Best Practices for Determining the Traffic Matrix in IP Networks

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Presenters and Contributors

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    - Juniper DCU
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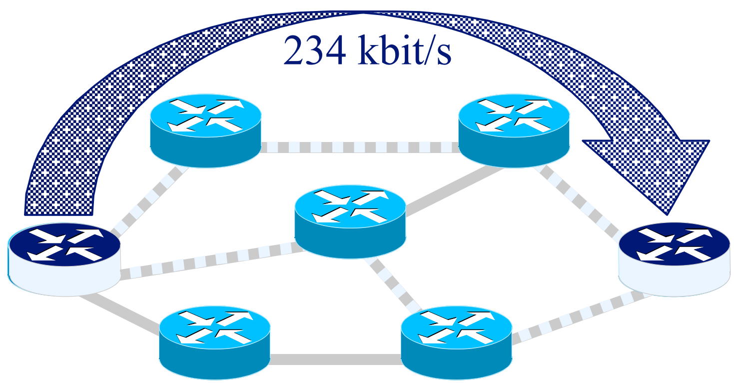
    - Adlex NetFlow collector deployment
  - Mikael Johansson, *KTH*
    - Traffic Matrix Estimation

Agenda

- Introduction
  - Traffic Matrix Properties
- Measurement in IP networks
  - NetFlow
  - NetFlow Deployment Case-Study
  - DCU (Juniper)
  - BGP Policy Accounting
- MPLS Networks
  - RSVP based TE
  - LDP
    - Data Collection
    - LDP deployment in Deutsche Telekom
- Traffic Matrices in Partial Topologies
- Estimation Techniques
  - Theory
  - Example Data
  - Case-Study
- Summary

Traffic Matrix

- Traffic matrix: the amount of data transmitted between every pair of network nodes
  - Demands
  - “end-to-end” in the core network
- Traffic Matrix can represent peak traffic, or traffic at a specific time
- Router-level or PoP-level matrices



Determining the Traffic Matrix

- Why do we need a Traffic Matrix?
  - Capacity Planning
    - Determine free/available capacity
    - Can also include QoS/CoS
  - Resilience Analysis
    - Simulate the network under failure conditions
  - Network Optimization
    - Topology
      - Find bottlenecks
    - Routing
      - IGP (e.g. OSPF/IS-IS) or MPLS

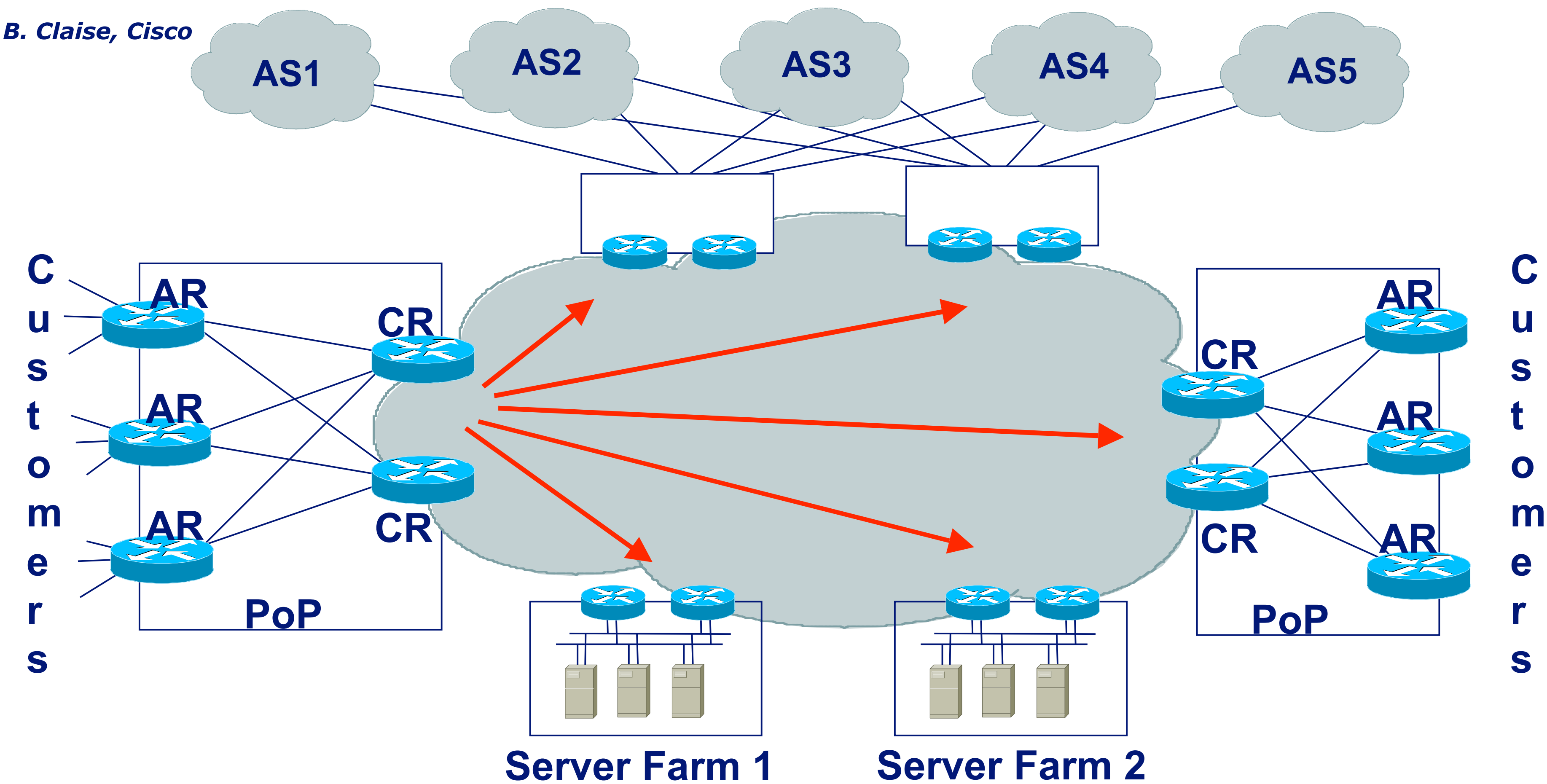
Types of Traffic Matrices

- Internal Traffic Matrix
  - PoP to PoP matrix
    - Can be from core (CR) or access (AR) routers
  - Class based

- External Traffic Matrix
  - PoP to External AS
    - BGP
    - Origin-AS or Peer-AS
      - Peer-AS sufficient for Capacity Planning and Resilience Analysis
    - Useful for analyzing the impact of external failures on the core network (capacity/resilience)

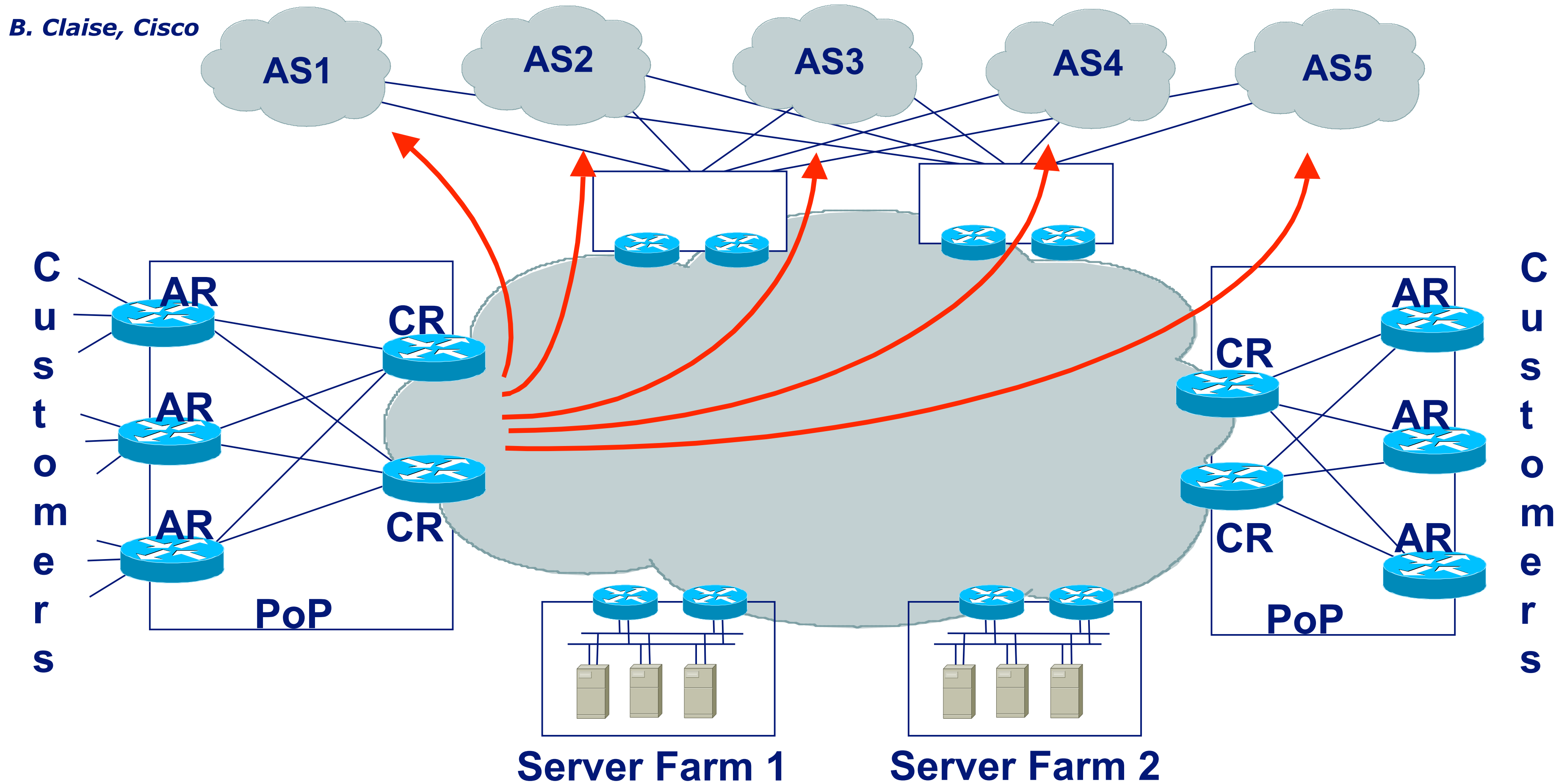
Internal Traffic Matrix

B. Claise, Cisco



"PoP to PoP", the PoP being the **AR** or **CR**

External Traffic Matrix



From "PoP to BGP AS", the PoP being the **AR** or **CR**

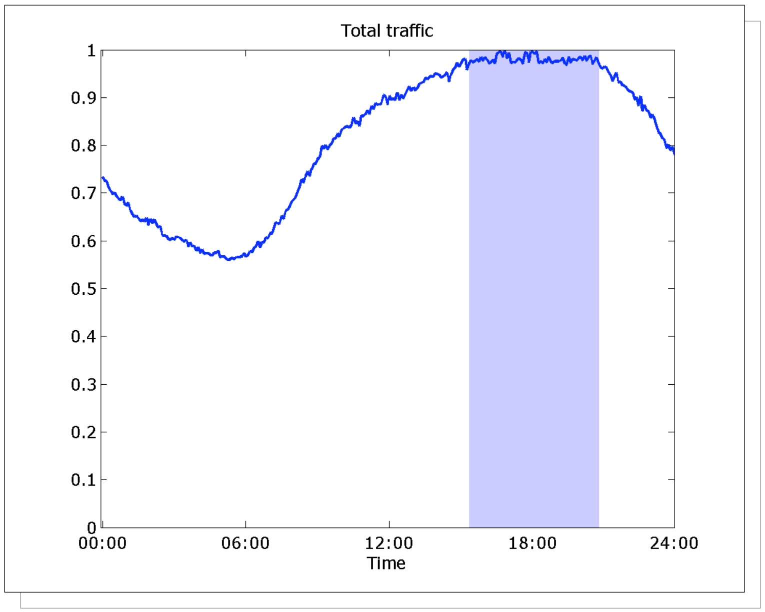
The external traffic matrix can influence the internal one

Traffic Matrix Properties

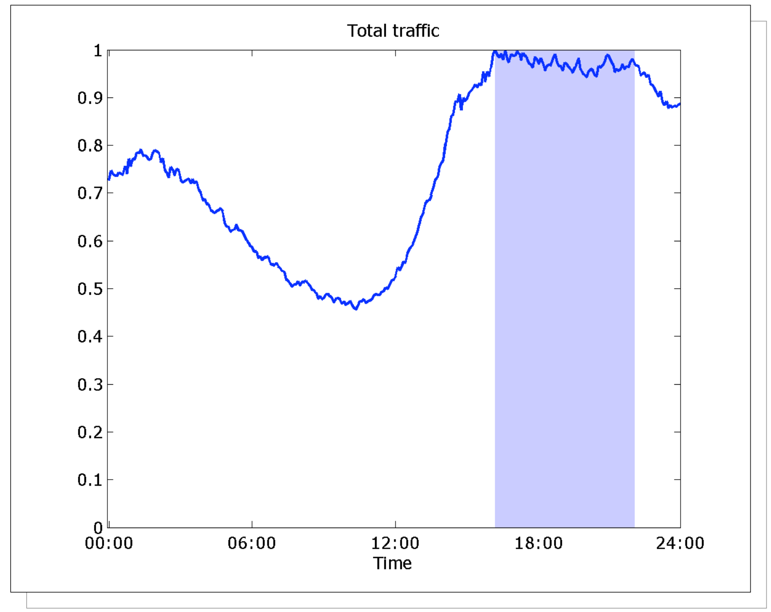
- Example Data from Tier-1 IP Backbone
  - Measured Traffic Matrix (MPLS TE based)
  - European and American subnetworks
  - 24h data
  - See [1]
- Properties
  - Temporal Distribution
    - How does the traffic vary over time
  - Spatial Distribution
    - How is traffic distributed in the network?
  - Relative Traffic Distribution
    - "Fanout"

