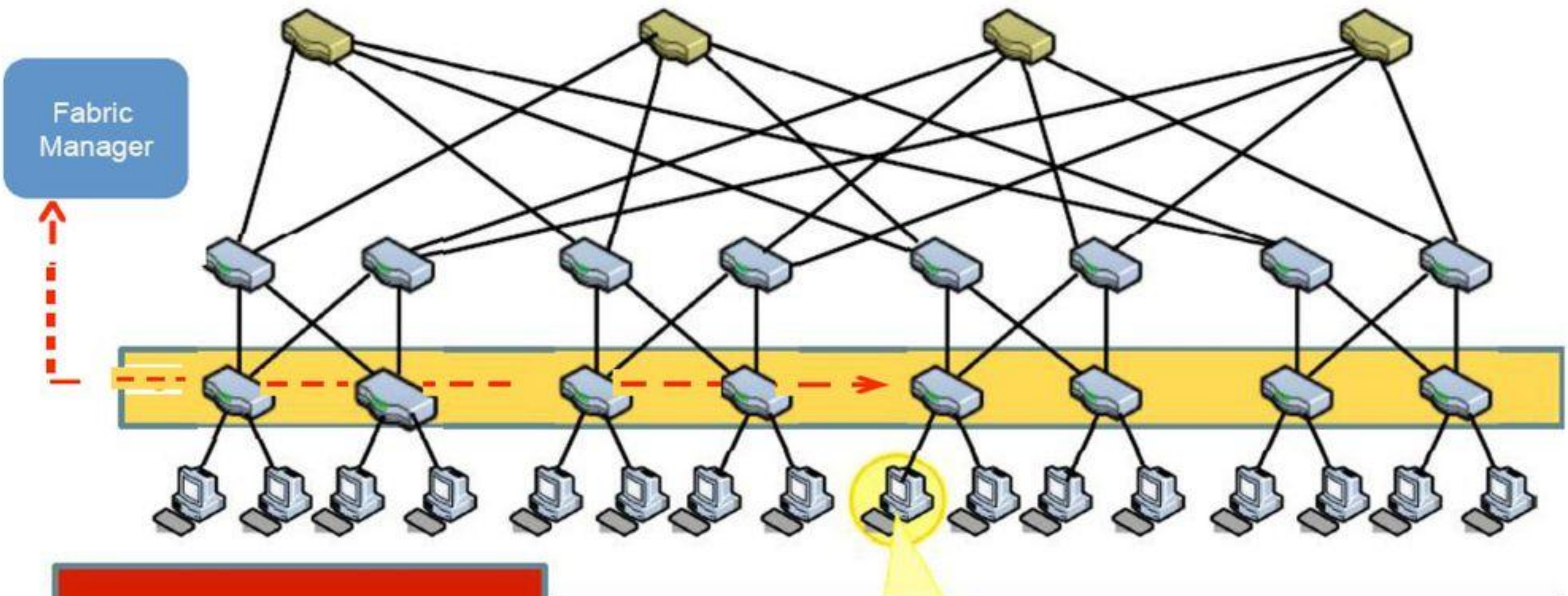
PortLand: Name Resolution

- Edge switch listens to end hosts, and discover new source MACs
- Installs <IP, PMAC> mappings, and informs fabric manager



PortLand: Name Resolution …

- Edge switch intercepts ARP messages from end hosts
- send request to fabric manager, which replies with PMAC



ARP replies contain only PMAC

Address	HWtype	HWAddress	Flags	Mask	Iface
10.5.1.2	ether	00:00:01:02:00:01	C		eth1

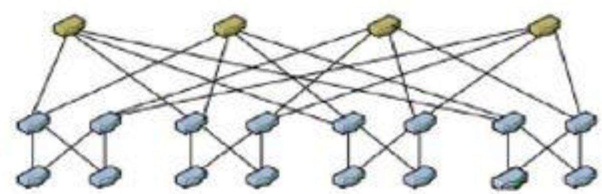
PortLand: Fabric Manager

- fabric manager: logically centralized, multi-homed server
- maintains topology and <IP,PMAC> mappings in “soft state”

