# Scalable and Efficient Self-configuring Networks

Changhoon Kim
chkim@cs.princeton.edu

# Today's Networks Face New Challenges

- Networks growing rapidly in size
  - Up to tens of thousands to millions of hosts
- Networking environments getting highly dynamic
  - Mobility, traffic volatility, frequent re-adjustment
- Networks being increasingly deployed in non-IT industries and developing regions
  - Limited support for management

**Networks must be scalable and yet easy to build and manage!**

# Pains In Large Dynamic Networks

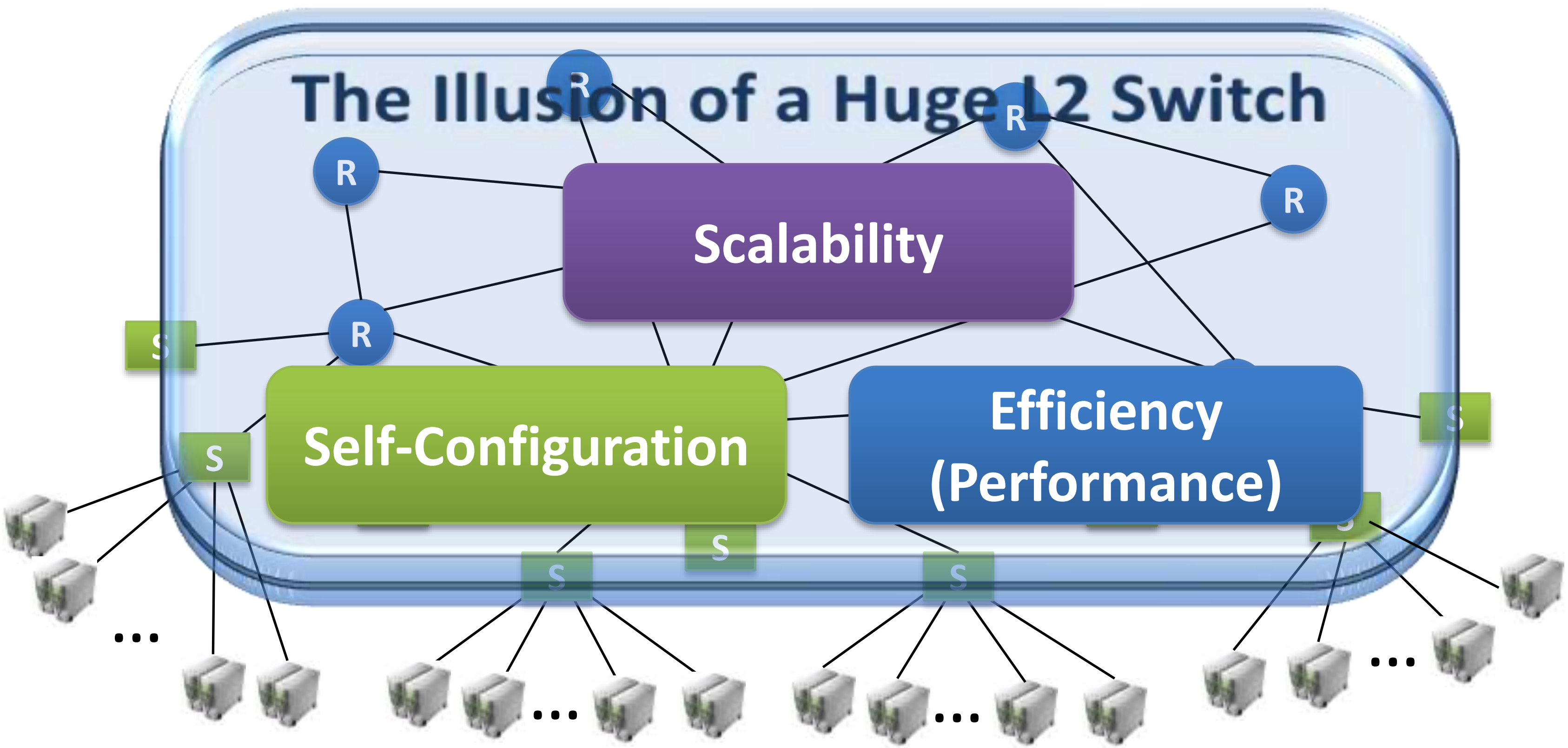
- Control-plane overhead to store and disseminate host state
  - Millions of host-info entries
    - Commodity switches/routers can store only ~32K/300K entries
  - Frequent state updates, each disseminated to thousands of switches/routers
- Status quo: Hierarchical addressing and routing
- Victimizes ease of management
  - Leads to complex, high-maintenance, fragile, hard-to-debug, and brittle network

# More Pains …

- Limited data-plane capacity
  - Tbps of traffic workload on core links
    - Fastest links today are only 10 ~ 40 Gbps
  - Highly volatile traffic patterns
- Status quo: Over-subscription
- Victimizes efficiency (performance)
  - Lowers server utilization and end-to-end performance
  - Trying to mitigate this via traffic engineering can make management harder

# All We Need Is Just A Huge L2 Switch, or An Abstraction of One!

- Host up to millions of hosts
- Obviate manual configuration
- Ensure high capacity and small end-to-end latency



# Research Strategy and Goal

- Emphasis on architectural solutions
  - Redesign underlying networks
- Focus on edge networks
  - Enterprise, campus, and data-center networks
  - Virtual private networks (VPNs)

**[ Research Goal ]**

**Design, build, and deploy architectural solutions enabling scalable, efficient, self-configuring edge networks**

# Why Is This Particularly Difficult?

- Scalability, self-configuration, and efficiency can conflict!
  - Self-configuration can significantly increase the amount of state and make traffic forwarding inflexible
  - Examples: Ethernet, VPN routing

**Present solutions to resolve this impasse**

# Universal Hammers

**Self-configuration** — *Flat Addressing*

- Utilize location-independent names to identify hosts
- Let network self-learn hosts' info

**Scalability** — *Traffic Indirection*

- Deliver traffic through intermediaries (chosen systematically or randomly)

**Efficiency** — *Usage-driven Optimization*

- Populate routing and host state only when and where needed

# Solutions For Various Edge Networks

| Enterprise, Campus Network | Data-Center Network | Virtual Private Network |
| --- | --- | --- |
| Config-free addressing and routing | Config-free addressing, routing, and traffic engineering | Config-free site-level addressing and routing |
| Huge overhead to store and disseminate individual hosts' info | Limited server-to-server capacity | Expensive router memory to store customers' info |
| Partition hosts' info over switches | Spread traffic randomly over multiple paths | Keep routing info only when it's needed |
| **SEATTLE** [SIGCOMM'08] | **VL2** [SIGCOMM'09] | **Relaying** [SIGMETRICS'08] |

# Strategic Approach for Practical Solutions

Clean Slate

Workable solution with sufficient improvement

SEATTLE

VL2

Relaying

Backwards Compatible

## Enterprise, Campus Network

- Heterogeneity of end-host environments

Clean slate on network

**Several independent prototypes**

## Data-Center Network

- Lack of programmability at switches and routers

Clean slate on end hosts

**Real-world Deployment**

## Virtual Private Network

- Immediate deployment
- Transparency to customers

Backwards compatible

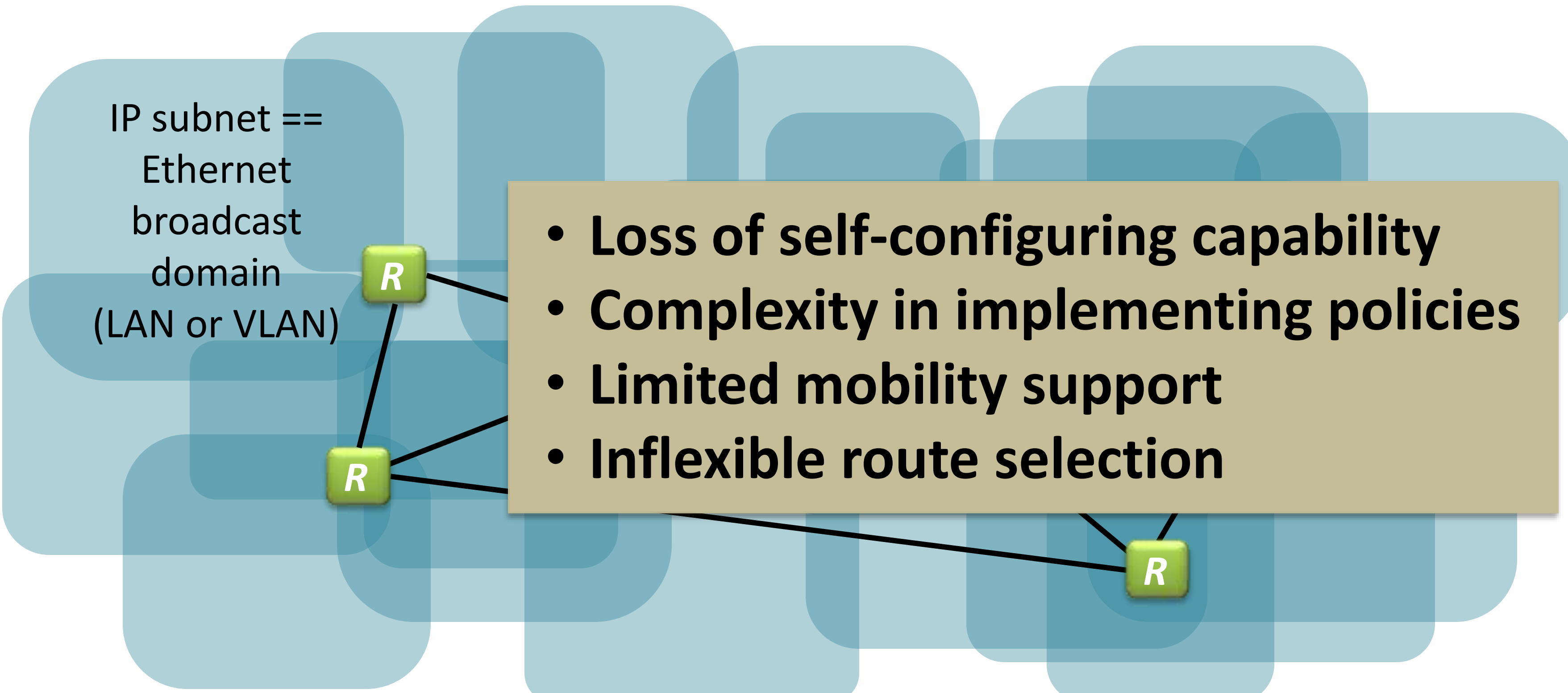
**Pre-deployment Evaluation**

# SEATTLE:
# A Scalable Ethernet Architecture for Large Enterprises

Work with Matthew Caesar and Jennifer Rexford

# Current Practice in Enterprises

A hybrid architecture comprised of several small Ethernet-based IP subnets interconnected by routers