Total traffic and busy periods

European subnetwork



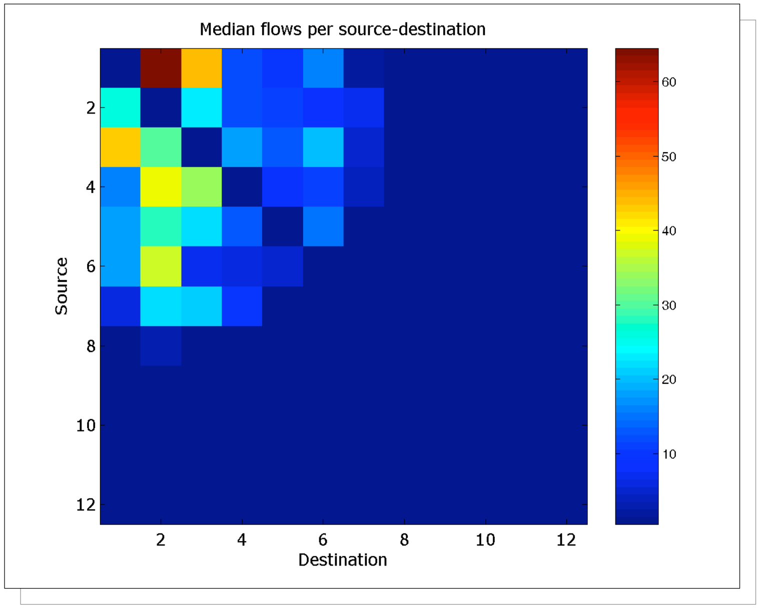
American subnetwork



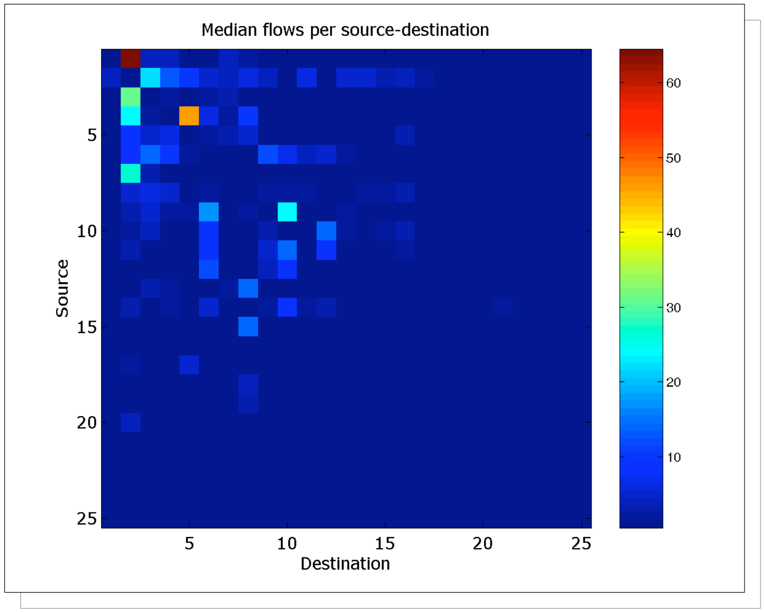
Total traffic very stable over 3-hour busy period

Spatial demand distributions

European subnetwork



American subnetwork

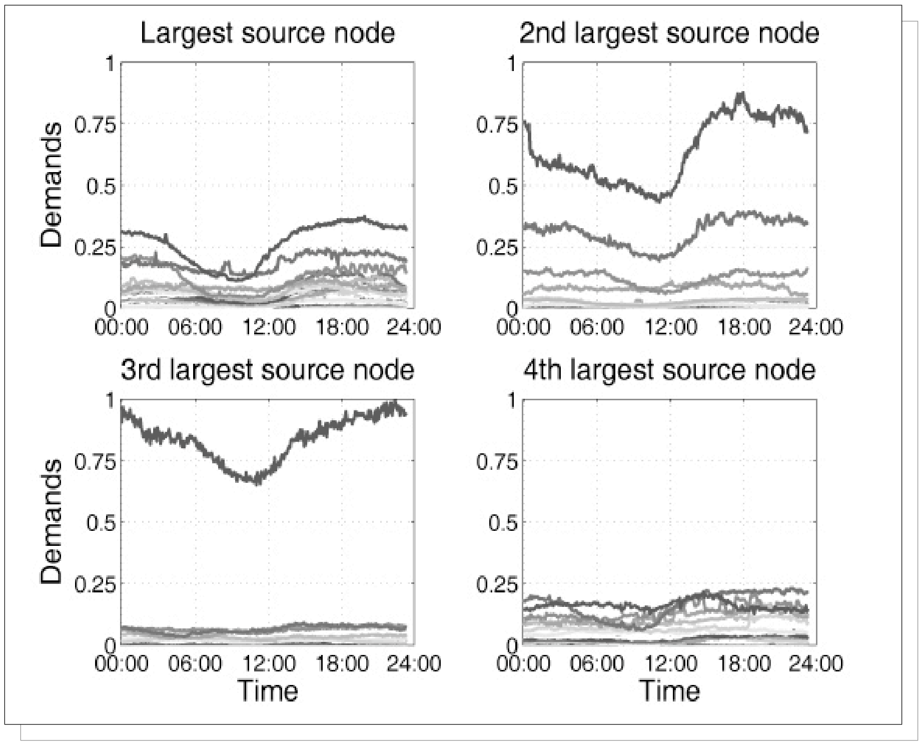


Few large nodes contribute to total traffic (20% demands – 80% of total traffic)

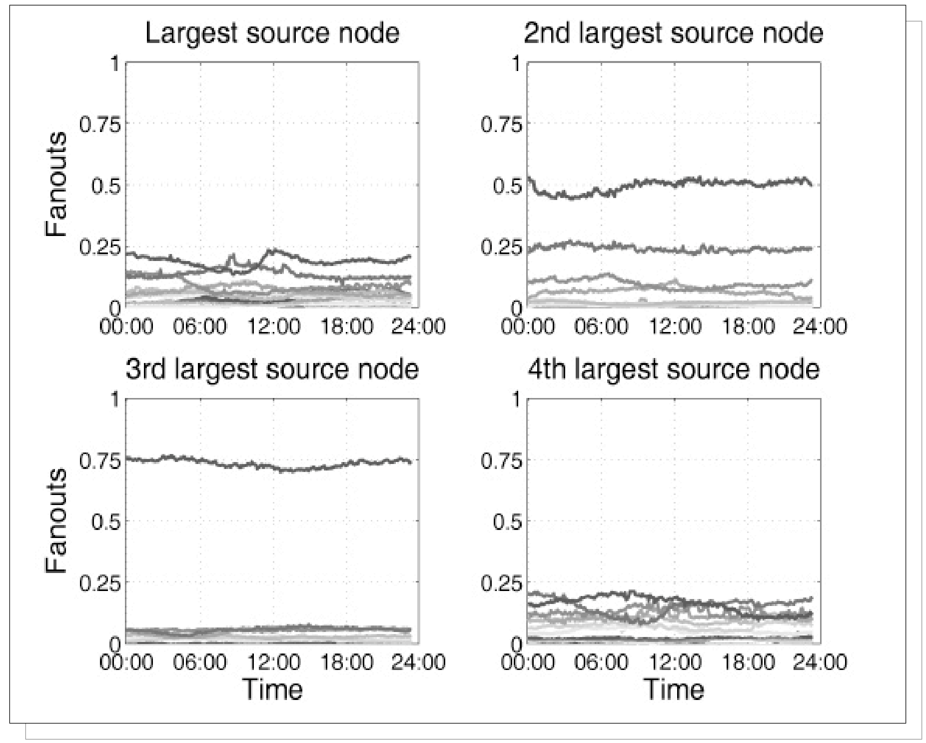
Fanout factors

Fanout: relative amount of traffic (as percentage of total)

Demands for 4 largest nodes, USA



Corresponding fanout factors



Fanout factors much more stable than demands themselves!

Traffic Matrix Collection

- Data is collected at fixed intervals
  - E.g. every 5 or 15 minutes
- Measurement of *Byte Counters*
  - Need to convert to rates
  - Based on measurement interval
- Create Traffic Matrix
  - Peak Hour Matrix
    - 5 or 15 min. average at the peak hour
  - Peak Matrix
    - Calculate the peak for every demand
    - Real peak or 95-percentile

Collection Methods

- NetFlow
  - Routers collect “flow” information
  - Export of raw or aggregated data
- DCU
  - Routers collect aggregated destination statistics
- MPLS
  - LDP
    - Measurement of LDP counters
  - RSVP
    - Measurement of Tunnel/LSP counters
- Estimation
  - Estimate Traffic Matrix based on Link Utilizations

NetFlow based Methods

NetFlow

- A “Flow” is defined by
  - Source address
  - Destination address
  - Source port
  - Destination port
  - Layer 3 Protocol Type
  - TOS byte
  - Input Logical Interface (ifIndex)
- Router keeps track of Flows and usage per flow
  - Packet count
  - Byte count

NetFlow Versions

- Version 5
  - the most complete version
- Version 7
  - on the switches
- Version 8
  - the Router Based Aggregation
- Version 9
  - the new flexible and extensible version

- Supported by multiple vendors
  - Cisco
  - Juniper
  - others

NetFlow Export

- A Flow is exported when
  - Flow expires
  - Cache full
  - Timer expired
- Expired Flows are grouped together into “NetFlow Export” UDP datagrams for export to a collector
  - Including timestamps
- UDP is used for speed and simplicity
- Exported data can include extra information
  - E.g. Source/Destination AS

NetFlow Export

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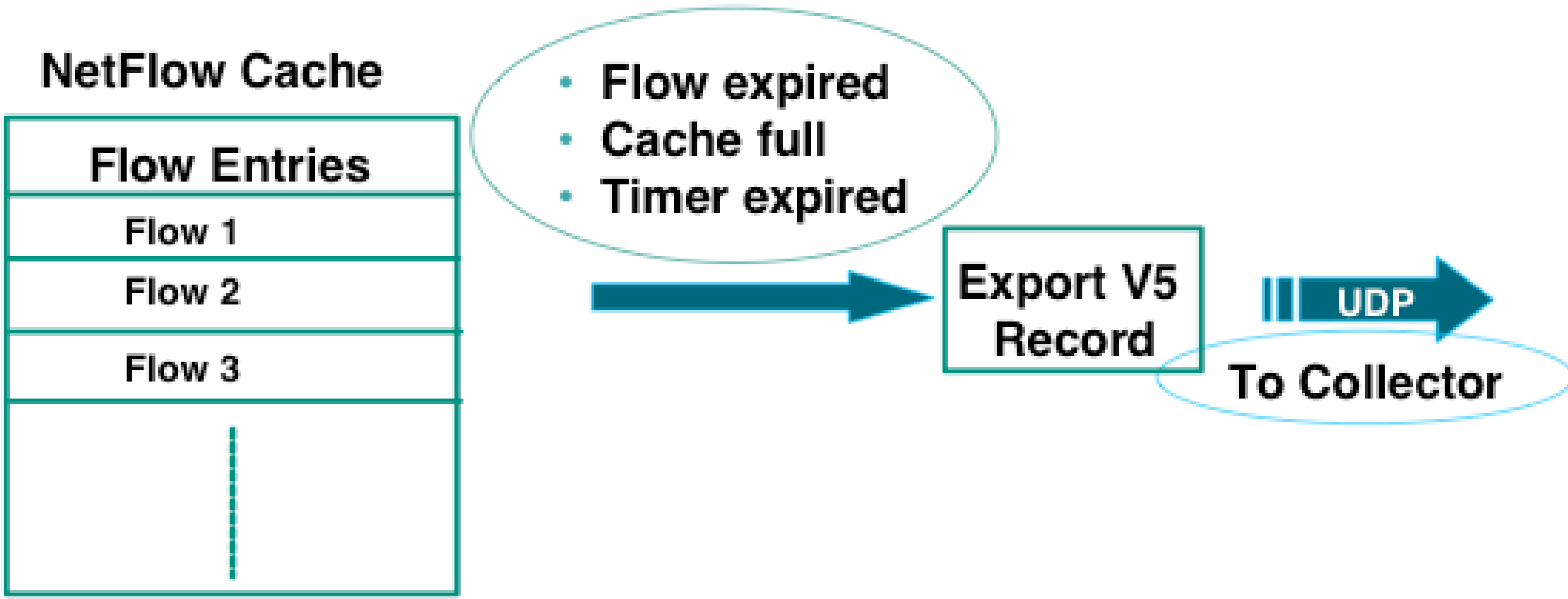


NetFlow Deployment

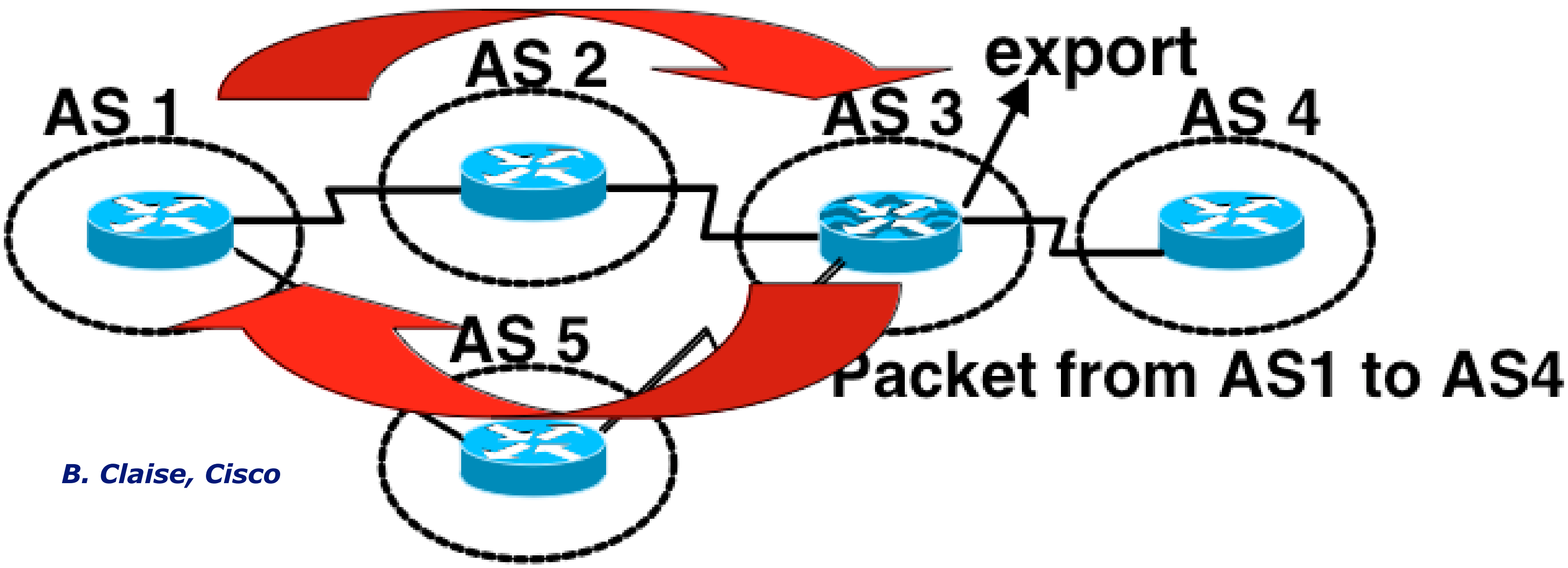
- How to build a Traffic Matrix from NetFlow data?
  - Enable NetFlow on all interfaces that source/sink traffic into the (sub)network
    - E.g. Access to Core Router links (AR->CR)
  - Export data to central collector(s)
  - Calculate Traffic Matrix from Source/Destination information
    - Static (e.g. list of address space)
    - BGP AS based
      - Easy for peering traffic
      - Could use “live” BGP feed on the collector
    - Inject IGP routes into BGP with community tag

BGP Passive Peer on the Collector

- Instead of exporting the peer-as or destination-as for the source and destination IP addresses for the external traffic matrix:
  - Don't export any BGP AS's
  - Export version 5 with IP addresses or version 8 with an prefix aggregation
- A BGP passive peer on the NetFlow collector machines can return all the BGP attributes:
  - source/destination AS, second AS, AS Path, BGP communities, BGP next hop, etc…
- Advantages:
  - Better router performance – less lookups
  - Consume less memory on the router
  - Full BGP attributes flexibility

NetFlow: Asymetric BGP traffic

- Origin-as
  - Source AS1, Destination AS4
- Peer-as
  - Source AS5, Destination AS4 WRONG!
- Because of the source IP address lookup in BGP



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NetFlow Version 8

- Router Based Aggregation
- Enables router to summarize NetFlow Data
- Reduces NetFlow export data volume
  - Decreases NetFlow export bandwidth requirements
  - Makes collection easier

- Still needs the main (version 5) cache
- When a flow expires, it is added to the aggregation cache
  - Several aggregations can be enabled at the same time
- Aggregations:
  - Protocol/port, AS, Source/Destination Prefix, etc.

