ECHO: Recreating Network Traffic Maps for Datacenters with Tens of Thousands of Servers

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Motivation

Network Performance and Efficiency → critical for DC operation

- Scalable Topologies
  - Dragonfly, Fat tree, Clos, etc.
  - Hotspot detection & elimination
- Flow Control
  - Load balancing
  - Speculative flow control
  - Hedera, etc.
- Network Switches Design
  - Low latency RPCs
  - RAMCloud, etc.
- Software-defined DC networks
  - OpenFlow
  - Nicira, etc.

Challenge

Where to find representative traffic patterns??

Executive Summary

- Network Workload Model: A scheme that accurately and concisely captures the traffic of a DC workload
  - User patterns only emerge in large-scale → scalability
  - Different level of detail per application → modularity/configurability

- Prior work on network modeling → mostly single-node, temporal behavior
  - No spatial patterns, scalability and modularity

- ECHO addresses limitations of previous schemes:
  - System-wide network modeling: Not confined to a single-node
  - Locality-aware: Accounts for spatial network traffic patterns
  - Hierarchical: Adjusts the level of granularity to the needs of each app/study
  - Scalable: Scales to DCs with ~30,000 servers
  - Lightweight: Low and upper-bound modeling overheads
  - Validated: ECHO is validated against real traces from applications in production DCs

Outline

- Simple Temporal Model
- DC Network Traffic Characterization
- ECHO Design
- Model Validation

Distribution Fitting Model

- Most well-known modeling approach for network
- Single-node as opposed to system-wide!
- Capture temporal patterns in per-server network traffic
- Identify known distributions (e.g., Gaussian, Poisson, Zipf, etc.) in network activity traces
- Represent server network activity as a superposition of identified distributions

$$BW = \sum_{i=0}^{N} Distributions = \sum_{i=0}^{N_1} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-\mu_i}{\sigma_i})^2} \Big|_{t_{i_{start}}}^{t_{i_{stop}}} + \sum_{i=0}^{N_2} \frac{\lambda^k e^{-\lambda}}{k!} \Big|_{t_{i_{start}}}^{t_{i_{stop}}} + \sum_{i=0}^{N_3} f_{others} \Big|_{t_{i_{start}}}^{t_{i_{stop}}} + \ldots$$

Distribution Fitting Model

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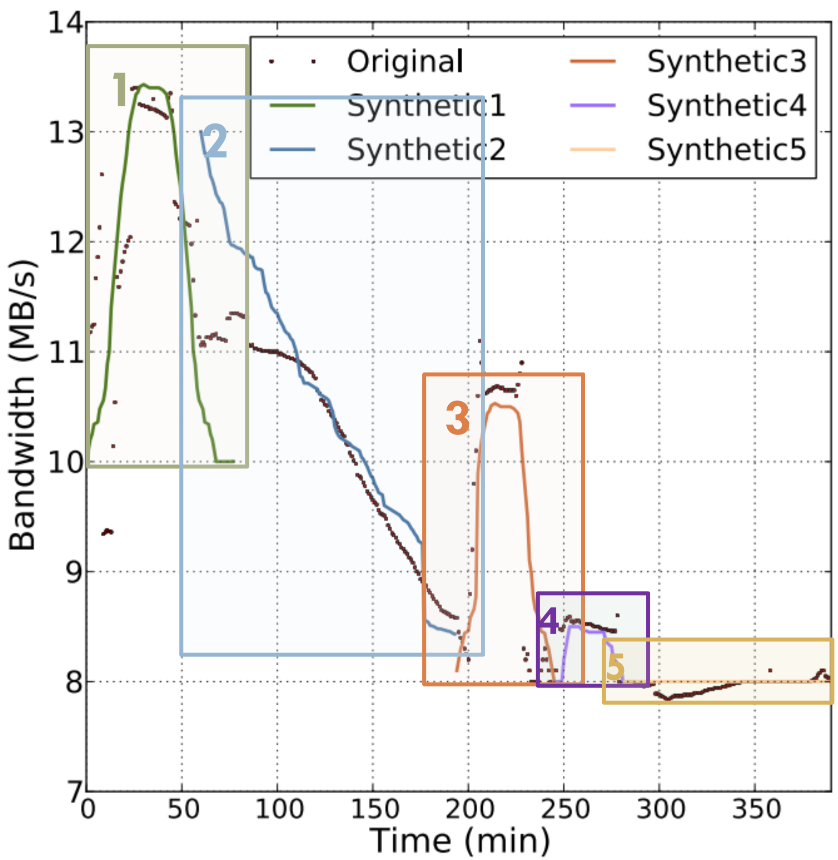
- Represent server network activity as a superposition of identified distributions