- **Loss of self-configuring capability**
- **Complexity in implementing policies**
- **Limited mobility support**
- **Inflexible route selection**

**Need a protocol that combines only the best of IP and Ethernet**

# Objectives and Solutions

| Objective | Approach | Solution |
| --- | --- | --- |
| 1. Avoid flooding | Resolve host info via unicast | Network-layer one-hop DHT |
| 2. Restrain broadcasting | Bootstrap hosts via unicast | |
| 3. Reduce routing state | Populate host info only when and where needed | Traffic-driven resolution with caching |
| 4. Enable shortest-path forwarding | Allow switches to learn topology | L2 link-state routing maintaining only switch-level topology |

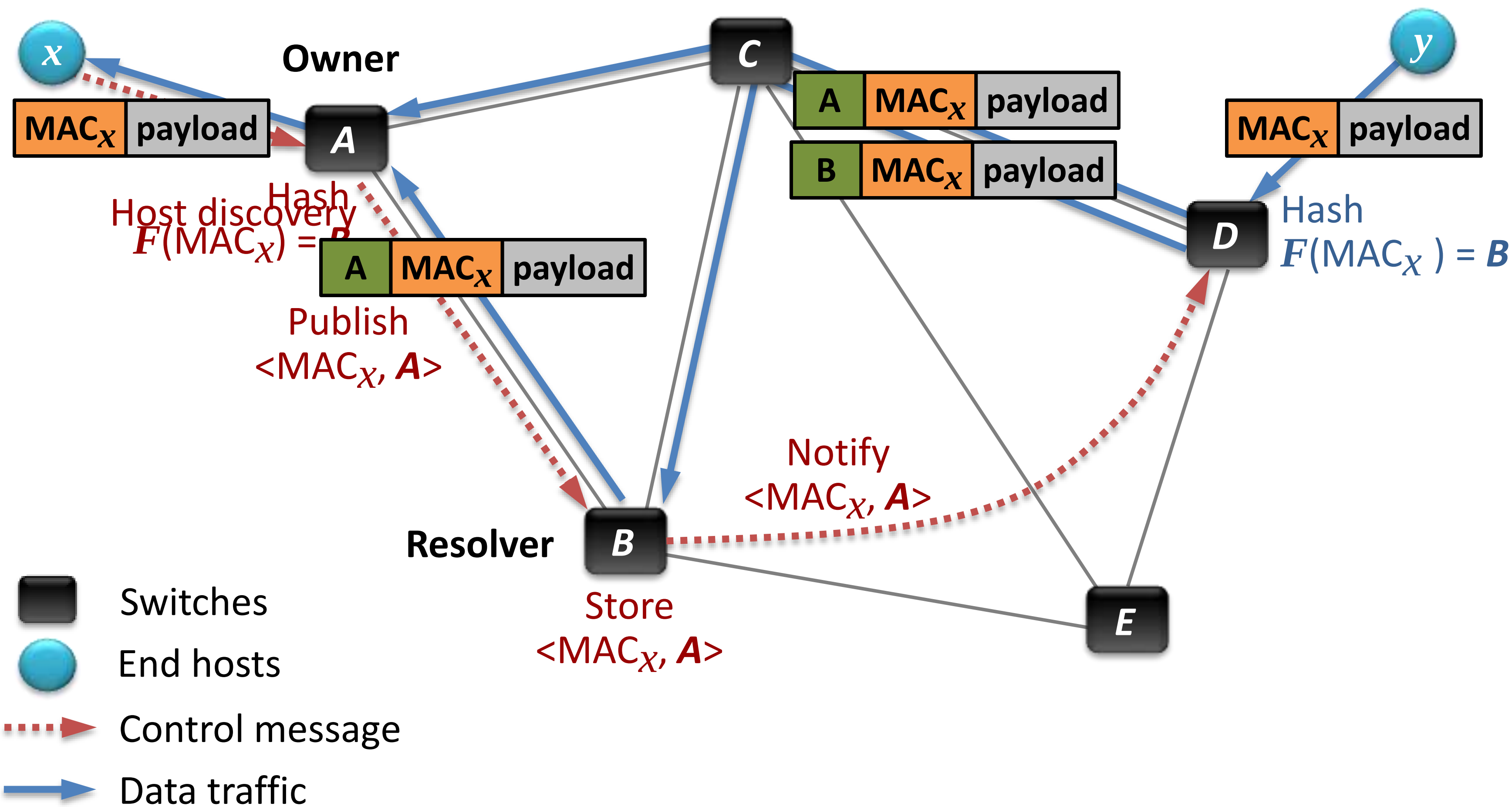
*** Meanwhile, avoid modifying end hosts**

# Network-layer One-hop DHT

- Switches maintain <*key*, *value*> pairs by commonly using a hash function $\boldsymbol{F}$
  - $\boldsymbol{F}$: Consistent hash mapping a key to a switch
  - LS routing ensures each switch knows about all the other live switches, enabling one-hop DHT operations
- Unique benefits
  - Fast, efficient, and accurate reaction to churns
  - Reliability and capacity naturally growing with network size