NetFlow: Version 8 Export

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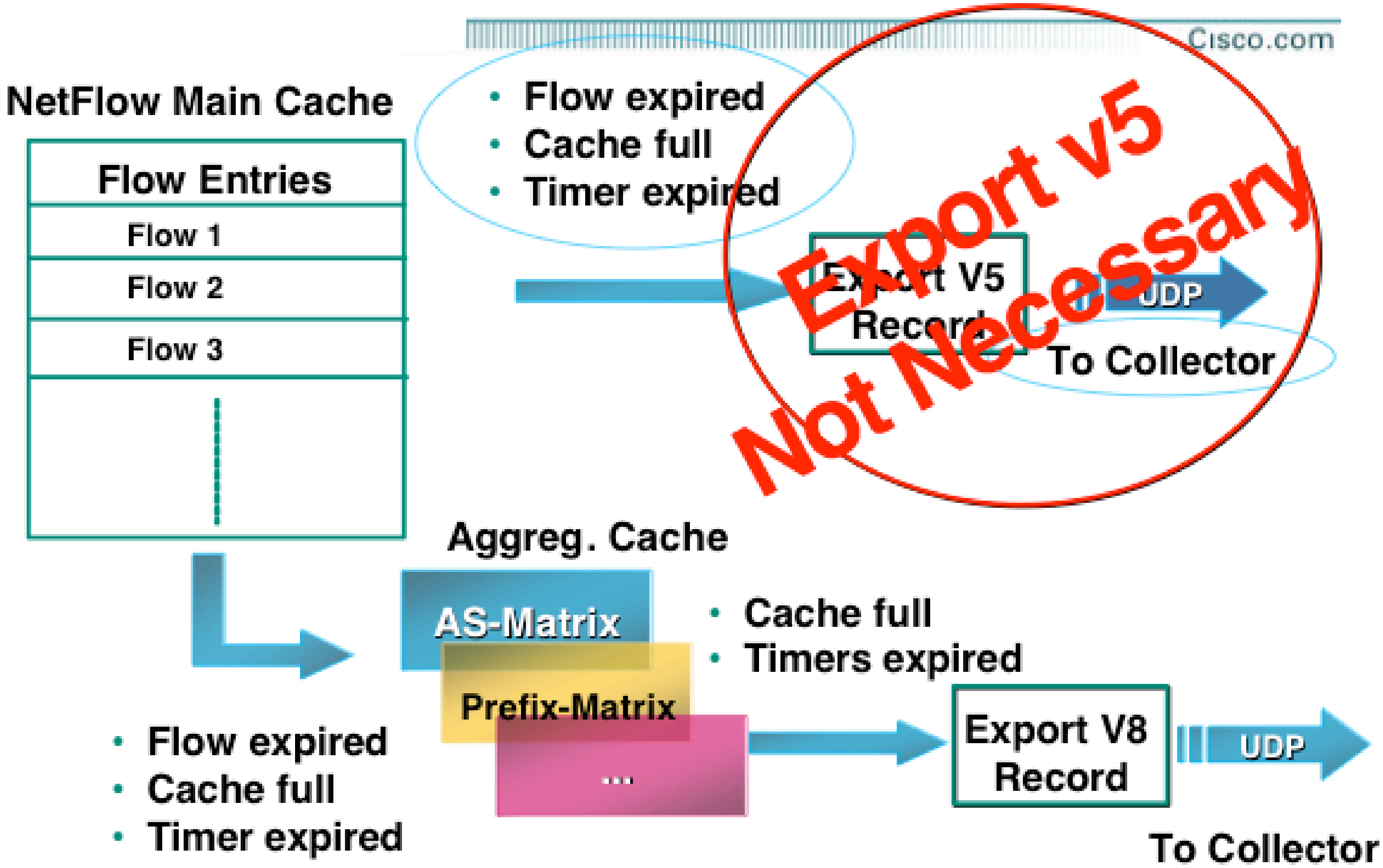

BGP NextHop TOS Aggregation

- New Aggregation scheme
  - Only for BGP routes
    - Non-BGP routes will have next-hop 0.0.0.0
- Configure on Ingress Interface
- Requires the new Version 9 export format
- Only for IP packets
  - IP to IP, or IP to MPLS

BGP NextHop TOS Aggregation

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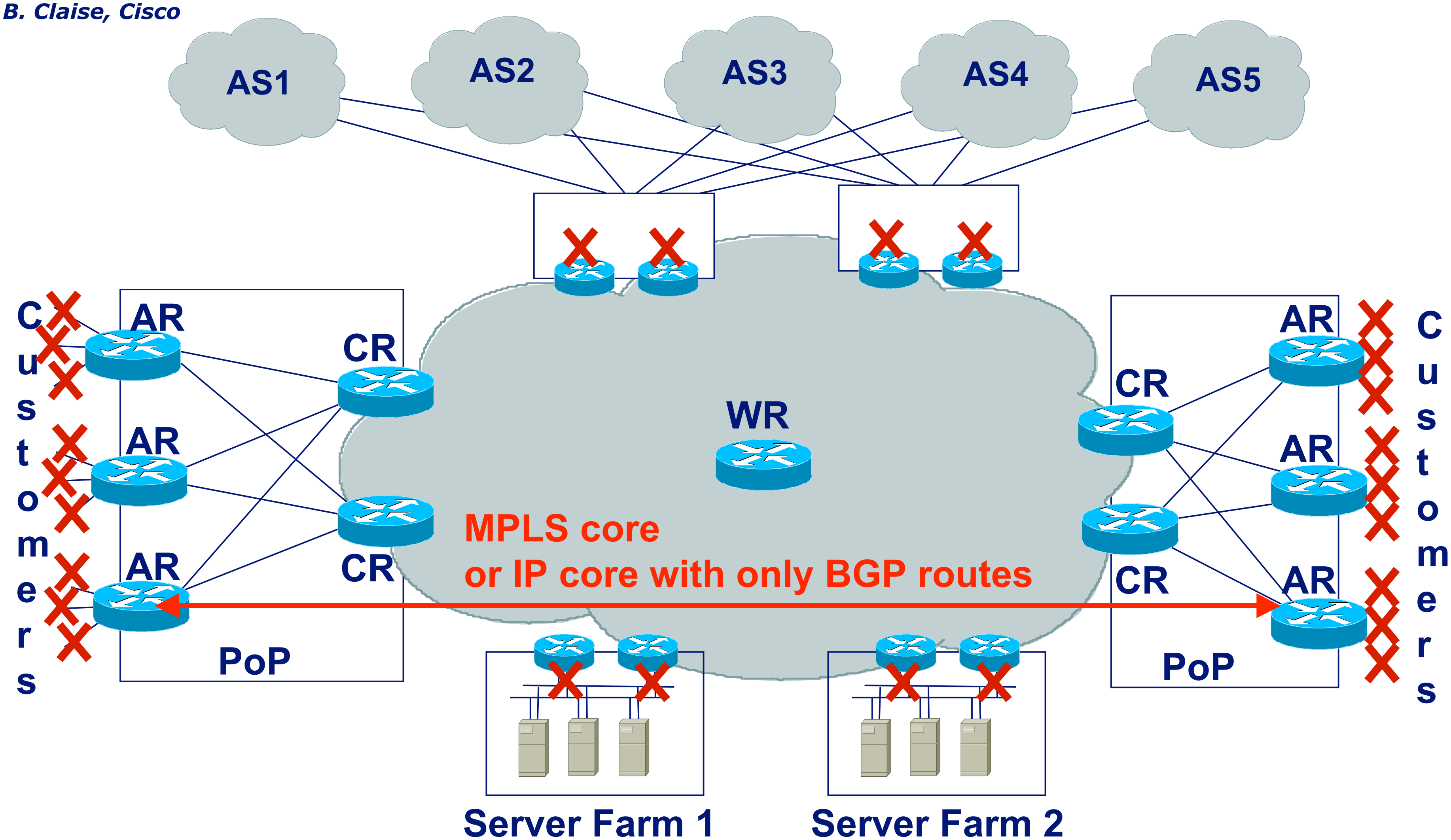

MPLS aware NetFlow

- Provides flow statistics per MPLS and IP packets
  - MPLS packets:
    - Labels information
    - And the V5 fields of the underlying IP packet
  - IP packets:
    - Regular IP NetFlow records
- Based on the NetFlow version 9 export
  No more aggregations on the router (version 8)
- Configure on ingress interface
- Supported on sampled/non sampled NetFlow

MPLS aware NetFlow: Example

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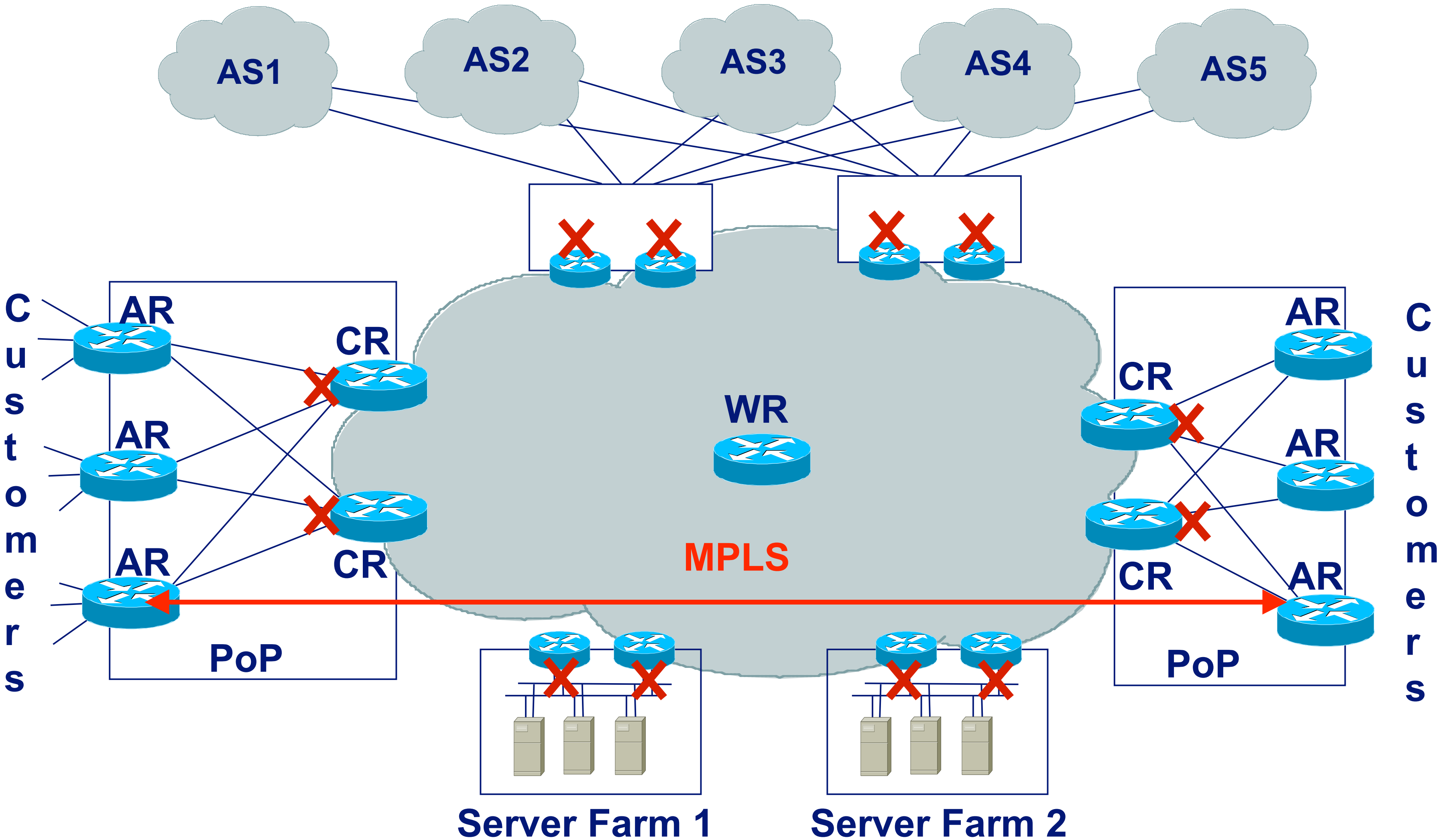


NetFlow Summary

- Building a Traffic Matrix from NetFlow data is not trivial
  - Need to correlate Source/Destination information with routers or PoPs
- “origin-as” vs “peer-as”
  - Asymetric BGP traffic problem
- BGP NextHop aggregation comes close to directly measuring the Traffic Matrix
  - NextHops can be easily linked to a Router/PoP
  - BGP only
- NetFlow processing is CPU intensive on routers
  - Use Sampling
    - E.g. only use every 1 out of 100 packets
    - Accuracy of sampled data