- Model = Gaussian +
  Exponential +
  Gaussian +
  Gaussian +
  Constant



Validation: Deviation between original and synthetic is 4.9% on average

Distribution Fitting Model

Positive:

- ✓ Simple, accurate and concise
- ✓ Captures temporal patterns in network activity
- ✓ Facilitates traffic characterization (traffic is expressed as well-studied distributions)

Negative:

- × **Does not track spatial patterns**
- × Bursts in network activity not easily emulated by known distributions → would complicate the model
- × Non-modular design

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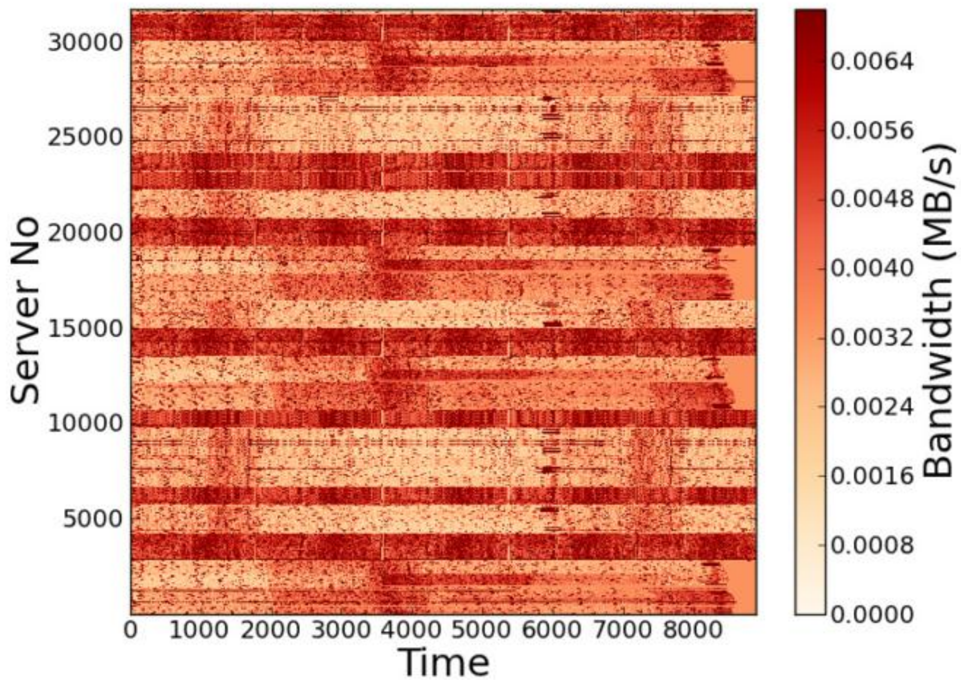
Methodology

- Workloads:
  - Entire Websearch application
  - Combine → Websearch query results aggregator
  - Render → Websearch query results display
- Experimental systems are production DCs with:
  - 30,000 servers running Websearch
  - 360 servers running Combine
  - 1350 servers running Render
- We collect per-server bandwidth traces of data sent and received over a period of 5 months (at 5msec granularity)