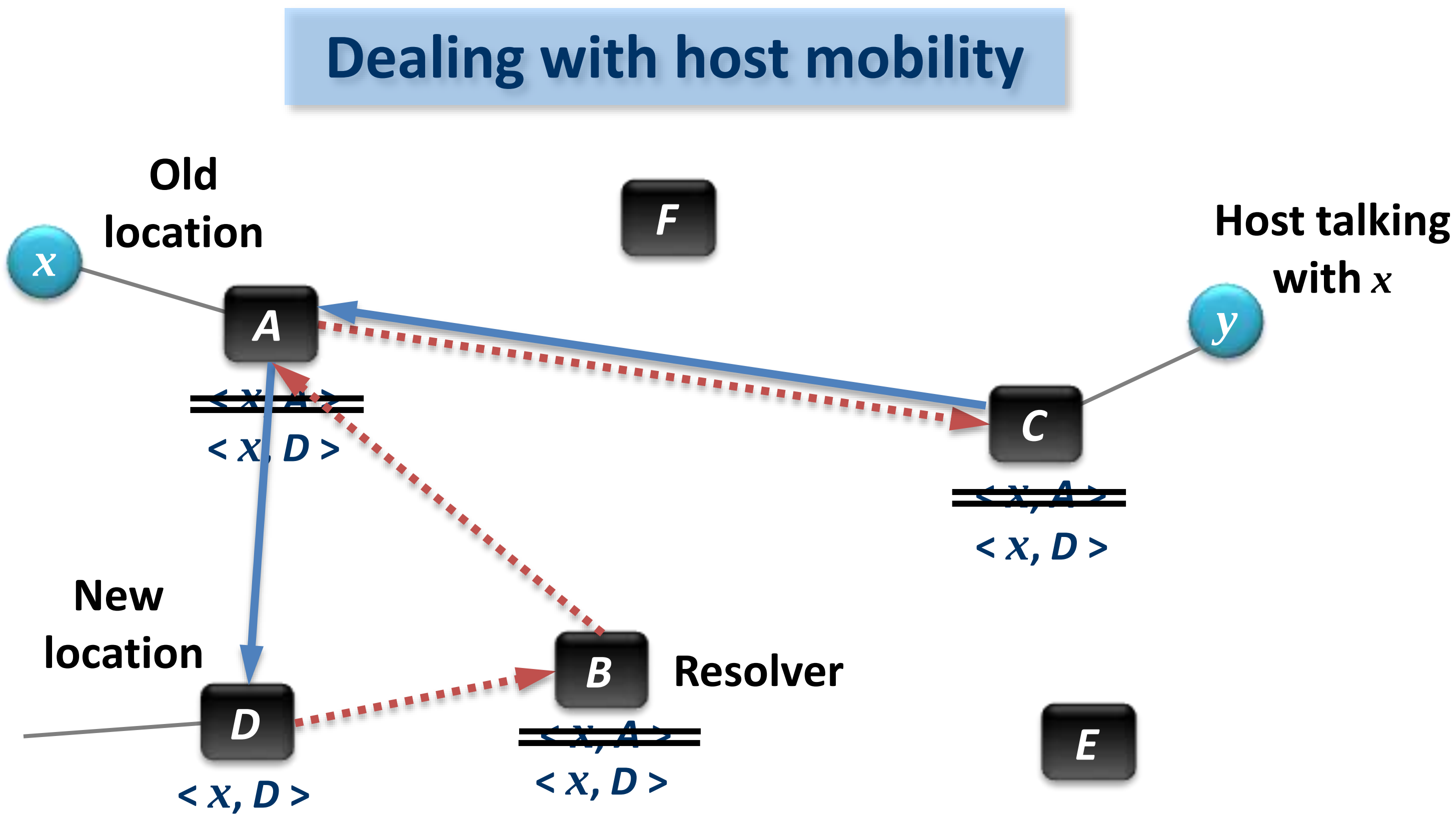
# Location Resolution

**<key, val> = <MAC addr, location>**



# Handling Host Dynamics

- Host location, MAC-addr, or IP-addr can change



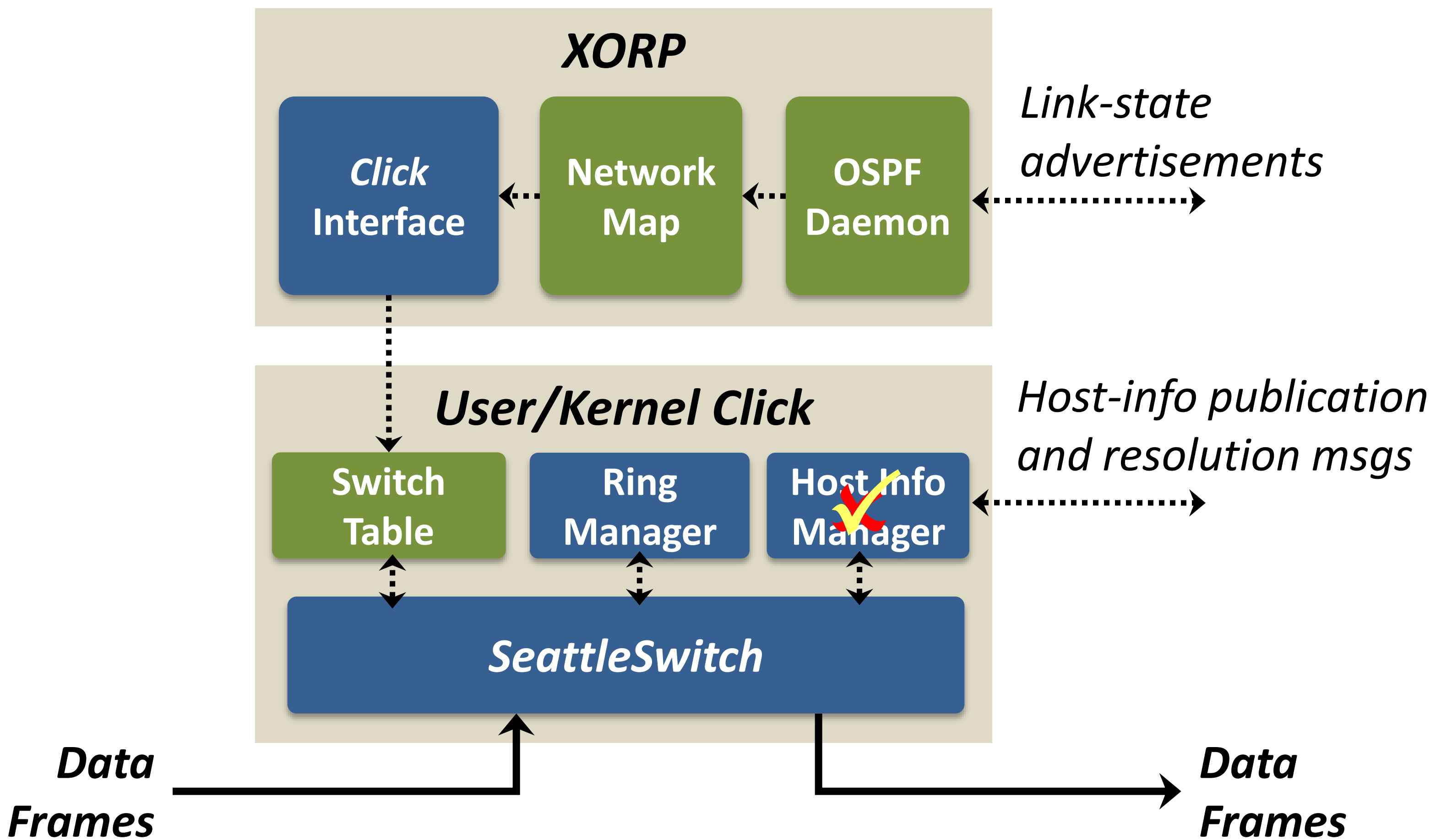

**MAC- or IP-address change can be handled similarly**

# Further Enhancements Implemented

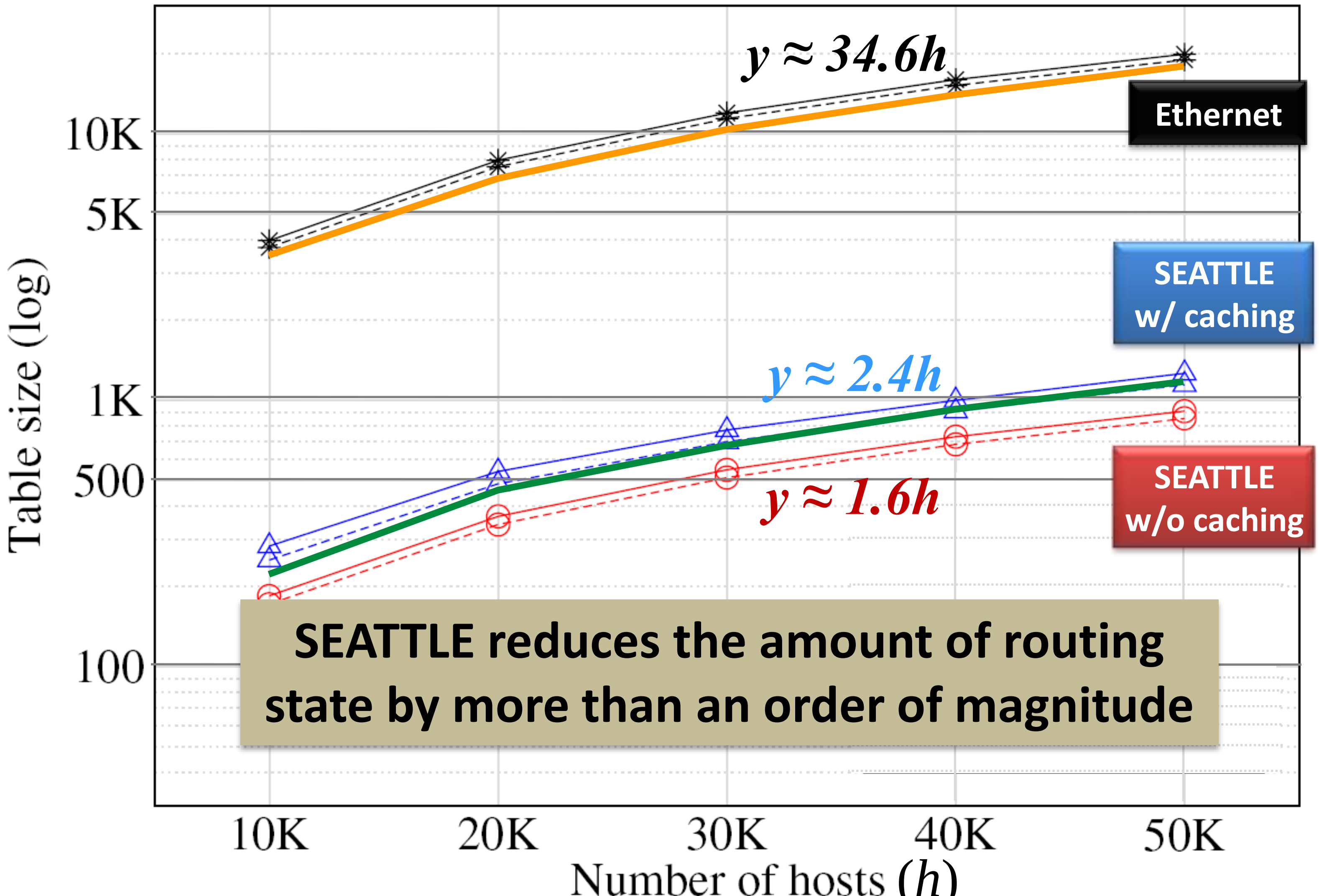
| Goals | Solutions |
|---|---|
| Handling network dynamics | Host-info re-publication and purging |
| Isolating host groups (e.g., VLAN) | Group-aware resolution |
| Supporting link-local broadcast | Per-group multicast |
| Dealing with switch-level heterogeneity | Virtual switches |
| Ensuring highly-available resolution service | Replicating host information |
| Dividing administrative control | Multi-level one-hop DHT |

# Prototype Implementation

- Link-state routing: ***XORP OSPFD***
- Host-info management and traffic forwarding: ***Click***