NetFlow Summary

- Various other features are available
- Ask vendors (Cisco, Juniper, etc.) for details on version support and platforms
- For Cisco, see Benoit Claise's webpage:
  - http://www.employees.org/~bclaise/

NetFlow Case-Study

Deployment Scenario

- NetFlow deployment in a large ISP network ("ISP X") using Adlex FlowTracker
  - Traffic Engineering Analysis (TEA)
- Goal is to obtain an accurate Traffic Matrix
  - Router to Router matrix
- Internal Traffic sources/sinks
  - typically blocks of customer address space in PoPs, such as such as broadband access devices (DSL or Cable Modem termination systems, dedicated corporate Internet access routers, dial NASes, etc).
- External traffic sources/sinks
  - typically public or private peering links (eBGP connections) in peering centers or transit PoPs

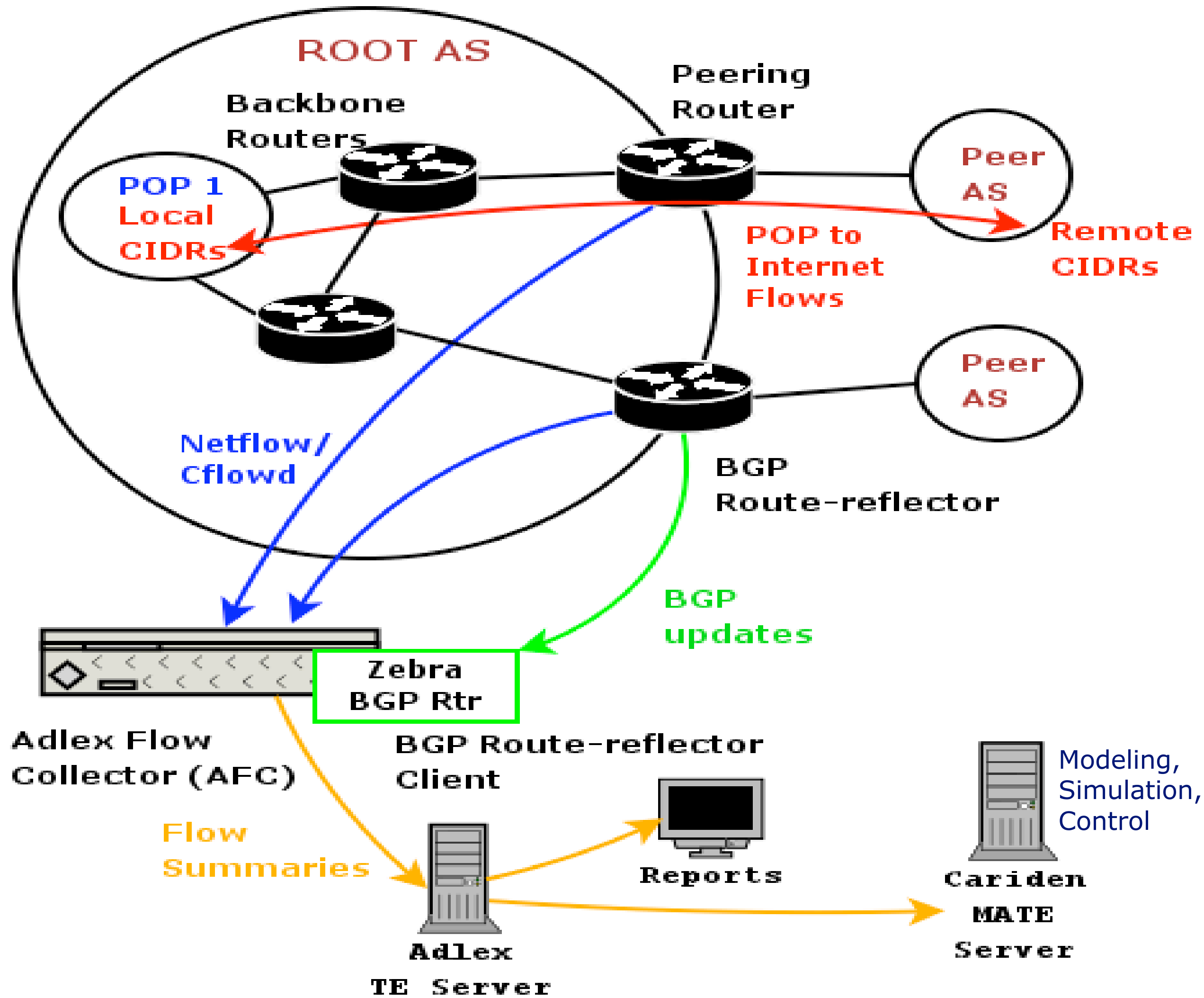
Associating Traffic with Routers

- Customer routes in each PoP are advertised into iBGP from the IGP
  - by each of the two backbone routers in each PoP
  - with the backone router's loopback address as the BGP Next Hop IP address for each of the local routes in the PoP
- The Adlex TEA system can pick them up from the BGP table via an integrated Zebra software router component in the Adlex Flow Collector (AFC)
- ISP uses Version 5 Netflow with Adlex Flow Collectors that are BGP Next-Hop aware at the local (PoP) and external (Internet) CIDR level

ISP X Phase 1: Internet Traffic

- Enable NetFlow on all interfaces on eBGP peering routers
  - Flows are captured at the Internet border, from the peering routers, as they pass through peering routers to/from Internet eBGP peers
- Adlex Traffic Engineering Report Server:
  - Retreives and aggregates summarized flows from multiple AFCs
  - Exports daily traffic matrix CSV files to Cariden MATE
    - For Modeling, Simulation and Control
- Hourly router-router values actually contain the the highest 15-minute average bandwidth period within that whole hour (4 periods/hour)
  - provides sufficient granularity to get near daily peak values between routers or PoPs

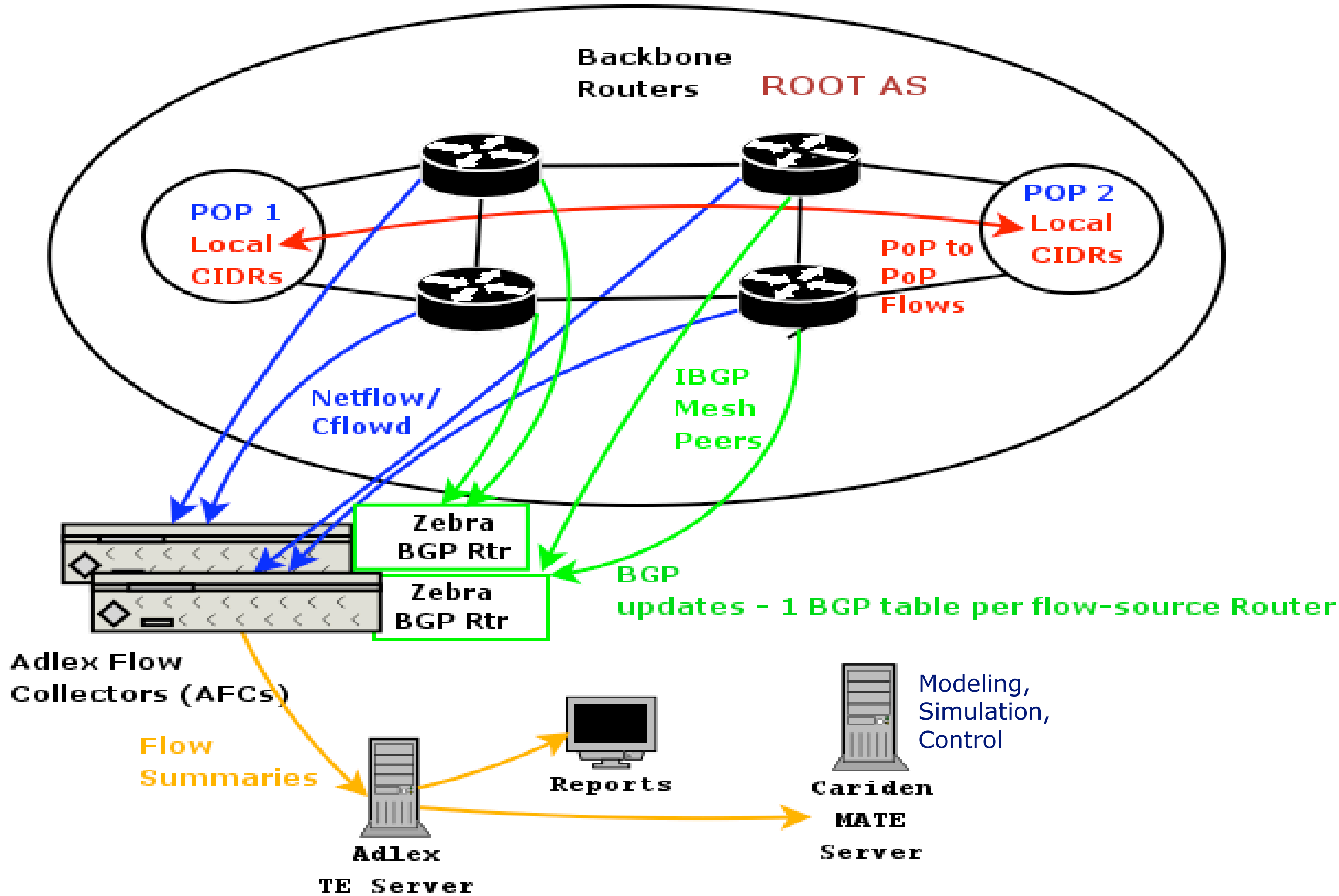
ISP X Phase 1: Internet Traffic



ISP X Phase 2: PoP-to-PoP Traffic

- Ingress-only Netflow exported from PoP-facing interfaces on Backbone routers
  - Enables capturing data flowing between POPs
- Flow assignment accuracy is optimized if each router that exports flows has those flows analyzed according to its own BGP table
  - Thus the traffic collection and analysis system must process a BGP table per-router
- BGP table per backbone router and per peering router

ISP X Phase 2: PoP-to-PoP Traffic



Example Results

Abbreviated header showing hourly columns:

```
  # Time Router A IP,Time Router B
IP,09/01/04 12:00:00 AM Max Bits/s Router A-
>B(bps),09/01/04 01:00:00 AM Max Bits/s
Router A->B(bps), 09/01/04 02:00:00 AM Max
Bits/s Router A->B(bps)
```

Abbreviated data showing source & dest router IPs and hourly max-15-minute values:

```
63.45.173.83,173.27.44.02,2639.64453125,2858
.09765625,15155.2001953125,10594.986328125,2
1189.97265625,8747.2353515625,104866.703125,
136815.5,31976.107421875,12642.986328125,851
0.578125,6489.88427734375,8192.0
```

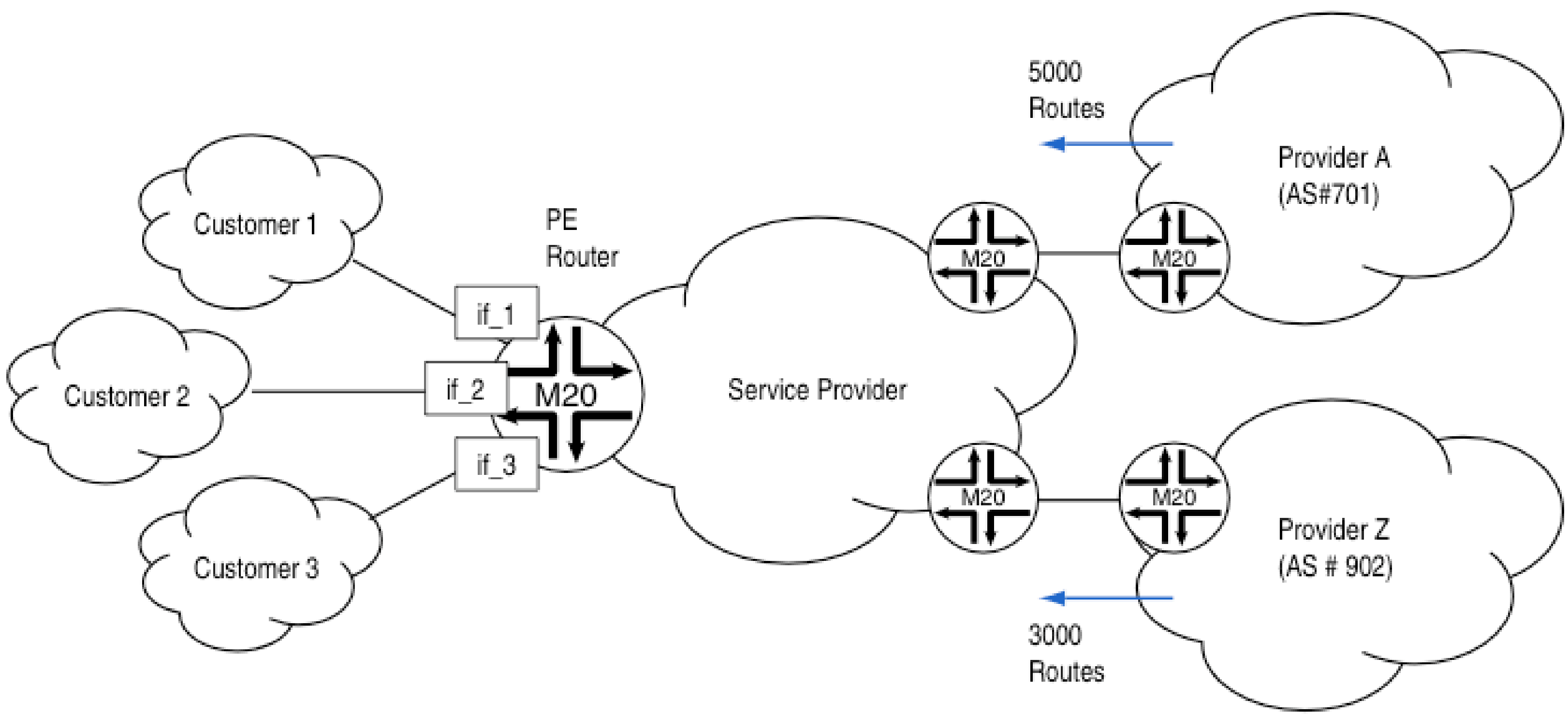
Destination Class Usage (DCU)

Destination Class Usage (DCU)