Understanding Network-wide Behavior

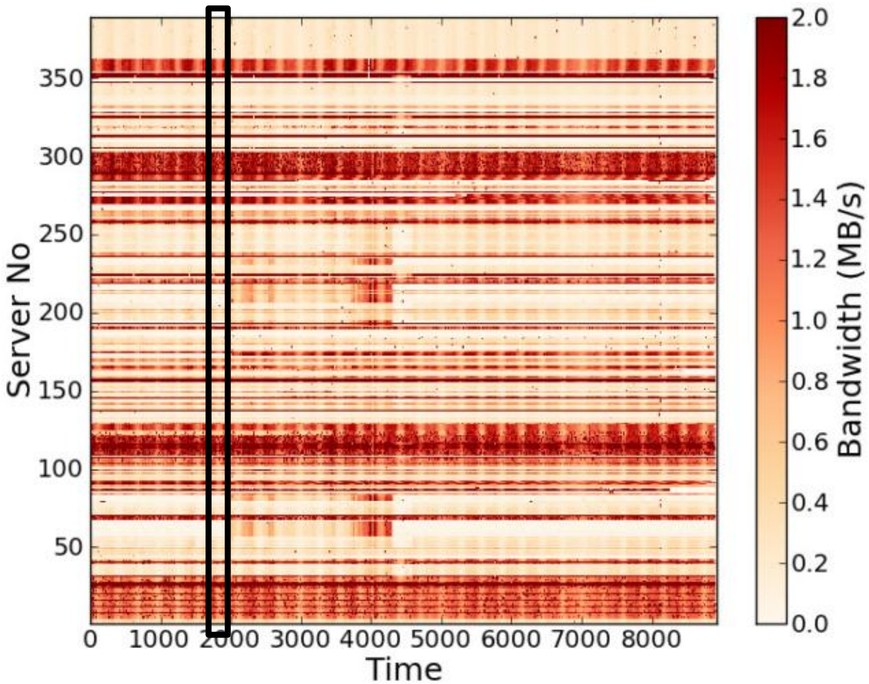
- Temporal variations of network traffic
  - Fluctuation over time
  - Differences between workloads
- Average spatial patterns in network activity
  - Locality in network traffic
  - Impact of application functionality to locality
- Temporal variations in spatial patterns
  - Changes over different time scales
  - Changes for different types of workloads

Temporal Variations in Network Traffic



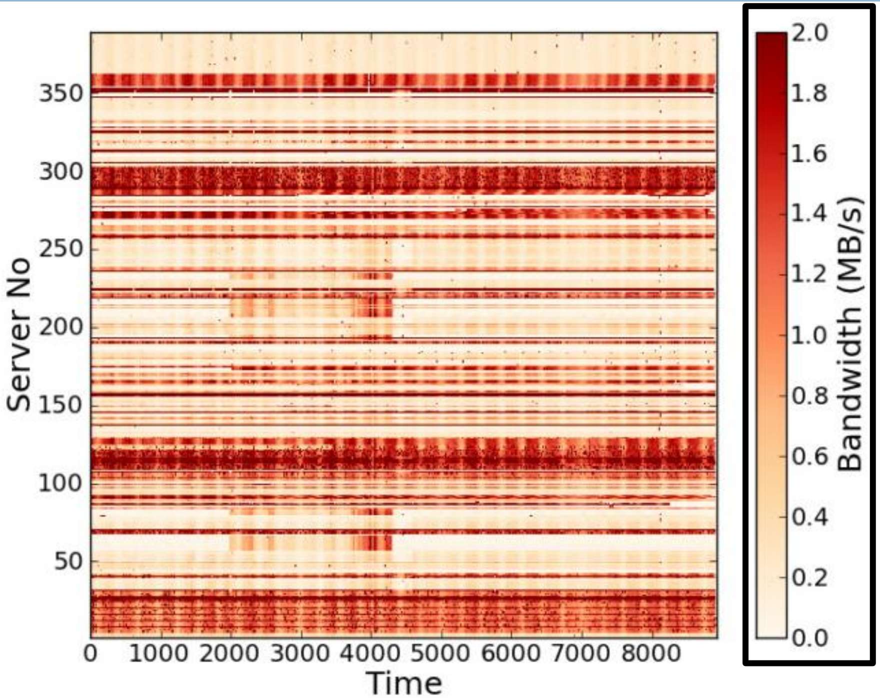
- Most servers are greatly underutilized → significant overprovisioning for latency-critical apps
- Some servers have higher utilization → mostly well load-balanced
- Similarity in network activity patterns over time
- Model should: capture fluctuation, remove information redundancy