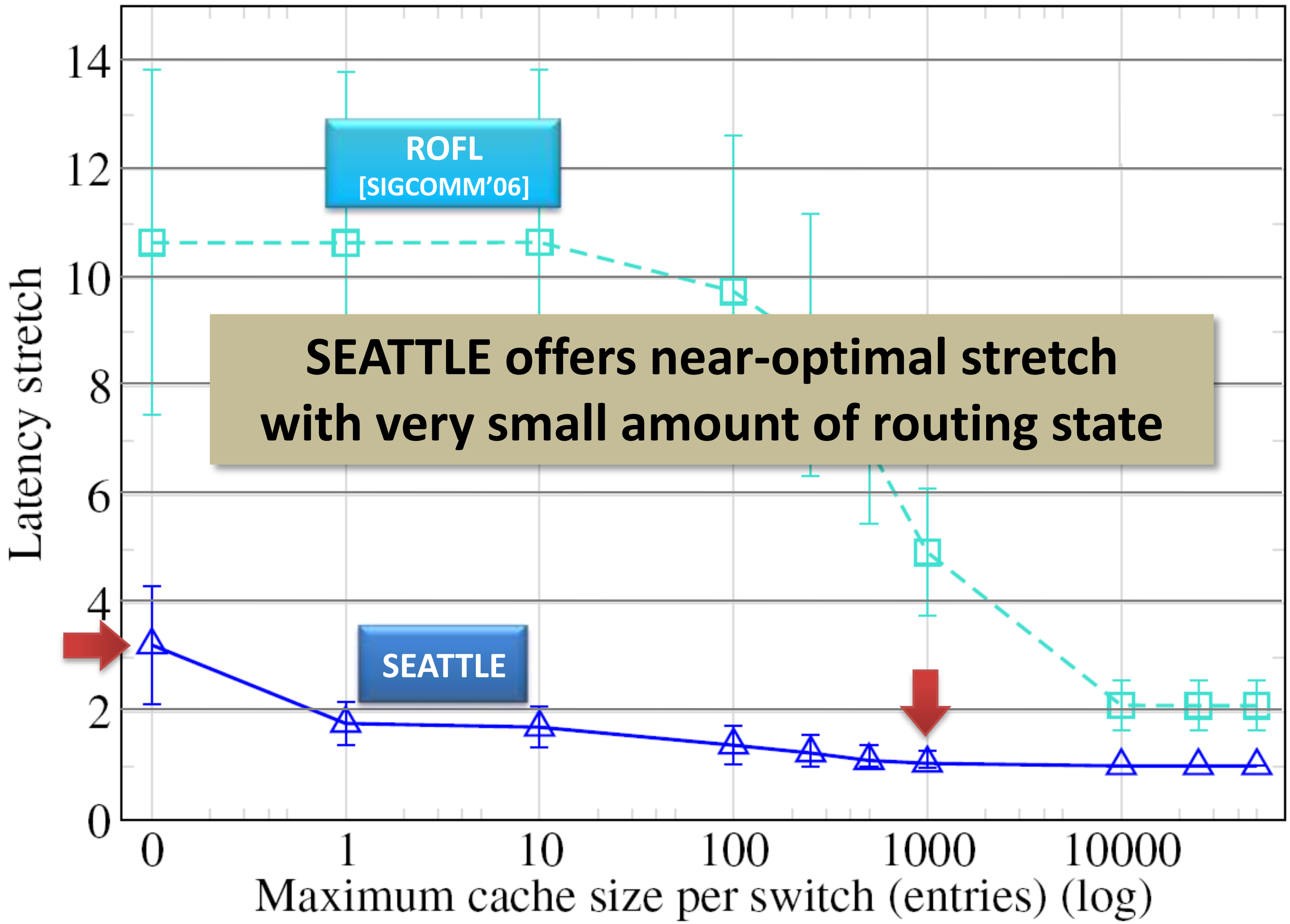
# Amount of Routing State




SEATTLE reduces the amount of routing state by more than an order of magnitude

# Cache Size vs. Stretch

Stretch = actual path length / shortest path length (in latency)



# SEATTLE Conclusion

- Enterprises need a huge L2 switch
  - Config-free addressing and routing, support for mobility, and efficient use of links
- Key lessons
  - Coupling DHT with LS routing offers huge benefits
  - Reactive resolution and caching ensures scalability

| | |
|---|---|
| *Flat Addressing* | *MAC-address-based routing* |
| *Traffic Indirection* | *Forwarding through resolvers* |
| *Usage-driven Opt.* | *Ingress caching, reactive cache update* |

# Further Questions

- What other kinds of networks need SEATTLE?
- What about other configuration tasks?
- What if we were allowed to modify hosts?

**These motivate my next work for data centers**

# VL2: A Scalable and Flexible Data-Center Network


Work with Albert Greenberg,
Navendu Jain, Srikanth Kandula,
Dave Maltz, Parveen Patel,
and Sudipta Sengupta

# Data Centers

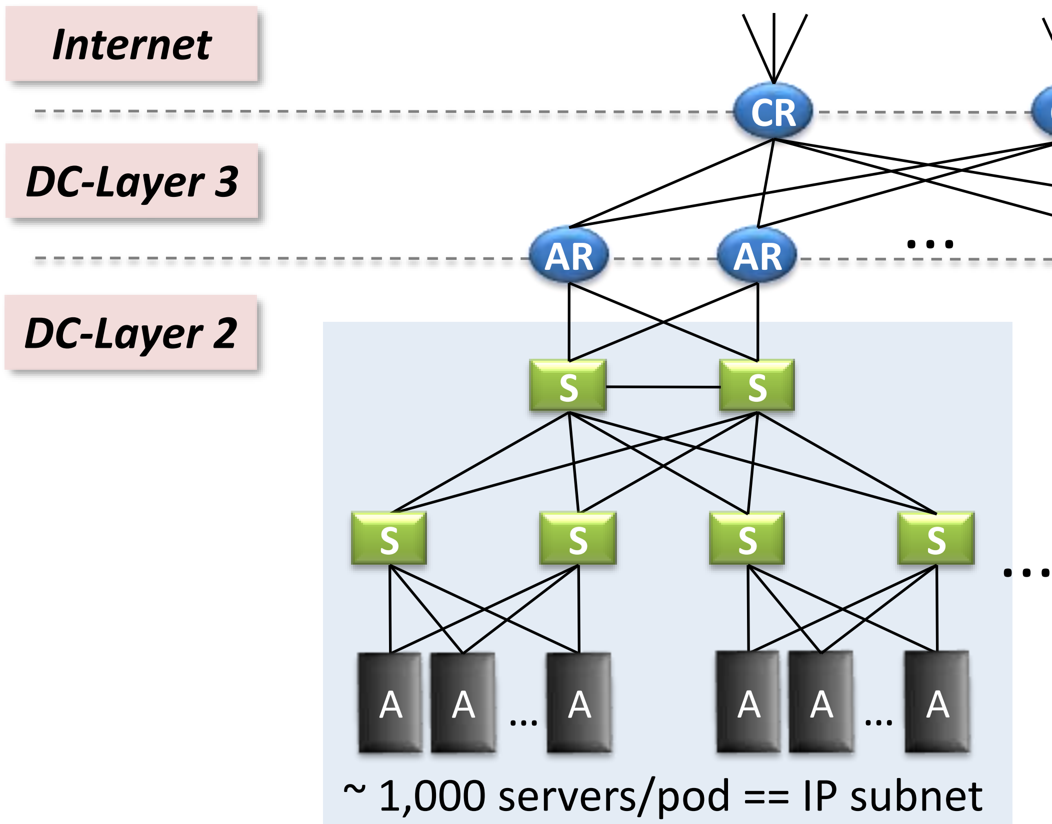
- Increasingly used for non-customer-facing decision-support computations
- Many of them will soon be outsourced to cloud-service providers
- Demand for large-scale, high-performance, cost-efficient DCs growing very fast

# Tenets of Cloud-Service Data Center

- **Scaling out**: Use large pools of commodity resources
  - Achieves reliability, performance, low cost
- **Agility**: Assign any resources to any services
  - Increases efficiency (statistical multiplexing gain)
- **Low Management Complexity**: Self-configuring
  - Reduces operational expenses, avoids errors

**Conventional DC <u>network</u> ensures none**

# Status Quo: Conventional DC Network




*Reference – "Data Center: Load balancing Data Center Services", Cisco 2004*

**Key**

- **CR** = Core Router (L3)
- **AR** = Access Router (L3)
- **S** = Switch (L2)
- **LB** = Load Balancer
- **A** = Rack of app. servers

**Poor utilization and reliability**

# Status Quo: Traffic Patterns in a Cloud

- Instrumented a cluster used for data mining, then computed representative traffic matrices
- Traffic patterns are highly divergent
  - A large number (100+) of representative TMs needed to cover a day's traffic
- Traffic patterns are unpredictable
  - No representative TM accounts for more than a few hundred seconds of traffic patterns