- Juniper specific!
- Policy based accounting mechanism
  - For example based on BGP communities
- Supports up to 16 different traffic destination classes
- Maintains per interface packet and byte counters to keep track of traffic per class
- Data is stored in a file on the router, and can be pushed to a collector
- But…
- *16 destination classes is in most cases too limited to build a useful full Traffic Matrix*

DCU Example

- Routing policy
  - associate routes from provider A with DCU class 1
  - associate routes from provider B with DCU class 2
- Perform accounting on PE



BGP Policy Accounting

BGP Policy Accounting

- Accounting traffic according to the route it traverses
- Account for IP traffic by assigning counters based on:
  - BGP community-list
  - AS number
  - AS-path
  - destination IP address
- 64 buckets
- Similar to Juniper DCU

MPLS Based Methods

MPLS Based Methods

Two methods to determine traffic matrices:

- Using RSVP-TE tunnels
- Using LDP statistics

Some comments on DT's practical implementation

Traffic Matrices in partial topologies

T-Systems

RSVP-TE in MPLS Networks

RSVP-TE (RFC 3209) can be used to establish LSPs

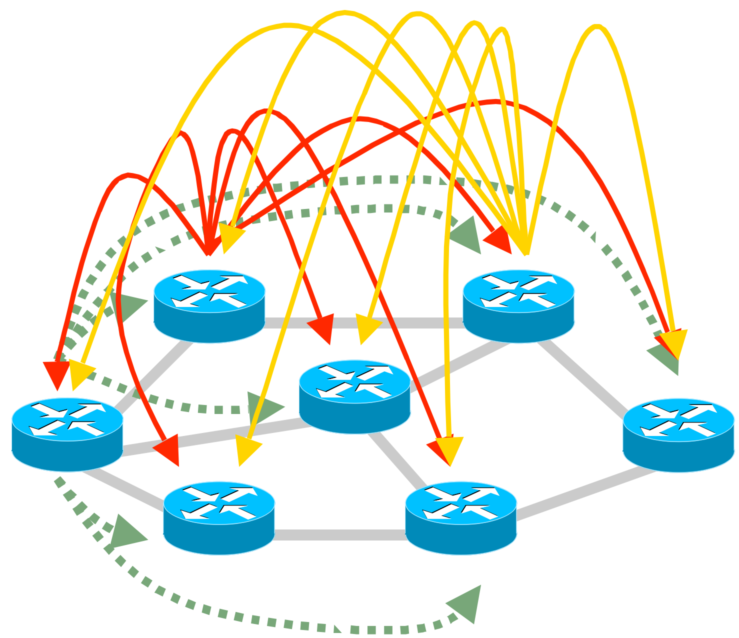
Example (IOS)

```
interface Tunne99
 description RouterA => RouterB
 tag-switching ip
 tunnel destination 3.3.3.3
 tunnel mode mpls traffic-eng
 tunnel mpls traffic-eng priority 5 5
 tunnel mpls traffic-eng bandwidth  1
 tunnel mpls traffic-eng path-option 3 explicit identifier 17
 tunnel mpls traffic-eng path-option 5 dynamic
!
ip explicit-path identifier 17 enable
 next-address 1.1.1.1
 next-address 2.2.2.2
 next-address 3.3.3.3
!
```

RSVP-TE in MPLS Networks
How to Obtain the Traffic Matrix (TM)?

Explicitly routed Label Switched Paths (TE-LSP) have associated byte counters;

A full mesh of TE-LSPs enables to measure the traffic matrix in MPLS networks directly;



RSVP-TE in MPLS Networks
Pro's and Con's

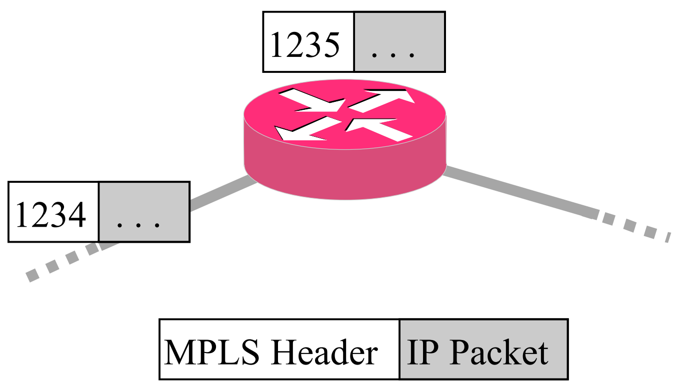
Advantage: Method that comes closest a traffic matrix measurement.

Disadvantages:

- A full mesh of TE-LSPs introduces an additional routing layer with significant operational costs;
- Emulating ECMP load sharing with TE-LSPs is difficult and complex:
  - Define load-sharing LSPs explicitly;
  - End-to-end vs. local load-sharing;
- Only provides Internal Traffic Matrix, no Router/PoP to peer traffic

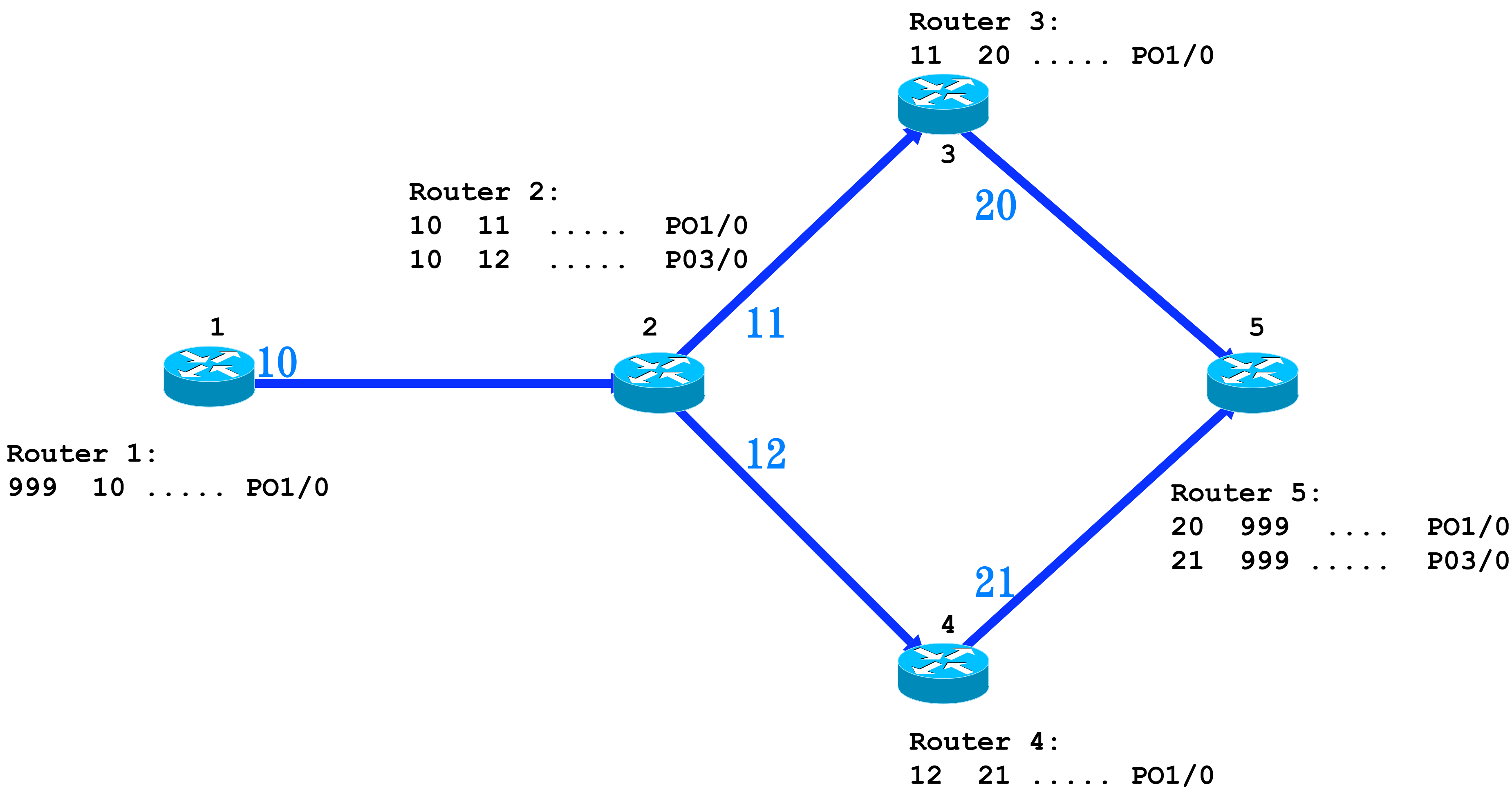
Traffic matrices with LDP statistics

- In a MPLS network, LDP can be used to distribute label information;
- Label-switching can be used without changing the routing scheme (e.g. IGP metrics);
- Many router operating systems provide statistical data about bytes switched in each *forwarding equivalence class* (FEC):



InLabel	OutLabel	Bytes	FEC	OutInt
1234	1235	4124	10.10.10.1/32	PO1/2
…	…	…		…

Traffic matrices with LDP statistics
Use of ECMP load-sharing

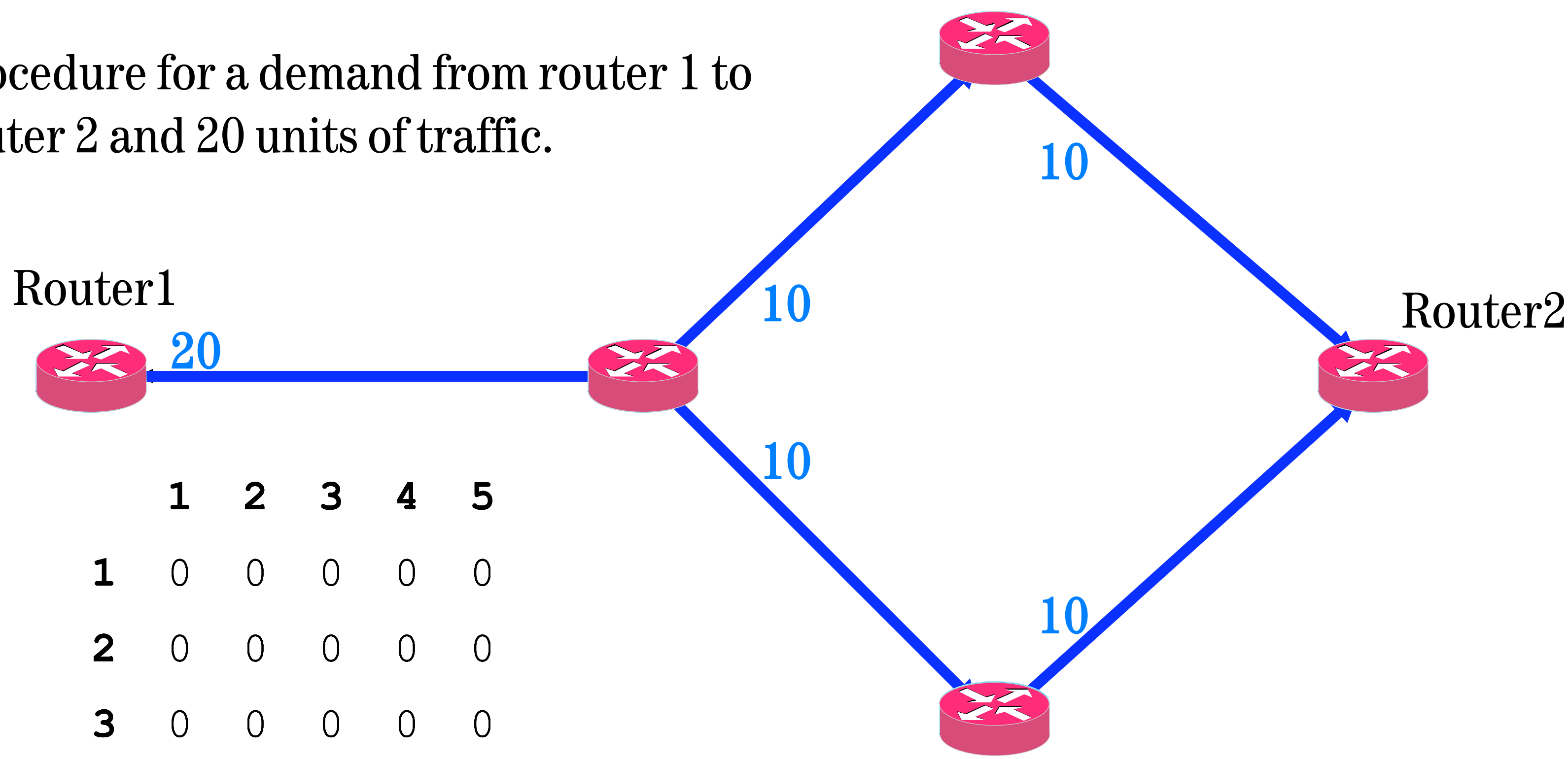


Traffic matrices with LDP statistics

- The given information allows for a forward chaining;
- For each router and FEC a set of residual paths can be calculated (given the topology and LDP information)
- From the LDP statistics we gather the bytes switched on each residual path;
- Problem: It is difficult to decide whether the router under consideration is the beginning or transit for a certain FEC;
- Idea: For the traffic matrix *TM*, add the paths traffic to *TM(A,Z)* and subtract from *TM(B,Z)*. [4]

Traffic matrices with LDP statistics
Example

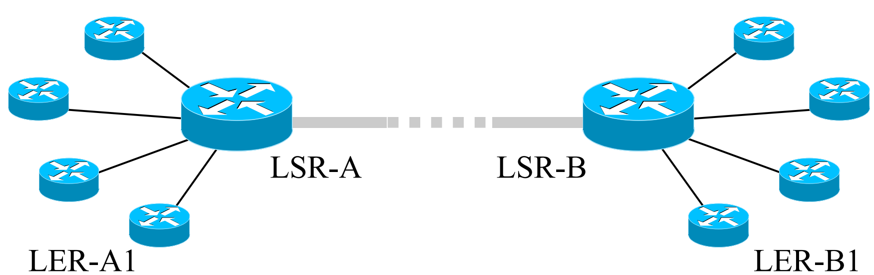
Procedure for a demand from router 1 to router 2 and 20 units of traffic.



	1	2	3	4	5
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	20	-2010010100			0

Practical Implementation
Cisco's IOS

- LDP statistical data available through "show mpls forwarding" command;
- Problem: Statistic contains no ingress traffic (only transit);
- If separate routers exist for LER- and LSR- functionality, a traffic matrix on the LSR level can be calculated
- A scaling process can be established to compensate a moderate number of combined LERs/LSRs.