Fabric Manager

IP	Pseudo MAC
10.5.1.2	00:00:01:02:00:01
10.2.4.5	00:02:00:02:00:01

ARP mappings



Network map

Soft state

~~Administrator configuration~~

Loop-free Forwarding and Fault-Tolerant Routing

- Switches build forwarding tables based on their position
  - edge, aggregation and core switches
- Use strict "up-down semantics" to ensure loop-free forwarding
  - Load-balancing: use any ECMP path via flow hashing to ensure packet ordering
- Fault-tolerant routing:
  - Mostly concerned with detecting failures
  - Fabric manager maintains logical fault matrix with per-link connectivity info; inform affected switches
  - Affected switches re-compute forwarding tables

BCube: A High-Performance, Server-centric Network Architecture for Modular Data Centers

Main Goal: network architecture for shipping-container based modular data centers

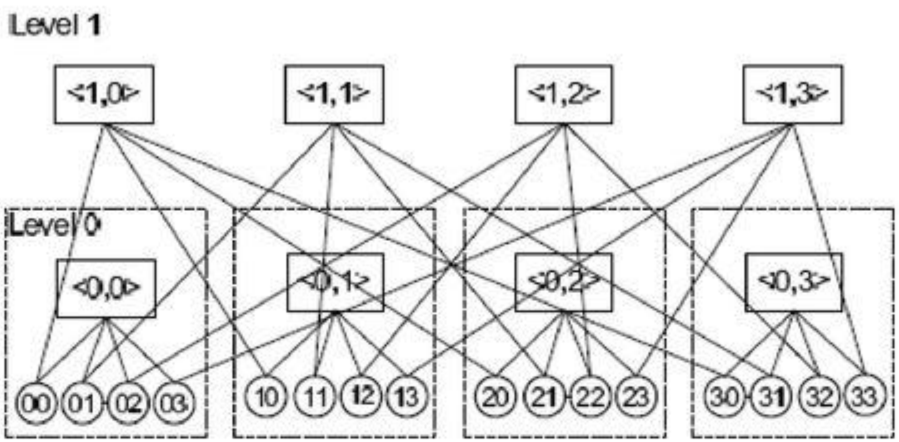
- Designed for shipping-container modular DC
- BCube construction: level structure
  - $BCube_k$ recursively constructed from $BCube_1$
- server-centric:
  - servers perform routing and forwarding
- Consider a variety of communication patterns
  - one-to-one, one-to-many, one-to-all, all-to-all
  - single path and multi-path routing

(Will not discuss in details; please read the paper!)

BCube Construction

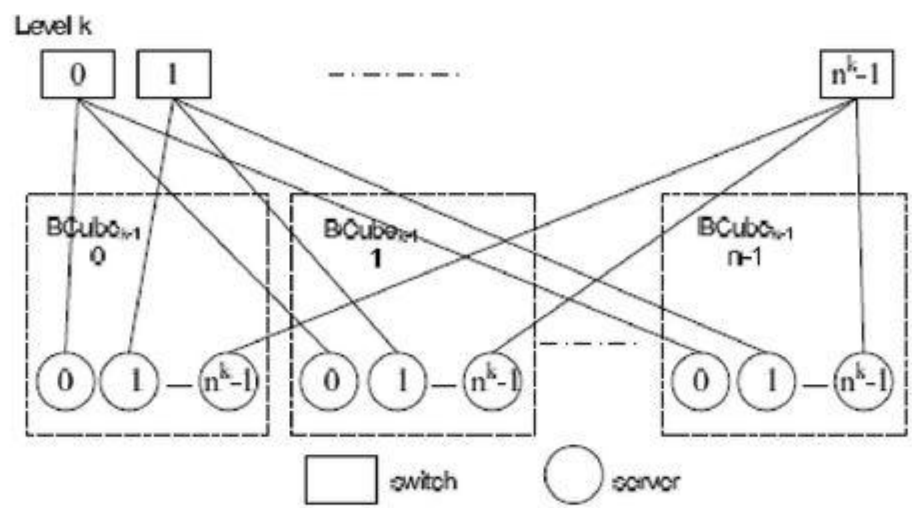
- Leveled structure: $BCube_k$ is recursively constructed from n $BCube_{k-1}$ and n^k n-port switches

$BCube_1$



n=4

$BCube_k$



One-to-All Traffic Forwarding

- Using a spanning tree
- Speed-up: L/(k+1) for a file of size L

Two-edge disjoint (server) spanning trees in $BCube_1$
for one-to-traffic