**Optimization approaches might cause more trouble than benefits**

# Objectives and Solutions

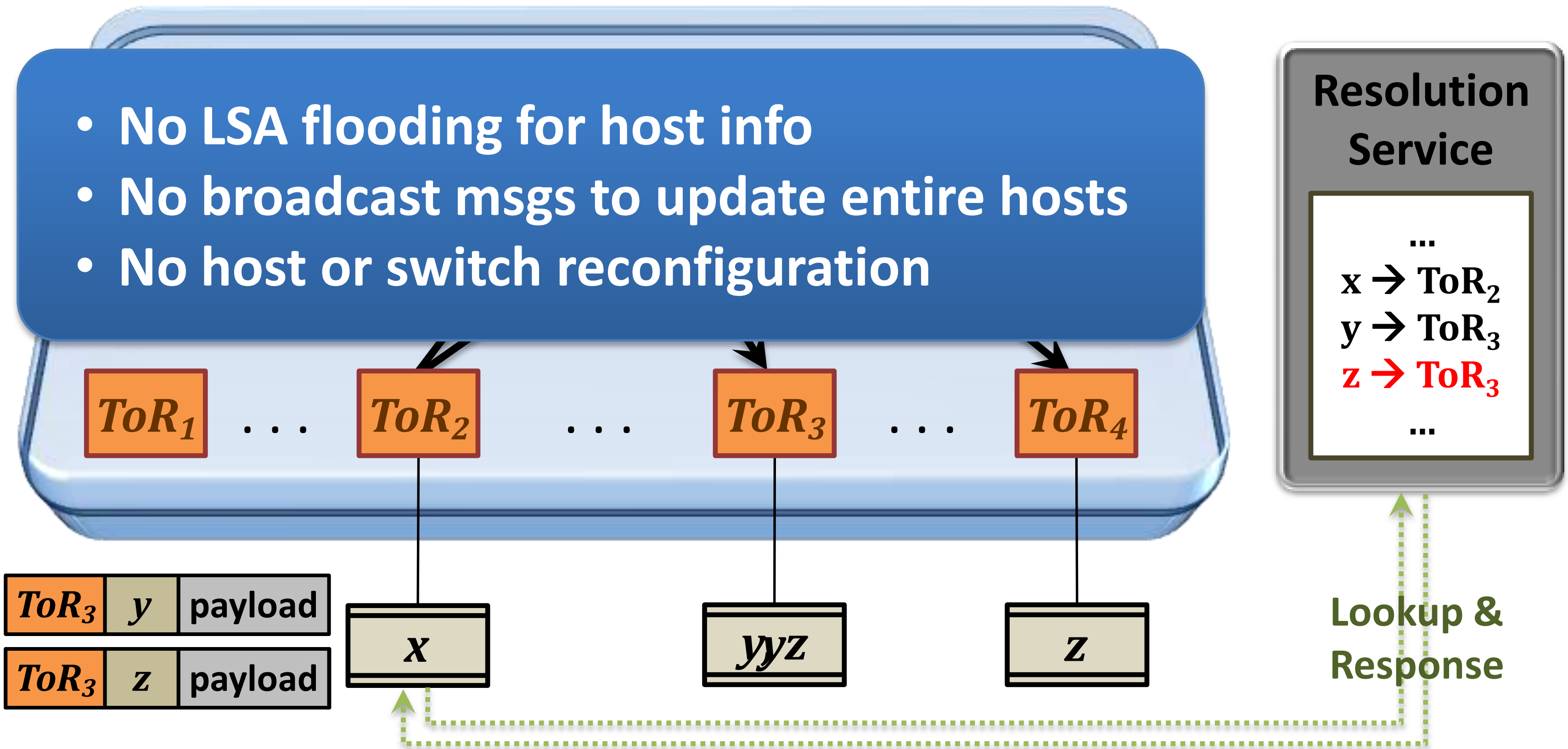
| Objective | Approach | Solution |
|---|---|---|
| 1. Ensure layer-2 semantics | Employ flat addressing | Name-location separation & resolution service |
| 2. Offer uniform high capacity between servers | Guarantee bandwidth for hose-model traffic | Random traffic indirection (VLB) over a topology with huge aggregate capacity |
| 3. Avoid hot spots w/o frequent reconfiguration | Use randomization to cope with volatility | |

*** Embrace end systems!**

# Addressing and Routing: Name-Location Separation

**Cope with host churns with very little overhead**

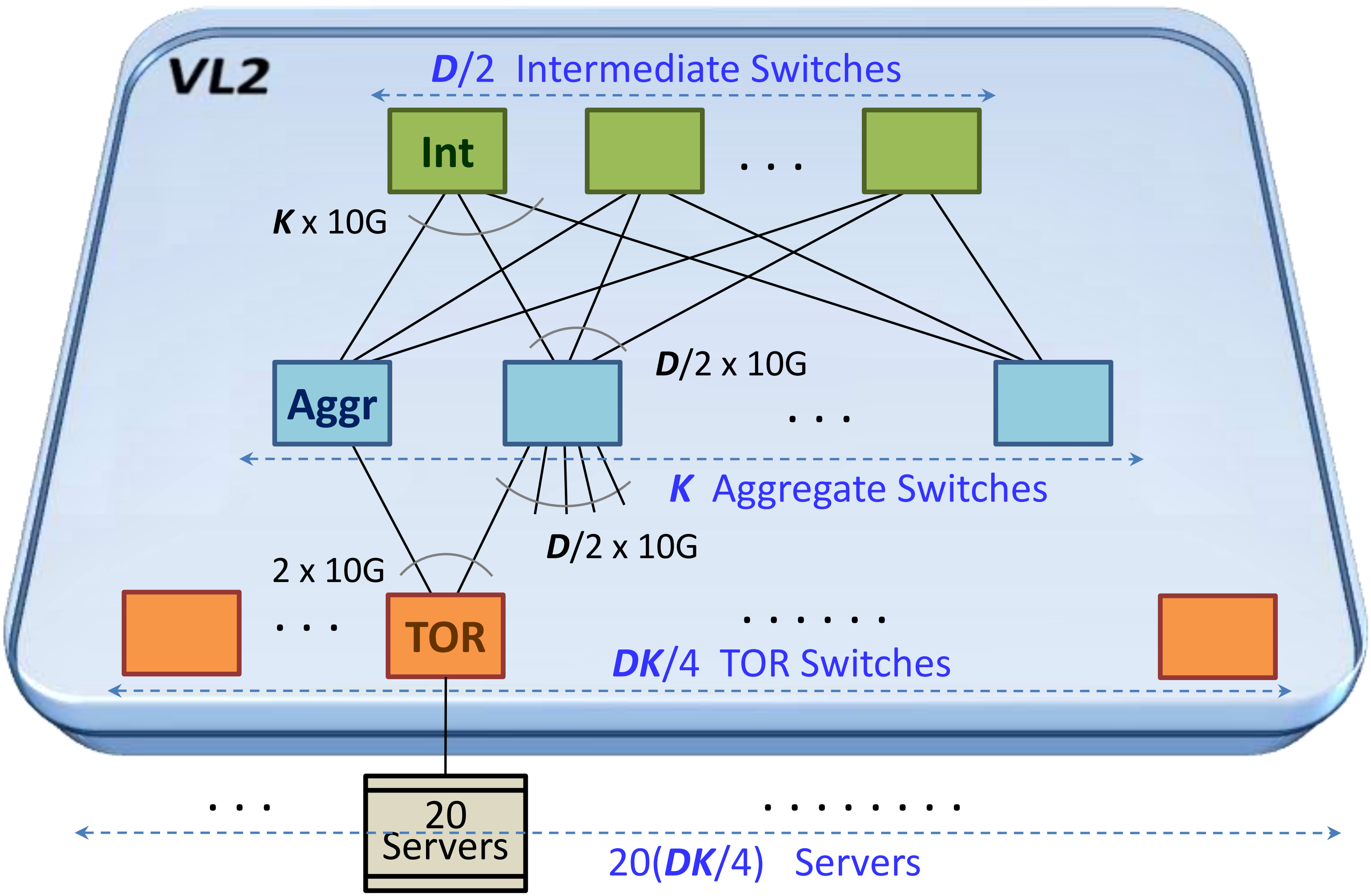
- No LSA flooding for host info
- No broadcast msgs to update entire hosts
- No host or switch reconfiguration