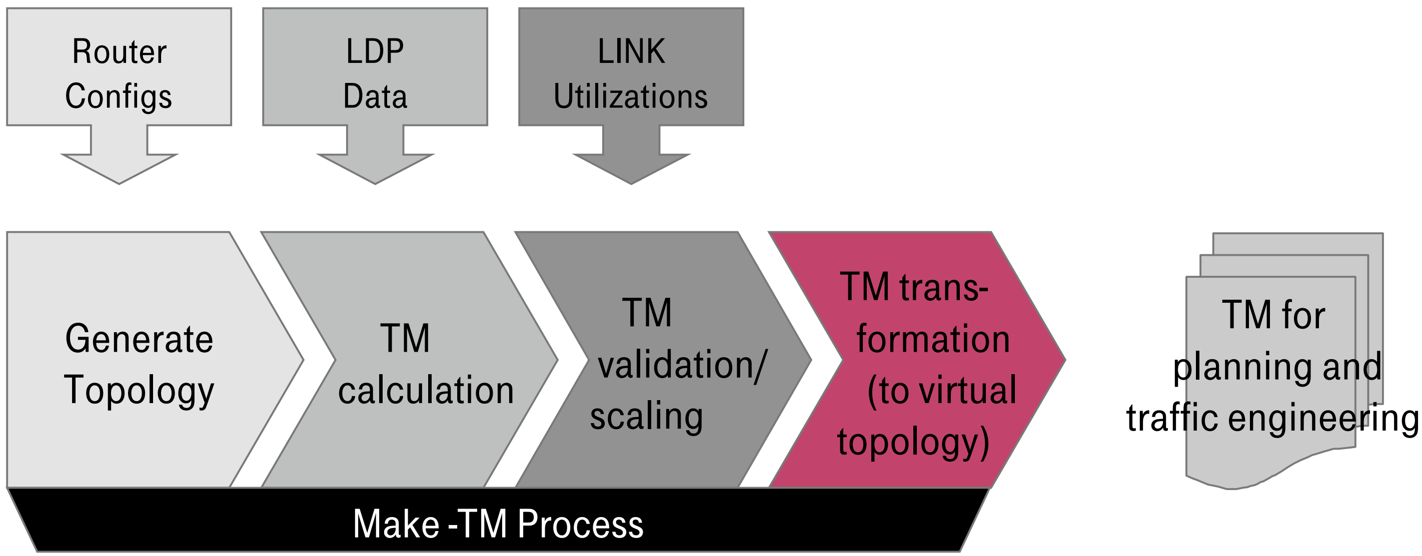
Practical Implementation
Juniper's JunOS

- LDP statistical data available through "show ldp traffic-statistics" command;
- Problem: Statistic is given only per FECs and not per outgoing interface;
- As a result one cannot observe the branching ratios for a FEC that is split due to load-sharing (ECMP);
- Assume that traffic is split equally;
- Especially for backbone networks with highly aggregated traffic this assumption is met quite accurately.

Practical Implementation
Results

- The method has been successfully implemented in Deutsche Telekom’s global MPLS Backbone;
- A continuous calculation of traffic matrices (15min averages) is accomplished in real-time for a network of 180 routers;
- The computation requires only one commodity PC;
- No performance degradation through LDP queries;
- Calculated traffic matrices are used in traffic engineering and network planning.

Practical Implementation
Deployment Process



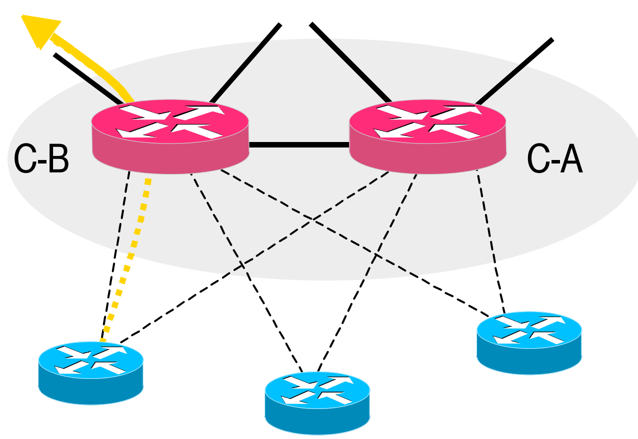
Conclusions for LDP method

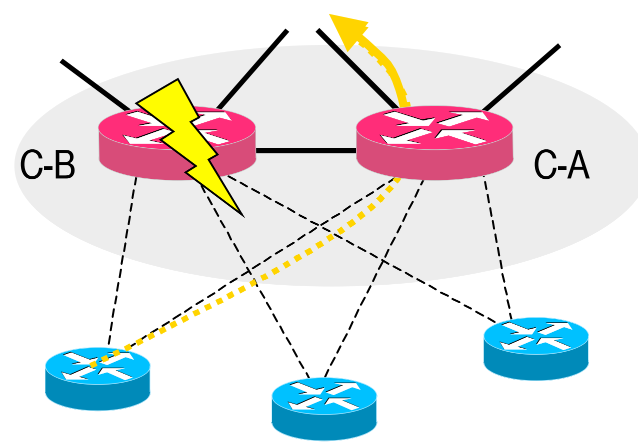
- Our method can be implemented in a multi-vendor network;
- It does not require the definition of explicitly routed LSPs;
- It allows for a continuous calculation;
- There are some restrictions concerning
  - vendor equipment;
  - network topology.
- See Ref. [4]

Traffic Matrices in Partial Topologies

Traffic Matrices in Partial Topologies

- In larger networks, it is often important to have a TM for a partial topology (not based on every router)
- Example: TM for core network (planning and TE)
- Problem: TM changes in failure simulations
- Demand moves to another router since actual demand starts outside the considered topology (red):



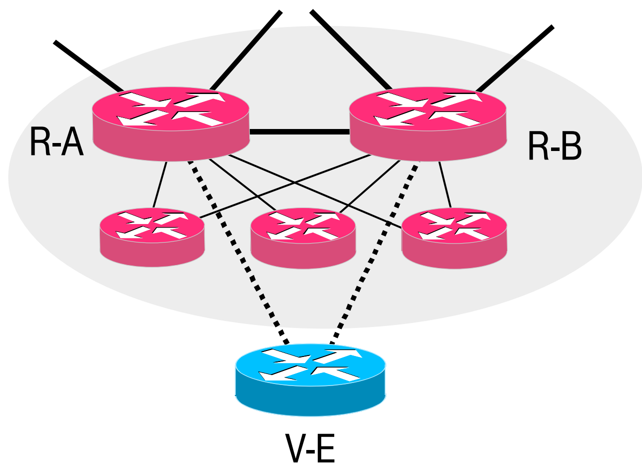


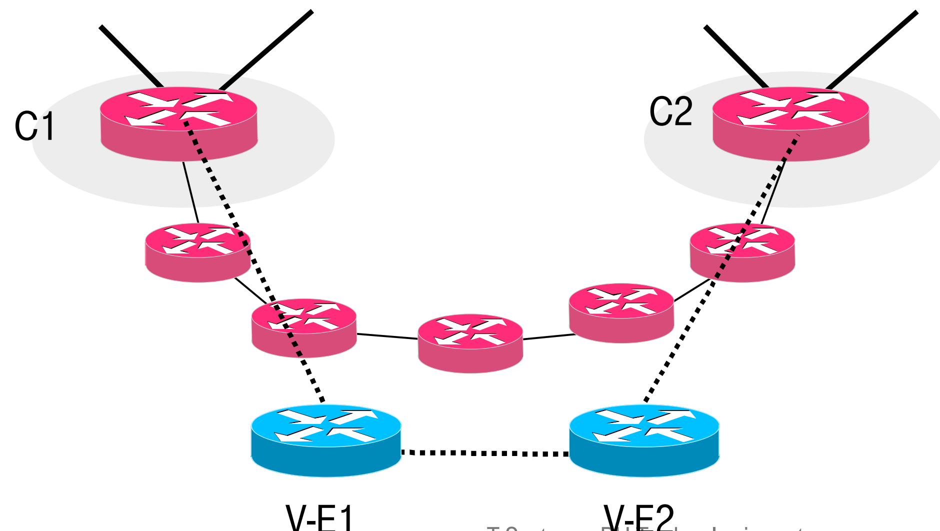
Traffic Matrices in Partial Topologies

- The same problem arises with link failures
- Results in inaccurate failure simulations on the reduced topology
- Metric changes can introduce demand shifts in partial topologies, too.
- But accurate (failure) simulations are essential for planning and traffic engineering tasks

Traffic Matrices in Partial Topologies
Use of Virtual Edge Router in Simulations

- Introduce virtual edge devices as new start-/endpoints for demands
- Map real demands to virtual edge devices;
- Model depends on real topology;
- Tradeoff between simulation accuracy and problem size.





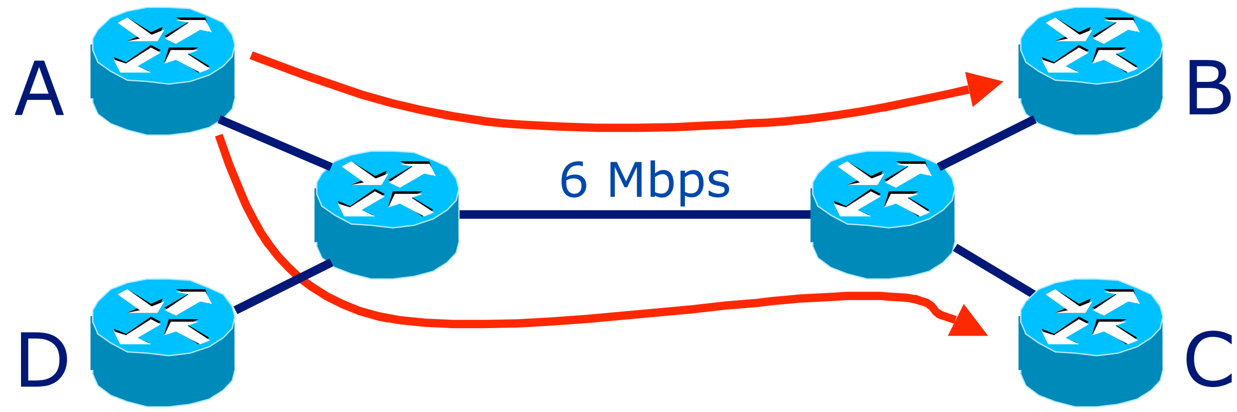
Estimation Techniques

Demand Estimation

- Problem:
  - Estimate point-to-point demands from measured link loads
- Network Tomography
  - Y. Vardi, 1996
  - Similar to: Seismology, MRI scan, etc.

- Underdetermined system:
  - N nodes in the network
  - O(N) links utilizations *(known)*
  - $O(N^2)$ demands *(unknown)*
- Must add additional assumptions (information)

Example

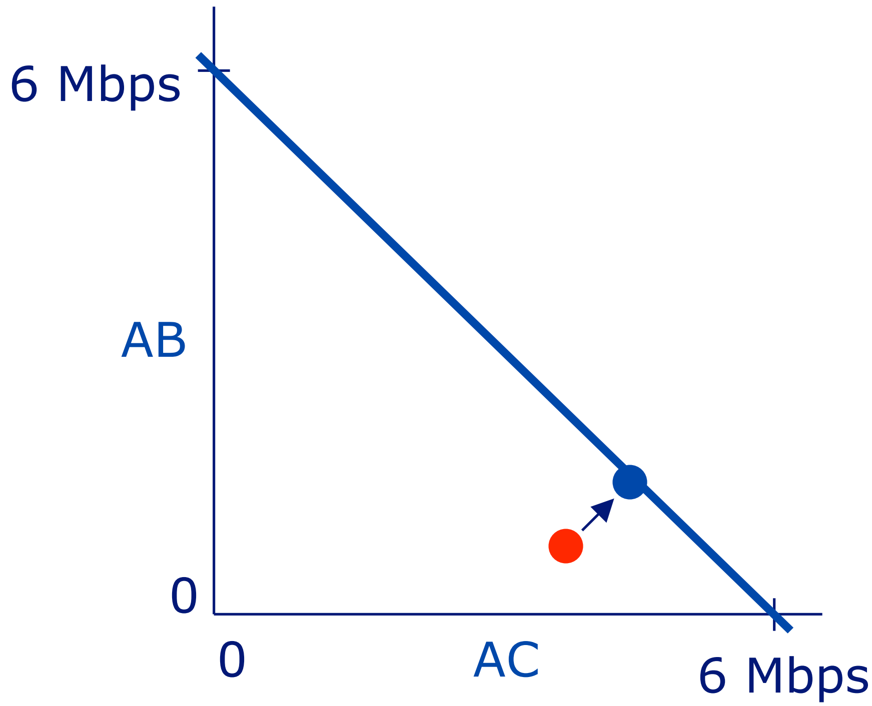


y: link utilizations
A: routing matrix
x: point-to-point demands

Solve: $\underline{y = Ax}$ -> In this example: $\underline{6 = AB + AC}$

Example

Solve: y = Ax -> *In this example: 6 = AB + AC*



Additional information

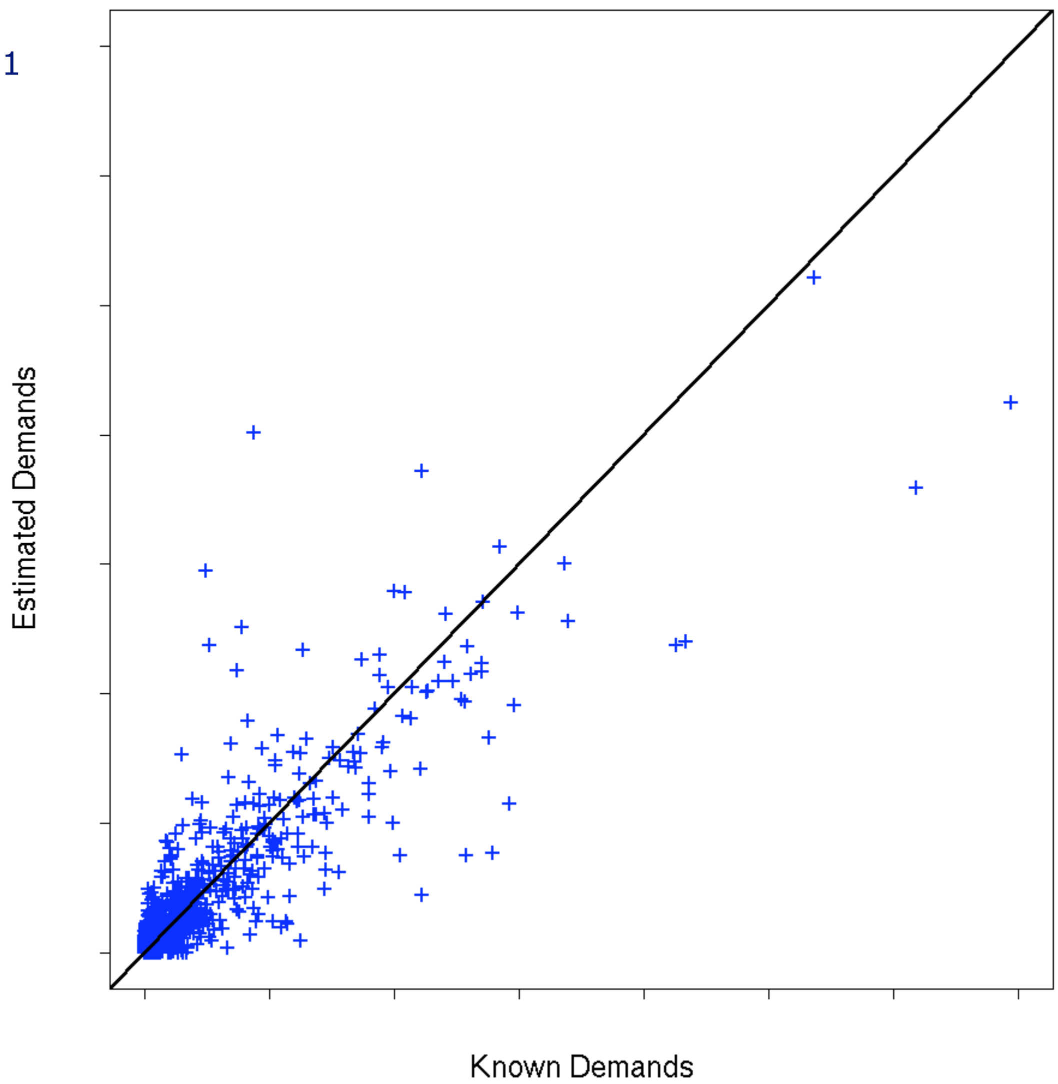
E.g. Gravity Model (every source sends the same percentage as all other sources of it's total traffic to a certain destination)