Temporal Variations in Network Traffic



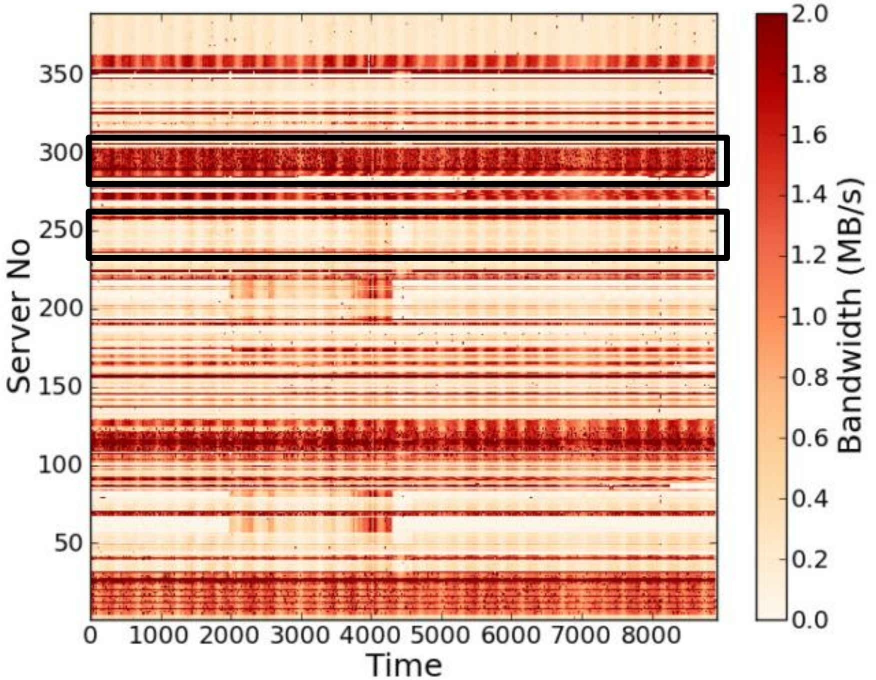
- Clearer diurnal patterns → 31 dark and 31 light vertical bands