Hosts use flat names

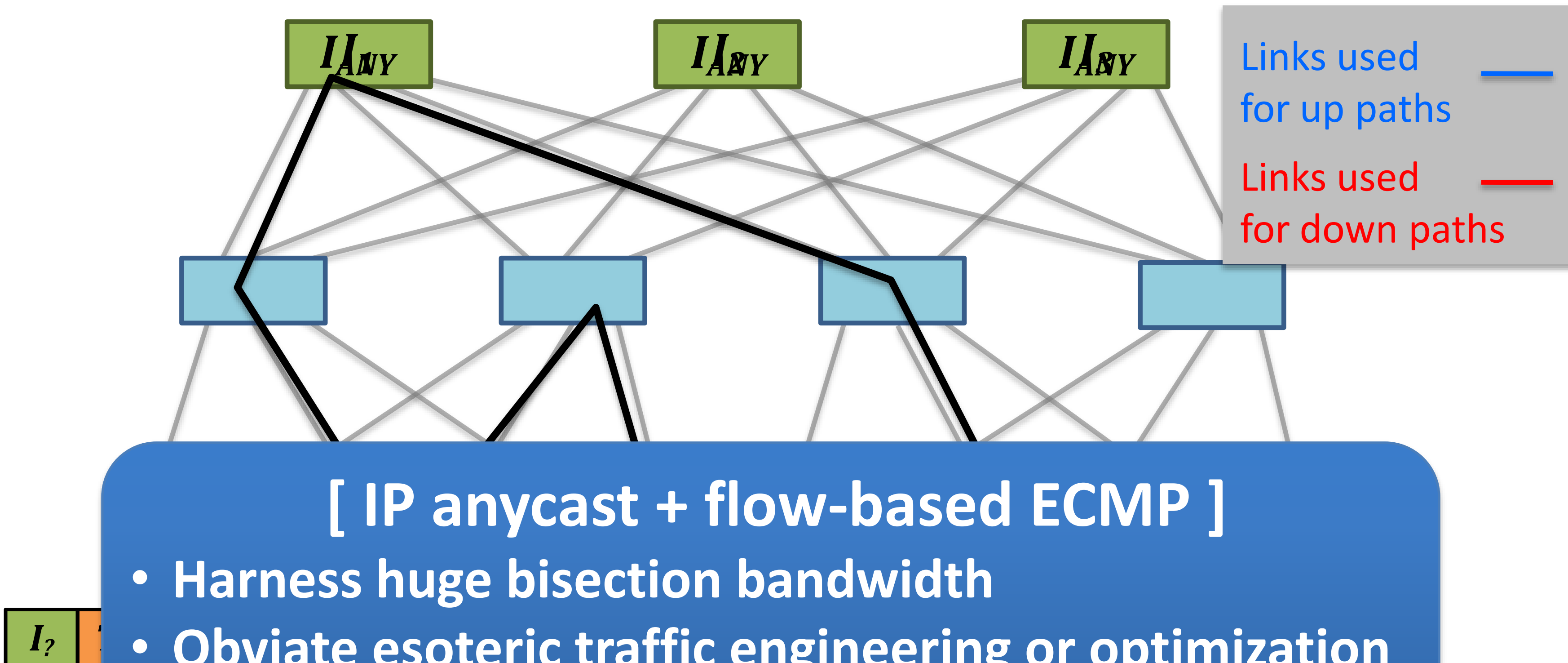
# Example Topology: Clos Net

**Offer huge aggregate capacity at modest cost**



# Traffic Forwarding: Random Indirection

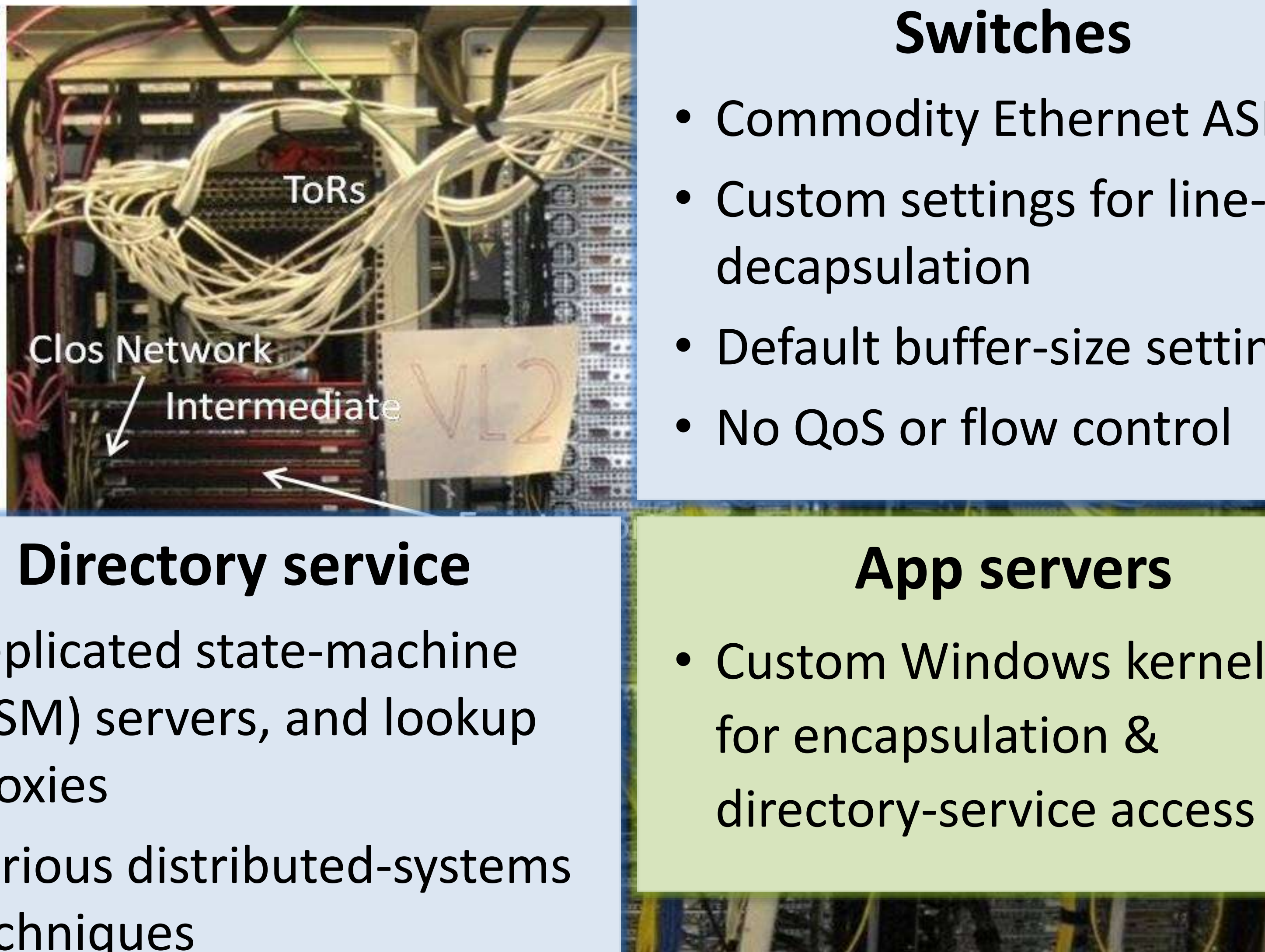
**Cope with arbitrary TMs with very little overhead**




**[ IP anycast + flow-based ECMP ]**

- Harness huge bisection bandwidth
- Obviate esoteric traffic engineering or optimization
- Ensure robustness to failures
- Work with switch mechanisms available today

# Implementation




## Switches

- Commodity Ethernet ASICs
- Custom settings for line-rate decapsulation
- Default buffer-size settings
- No QoS or flow control

## Directory service

- Replicated state-machine (RSM) servers, and lookup proxies
- Various distributed-systems techniques

## App servers

- Custom Windows kernel for encapsulation & directory-service access

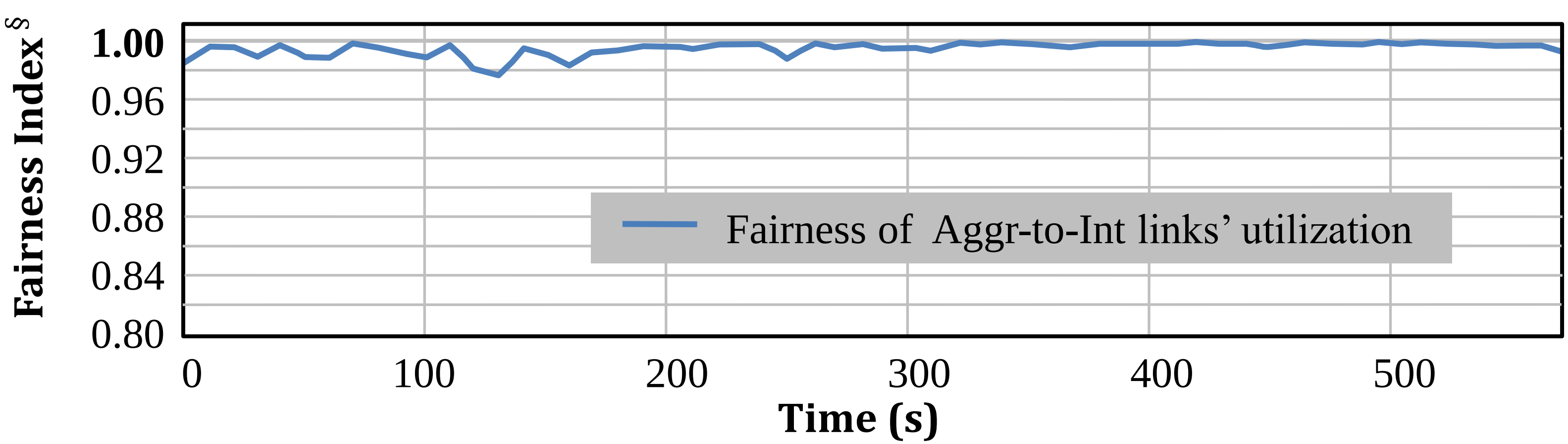
# Data-Plane Evaluation

- Ensures uniform high capacity
  - Offered various TCP traffic patterns, then measured overall and per-flow goodput

| | VL2 | Fat Tree | Dcell |
|---|---|---|---|
| **Goodput efficiency** | **93+%** | 75+% (w/o opt)<br>95+% (with opt) | 40 ~ 60% |
| **Fairness between flows** | **0.995**[§] | n/a | n/a |

[§] Jain's fairness index defined as $(\sum x_i)^2/(n\cdot\sum x_i^2)$

- Works nicely with real traffic as well



# VL2 Conclusion

- Cloud-service DC needs a huge L2 switch
  - Uniform high capacity, oblivious TE, L2 semantics
- Key lessons
  - Hard to outsmart haphazardness; tame it with dice
  - Recipe for success: Intelligent hosts + Rock-solid network built with proven technologies

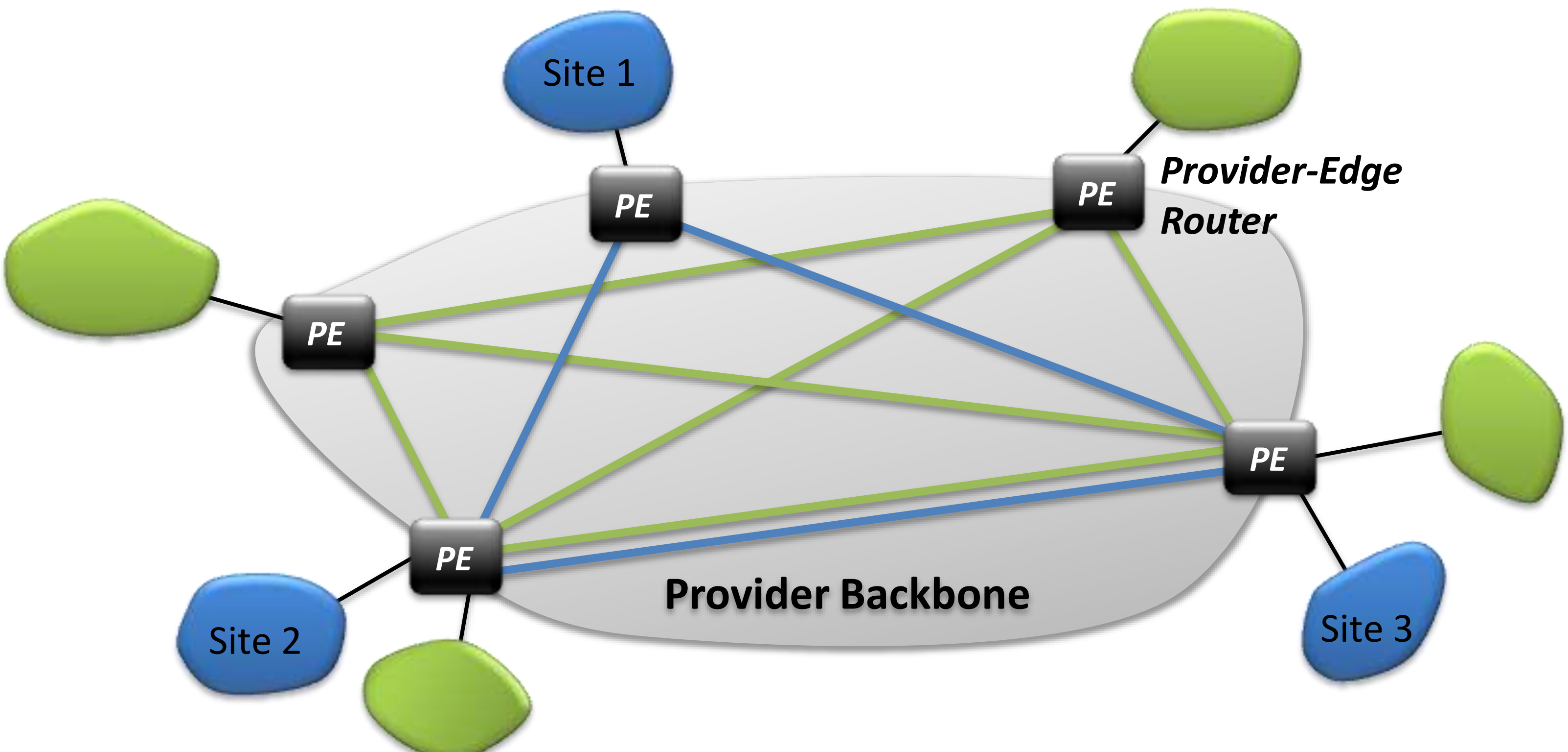
| | |
|---|---|
| *Flat Addressing* | *Name-location separation* |
| *Traffic Indirection* | *Random traffic spreading (VLB + ECMP)* |
| *Usage-driven Opt.* | *Utilizing ARP, reactive cache update* |