Example: Total traffic sourced at Site A is *50Mbps.*
Site B sinks *2%* of total network traffic, C sinks *8%.*
AB =1 Mbps and AC =4 Mbps

Final Estimate: AB = 1.5 Mbps and AC = 4.5 Mbps

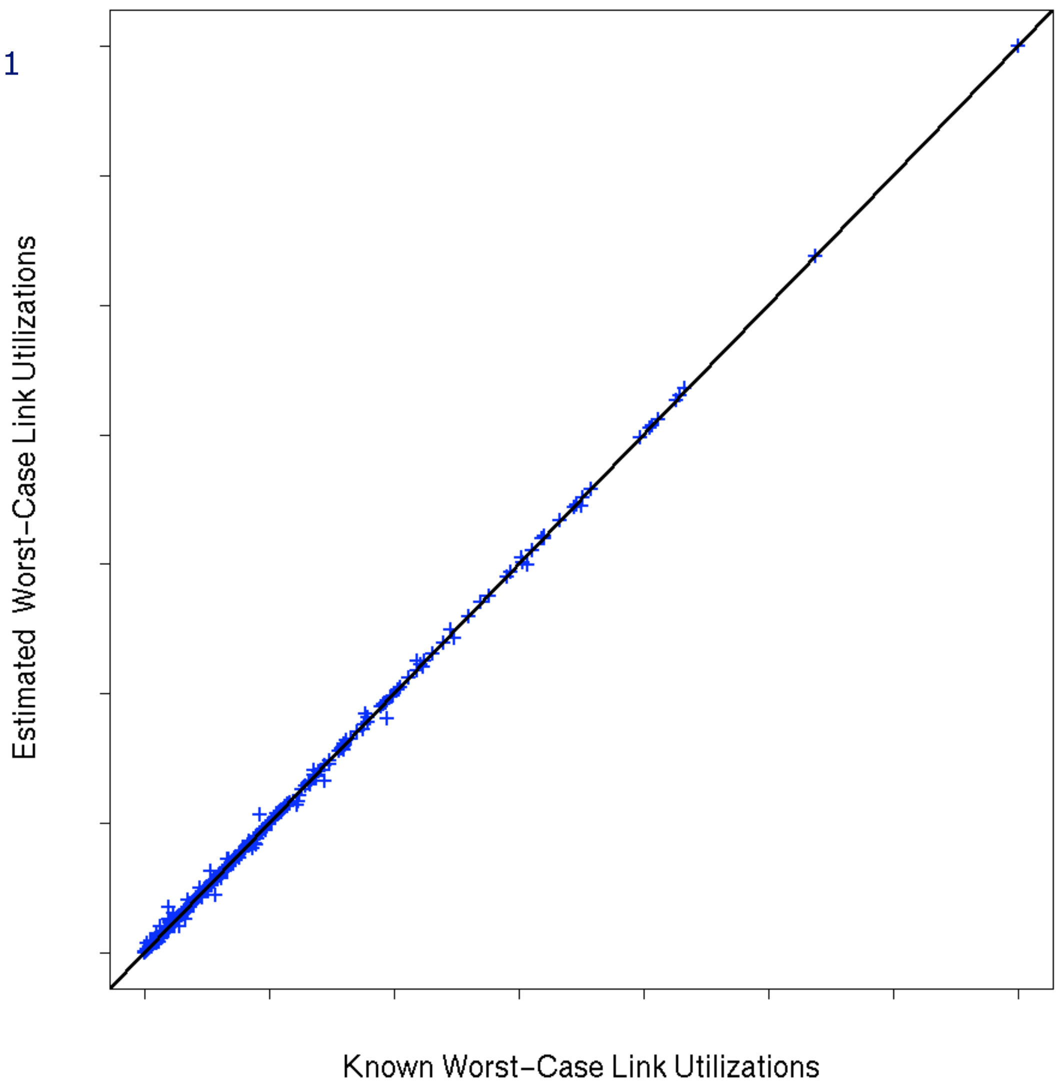
Real Network: Estimated Demands

International Tier-1
IP Backbone



Estimated Link Utilizations!

International Tier-1
IP Backbone



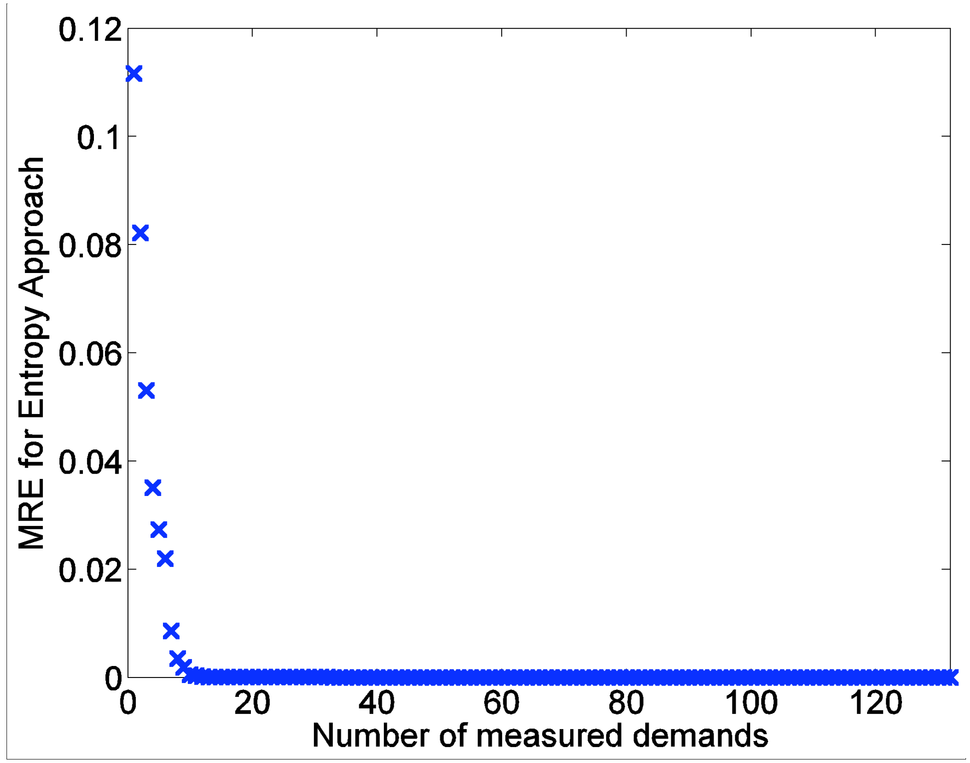
Demand Estimation Results

- Individual demands
  - Inaccurate estimates…
- Estimated worst-case link utilizations
  - Accurate!
- Explanation
  - Multiple demands on the same path indistinguishable, but their sum is known
  - If these demands fail-over to the same alternative path, the resulting link utilizations will be correct

Estimation with Measurements

- Estimation techniques can be used in combination with demand meadsurements
  - E.g. NetFlow or partial MPLS mesh

- This example: Greedy search to find demands which decreases MRE (Mean Relative Error) most.
  - A small number of measured demands account for a large drop in MRE



Data from [1]

Estimation Summary

- Algorithms have been published
  - Commercial tools are available
  - Implement yourself?
- Can be used in multiple scenarios:
  - Fully estimate Traffic Matrix
  - Estimate Peering traffic when Core Traffic Matrix is know
  - Estimate unknown demands in a network with partial MPLS mesh (LDP or RSVP)
  - Combine with NetFlow
    - Measure large demands, estimate small ones
- Also see AT&T work
  - E.g. Nanog29: *How to Compute Accurate Traffic Matrices for Your Network in Seconds* [2]

Traffic Matrix Estimation Case-Study

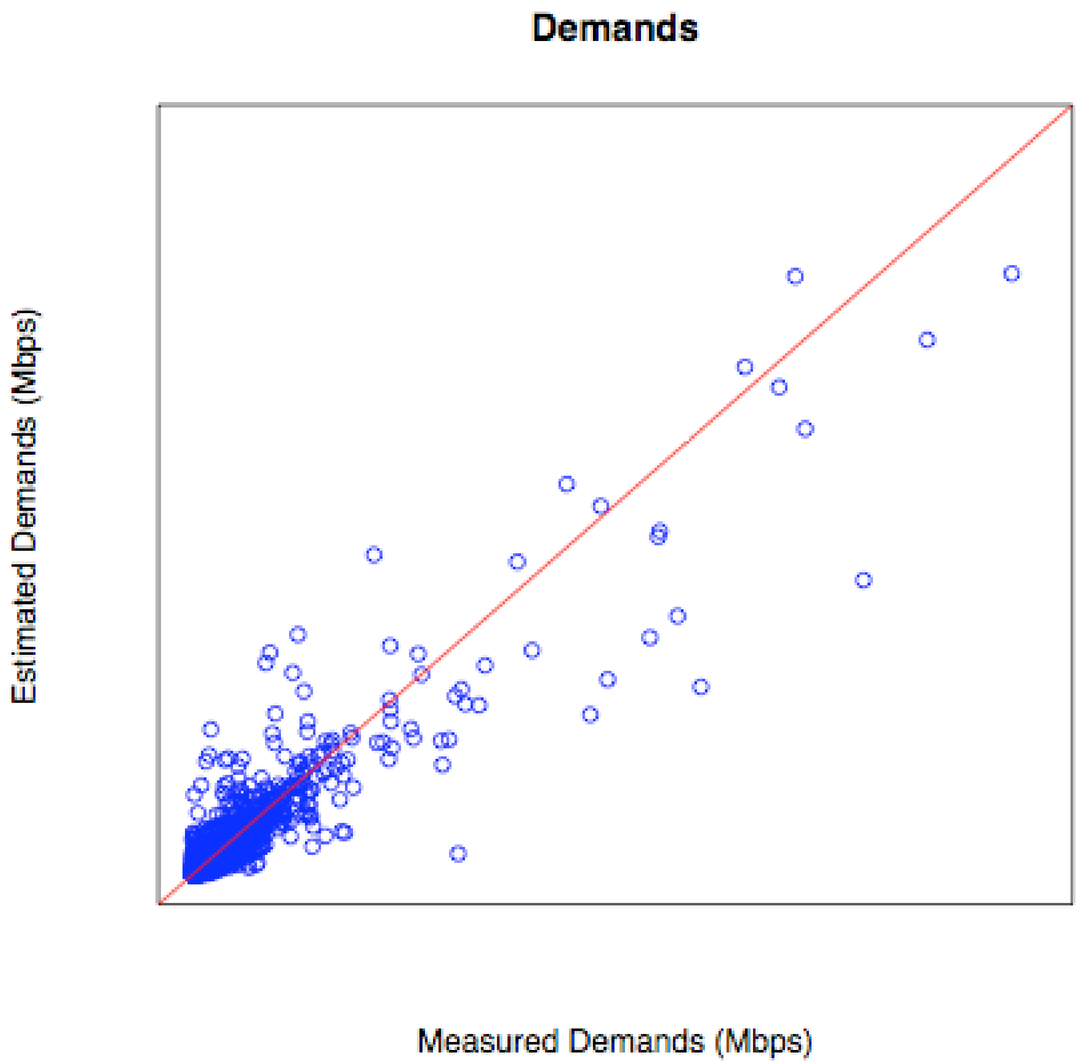
TM Estimation Case-Study

- Large ISP network
  - 77 Routers
  - 166 Circuits
- Known Traffic Matrix
  - Direct MPLS measurement
- Case-study will evaluate:
  - How does estimated TM compare to known TM?
  - How well do tools that require a TM work when given the estimated TM?
- TM estimation using Cariden MATE Software
  - Demand Deduction tool

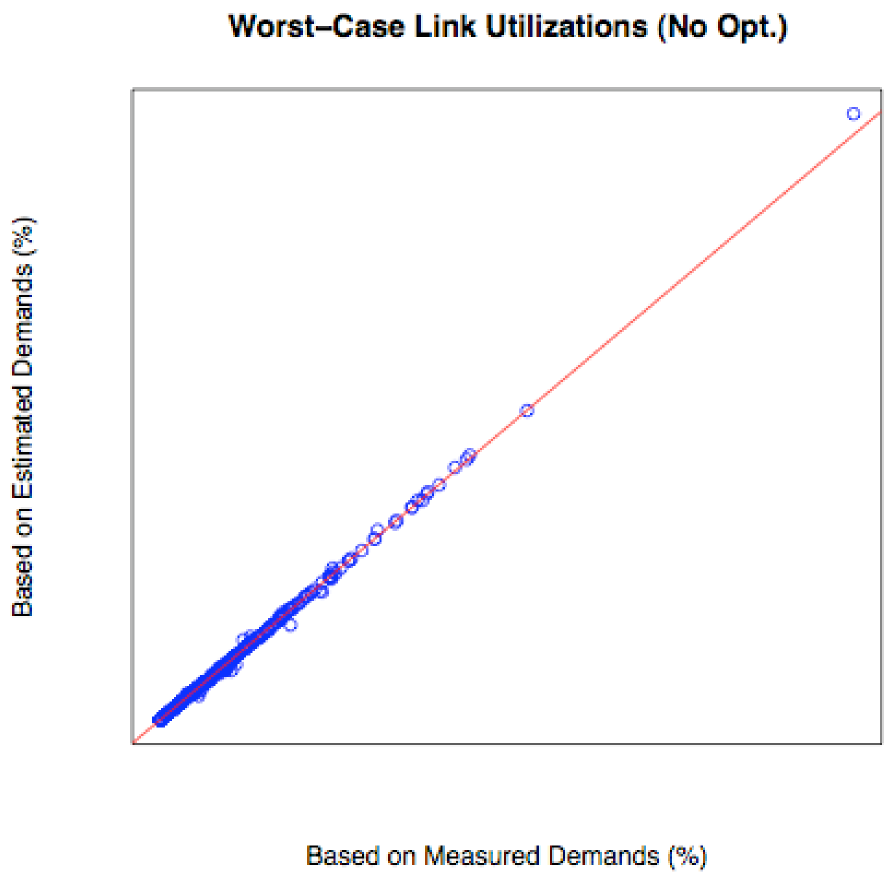
Procedure

- Start with current network and known TM
  - save as "PlanA" (with TM "Known")
- IGP Simulation for non-failure
- Save Link Utilizations and Node In/Out traffic
- Estimate Traffic Matrix
  - New TM: "Estimated"
  - Save as "PlanB"
- Do an IGP *Metric Optimization* on both networks
  - Using known TM in planA
  - Using estimated TM in PlanB
- Simulate IGP routing on both optimized networks
  - using *known* Traffic matrix for both
- Compare Results!