# Relaying: A Scalable VPN Routing Architecture

Work with Alex Gerber, Shubho Sen, Dan Pei, and Carsten Lund

# Virtual Private Network

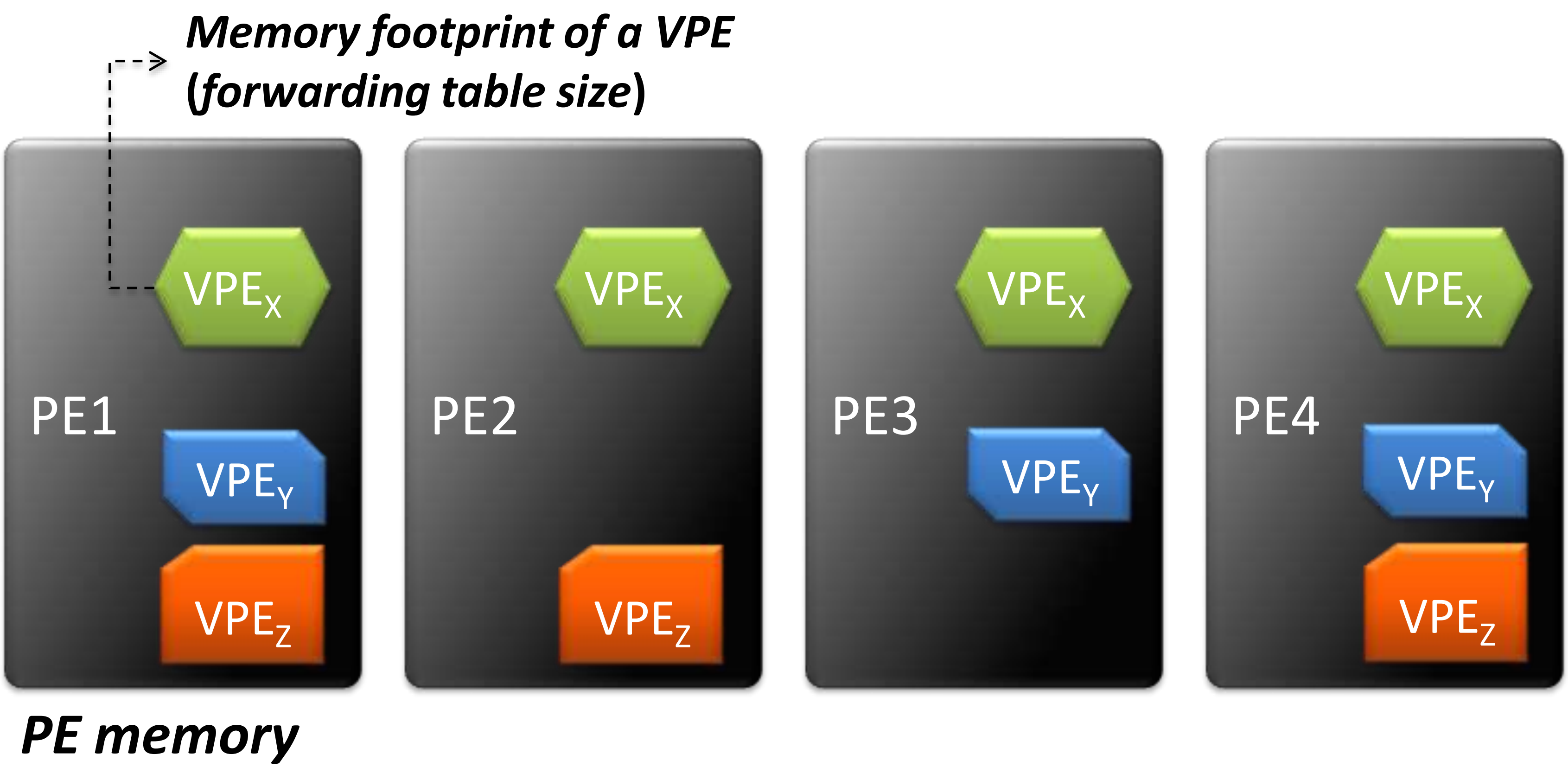
- Logically-isolated communication channels for corporate customers, overlayed over provider backbone
  - Direct any-to-any reachability among sites
  - Customers can avoid full-meshing via outsourcing routing



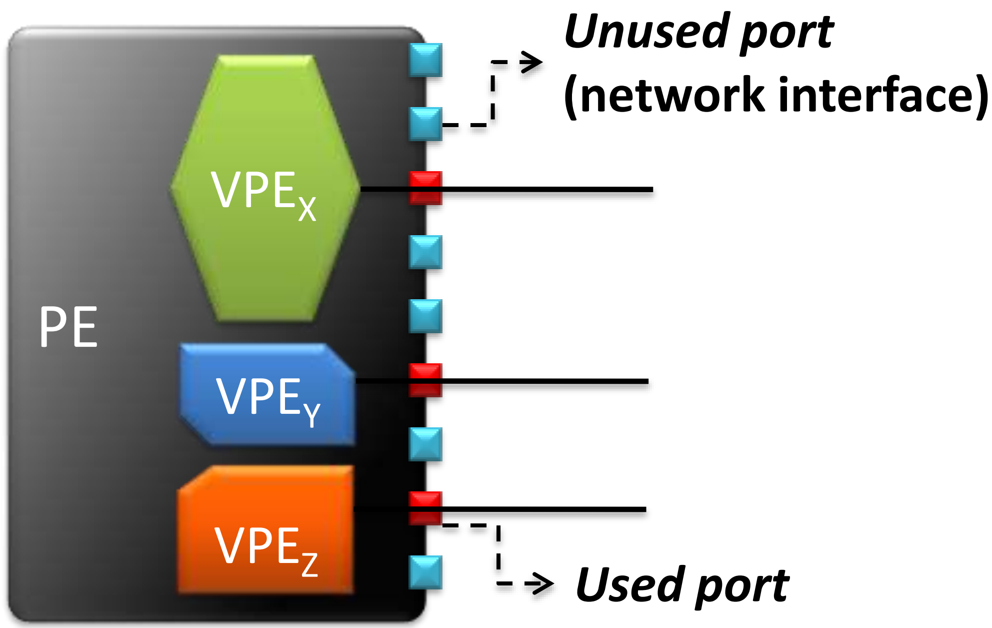
# VPN Routing and Its Consequence

**Site-level Flat Addressing**:

Virtual PEs (VPEs) self-learn and maintain full routing state in the VPN (i.e., routes to every address block used in each site)



# Mismatch in Usage of Router Resources




- Memory is full, whereas lots of ports still unused
- Revenue is proportional to provisioned bandwidth
- Large VPN with a thin connection per site is the worst case
- Unfortunately, there are many such worst cases
- Providers are seriously pinched