Estimated Demands

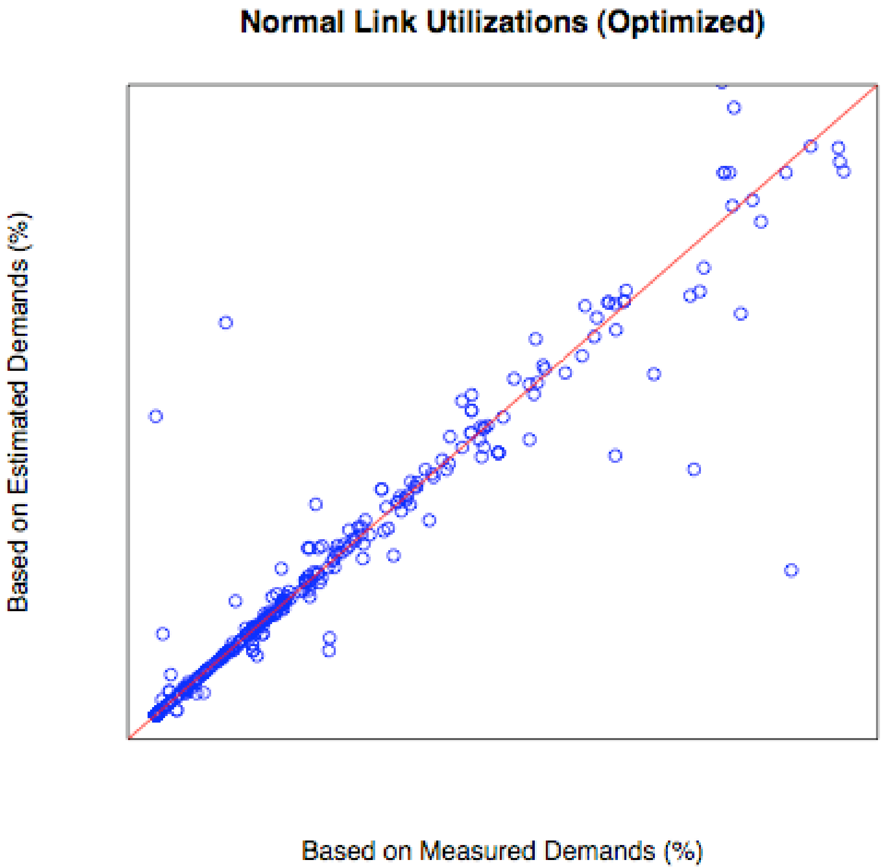


Worst-Case Link Util. (No. Opt)



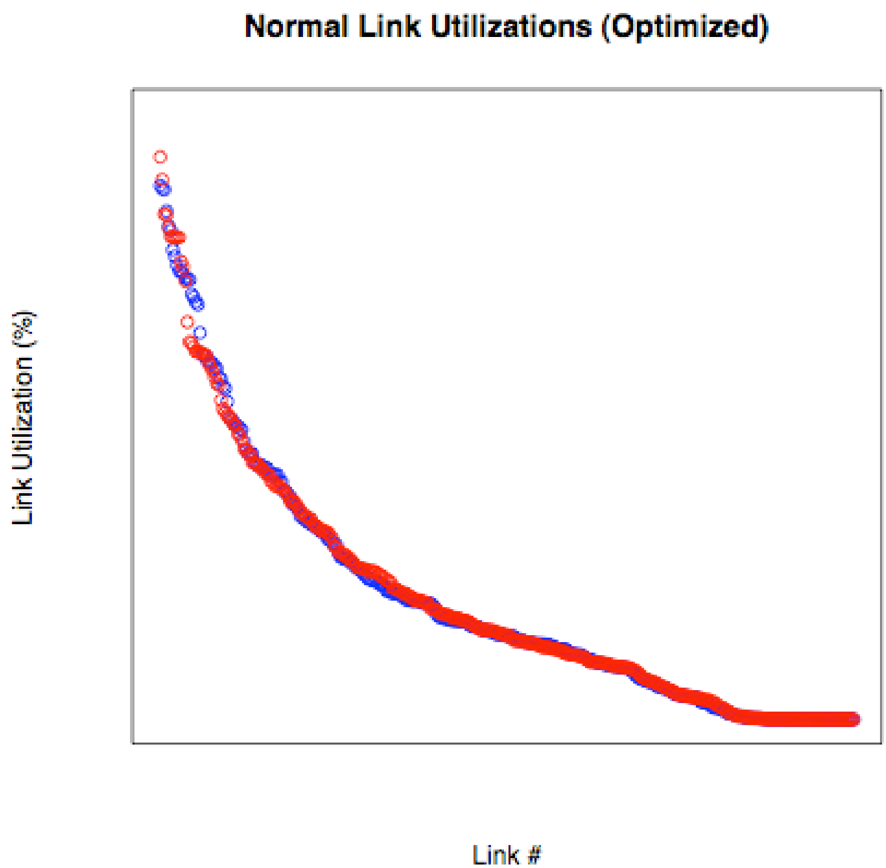
- No Metric Optimization
- PlanA Traffic Matrix:
  - Known
- PlanB Traffic Matrix:
  - Estimated
- IGP Simulation
  - Circuit + SRLG failures
- Compare Worst-Case Link Utilizations (in %)

Normal Link Utilizations (Opt.)



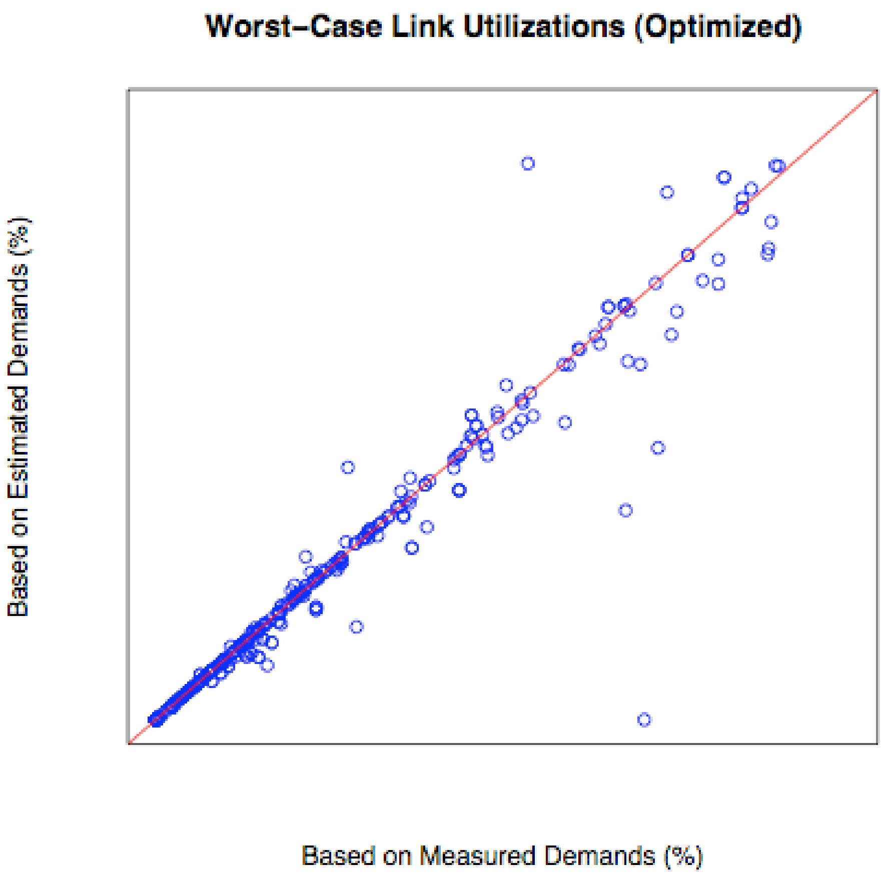
- IGP Metric Optimization
  - PlanA Traffic Matrix:
    - Known
  - PlanB bandwidth level:
    - Estimated
- IGP Simulation
  - PlanA Traffic Matrix:
    - Known
  - PlanB bandwidth level:
    - Original
- Compare Base Link Utilizations (in %)
  - non-failure

Normal Link Utilizations (Opt.)



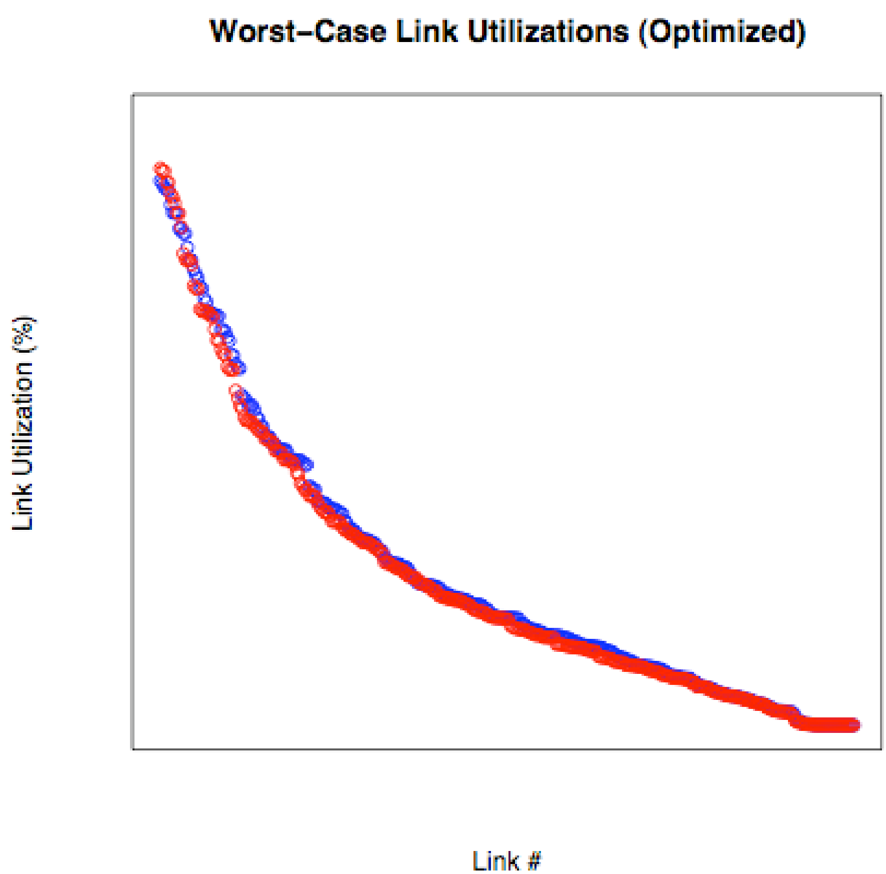
- Scenario: same as previous slide
- Compare *Sorted* Link Utilizations
  - non-failure
- Colors:
  - based on measured demands: BLUE
  - based on estimated demands: RED

Worst-Case Link Utilizations (Opt)



- Scenario: same
- Compare Worst-Case Link Utilizations (in %)
  - Circuits + SRLG failures

Worst-Case Link Utilizations (Opt)



- Scenario: same
- Compare *Sorted* Worst-Case Link Utilizations (in %)
  - Circuits + SRLG failures
- Colors:
  - based on measured demands: BLUE
  - based on estimated demands: RED

TM Estimation Case-Study

- Works very well on this ISP topology/traffic!
  - Also on AT&T, and all other networks we tried
- Even more accurate if used in combination with demand measurements
  - E.g. from NetFlow, DCU or MPLS

Summary & Conclusions

Overview

- “Traditional” NetFlow (Version 5)
  - Requires a lot of resources for collection and processing
  - Not trivial to convert to Traffic Matrix
- BGP NextHop Aggregation NetFlow provides almost direct measurement of the Traffic Matrix
  - Verion 9 export format
  - Only supported by Cisco in newer IOS versions
- Juniper DCU is too limited (only 16 classes) to build a full Traffic Matrix
  - But could be used as adjunct to TM Estimation

Overview

- MPLS networks provide easy access to the Traffic Matrix
  - Directly measure in RSVP TE networks
  - Derive from switching counters in LDP network
- Very convenient if you already have an MPLS network, but no reason to deploy MPLS just for the TM

- Estimation techniques can provide reliable Traffic Matrix data
  - Very useful in combination with partially know Traffic Matrix (e.g. NetFlow, DCU or MPLS)

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5. Y. Vardi. “Network Tomography: Estimating Source-Destination Traffic Intensities from Link Data.” J.of the American Statistical Association, pages 365–377, 1996.