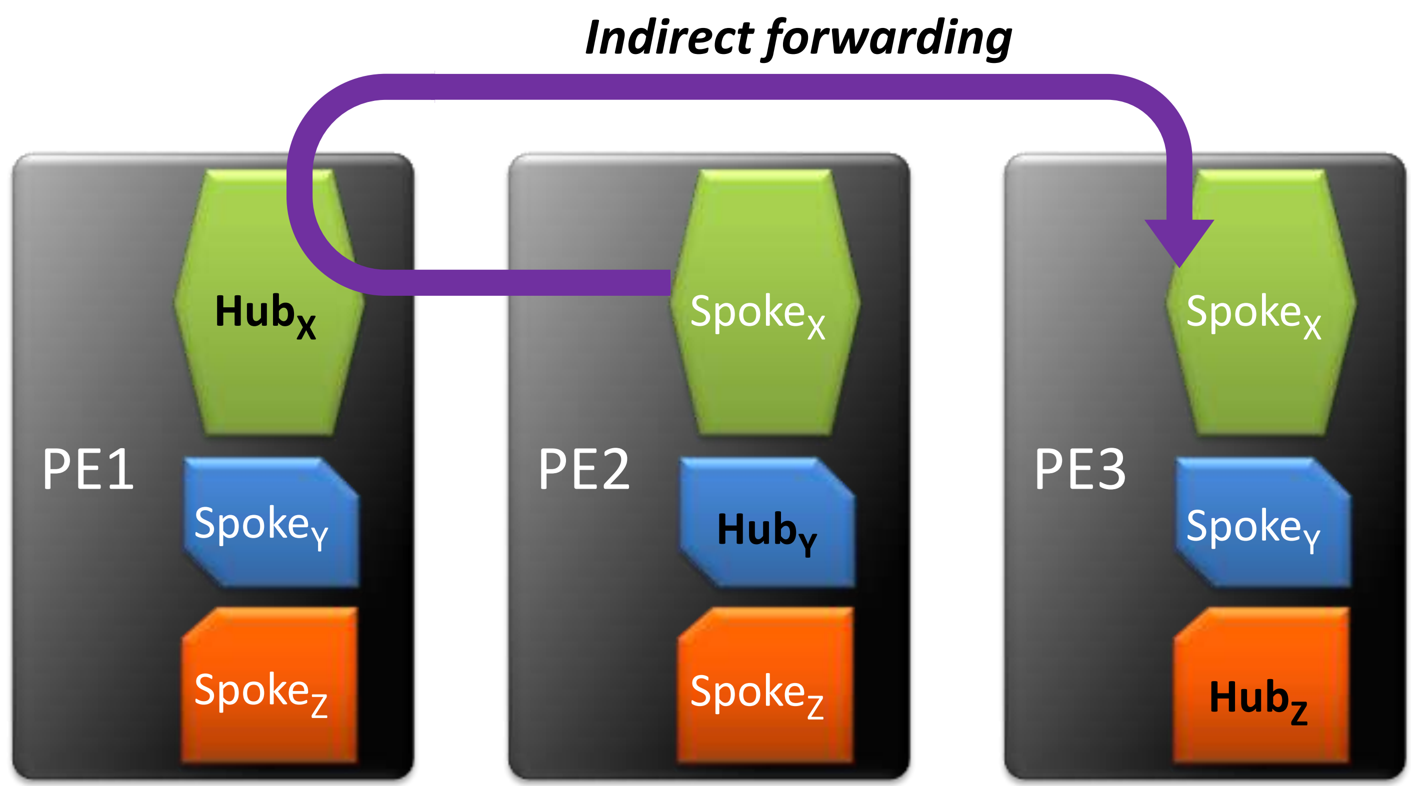
# Key Questions

- What can we do better with existing resources and capabilities only, while maintaining complete transparency to customers?

- Do we really need to provide direct reachability for every pair of sites?
  - Even when most (84%) PEs communicate only with a small number (~10%) or popular PEs …

# Relaying Saves Memory

- Each VPN has two different types of PEs
  - **Hubs**: Keep full routing state of a VPN
  - **Spokes**: Keep local routes and a single default route to a hub
- A spoke uses a hub consistently for all non-local traffic



# Real-World Deployment Requires A Mgmt-Support Tool

- Two operational problems to solve
  - Hub selection: Which PEs should be hubs?
  - Hub assignment: Which hub should a given spoke use?
- Constraint
  - Stretch penalty must be bounded to keep SLAs
- Solve the problems individually for each VPN
  - Hub selection and assignment decision for a VPN is totally independent of that of other VPNs
  - Ensures both simplicity and flexibility

# Latency-Constrained Relaying (LCR)

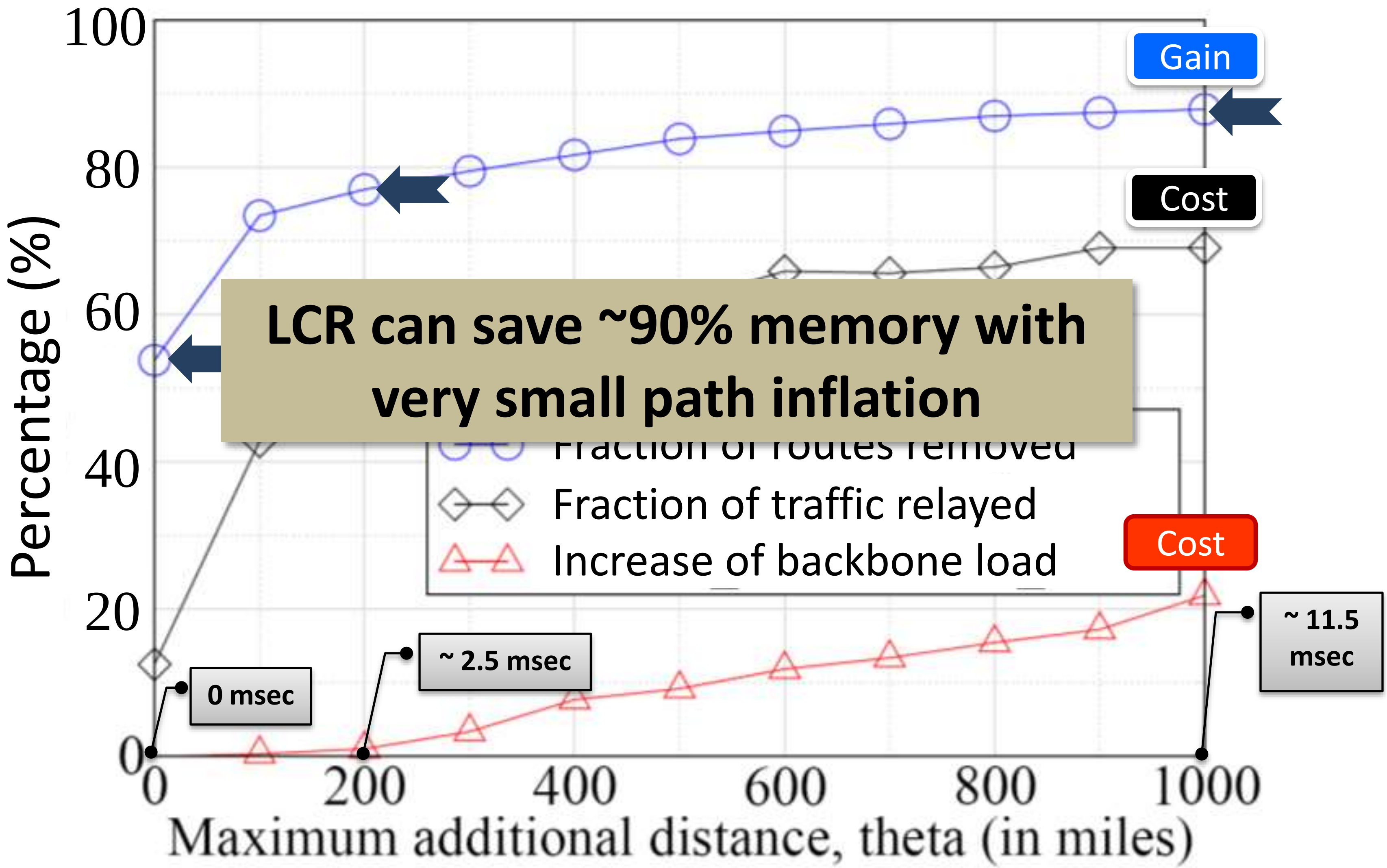
- Notation
  - PE set: $P = \{1, 2, \cdots, n\}$
  - Hub set: $H \subseteq P$
  - The hub of PE$_i$: $hub(i) \in H$
  - Usage-based conversation matrix: $C = (c_{i,j})$
  - Latency matrix: $L = (l_{i,j})$
- Formulation
  - Choose as few hubs as possible, while limiting additional distance due to Relaying

$$
\begin{aligned}
\min \quad & |H| \\
s.t. \quad & \forall s, d \in P \ \ whose \ \ c_{s,d} = 1, \\
& l_{s,hub(s)} + l_{hub(s),d} - l_{s,d} \le \theta
\end{aligned}
$$

→ Parameter

# Memory Saving and Cost of LCR

Based on entire traffic in 100+ VPNs for a week in May, 2007



# Deployment and Operation

- Oblivious optimization also leads to significant benefits
- Can implement this via minor routing protocol configuration change at PEs
- Performance degrades very little over time
  - Cost curves are fairly robust
  - Weekly/monthly adjustment: 94/91% of hubs remain as hubs
- Can ensure high availability
  - Need more than one hub located at different cities
  - 98.3% of VPNs spanning 10+ PEs have at least 2 hubs anyway
  - Enforcing "|H| > 1" reduces memory saving by only 0.5%

# Relaying Conclusion

- VPN providers need a huge L2-like switch
  - Site-level PNP networking, any-to-any reachability, and scalability
- Key lessons
  - Traffic locality is our good friend
  - Presenting an immediately-deployable solution requires more than just designing an architecture

| | |
|---|---|
| *Flat Addressing* | *Hierarchy-free site addressing* |
| *Traffic Indirection* | *Forwarding through a hub* |
| *Usage-driven Opt.* | *Popularity-driven hub selection* |

# Goals Attained

**Self-config** + **Scalability** + **Efficiency**

| | SEATTLE | VL2 | Relaying |
|---|---|---|---|
| Self-config | Eliminates addressing and routing configuration | Additionally eliminates configuration for traffic engineering | Retains self-configuring semantics for VPN customers |
| Scalability | Significantly reduces control overhead and memory consumption | Allows a DC to host over 100K servers w/o oversubscription | Allows existing routers to serve an order of mag. more VPNs |
| Efficiency | Improves link utilization and convergence | Boosts DC-server utilization by enabling agility | Only slightly increases end-to-end latency and traffic workload |

# Summary and Future Work

- Designed, built, and deployed **huge L2-like switches** for various networks
- The **universal hammers** are applicable for various situations
- Future work
  - Other universal hammers?
  - Self-configuration on the Internet scale?
  - Architecture for distributed mini data centers?