Temporal Variations in Network Traffic



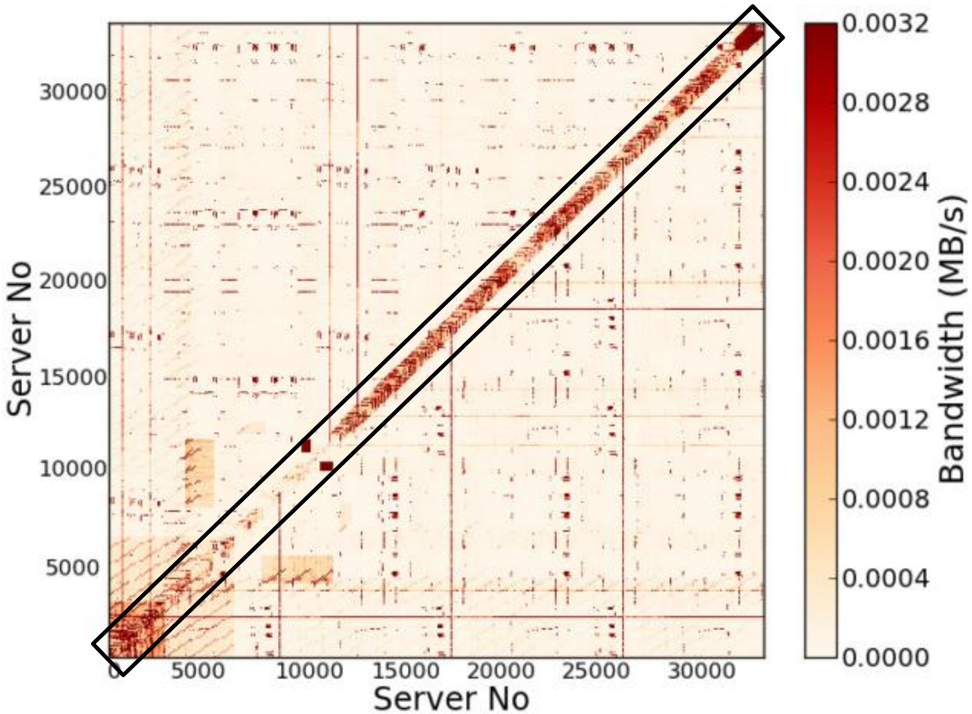
- Clearer diurnal patterns → 31 dark and 31 light vertical bands
- Higher utilization → not as much overprovisioning for servers that aggregate query results

Temporal Variations in Network Traffic



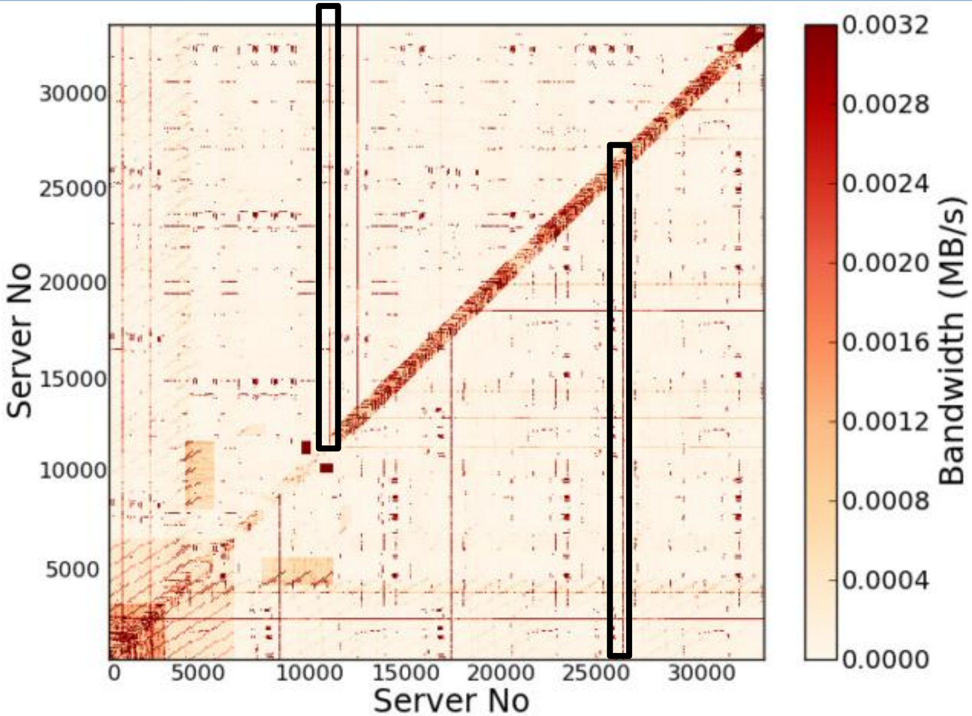
- Clearer diurnal patterns → 31 dark and 31 light vertical bands
- Higher utilization → not as much overprovisioning for servers that aggregate query results
- Not equally load-balanced → impact of queries serviced by each server

Spatial Patterns in Network Activity



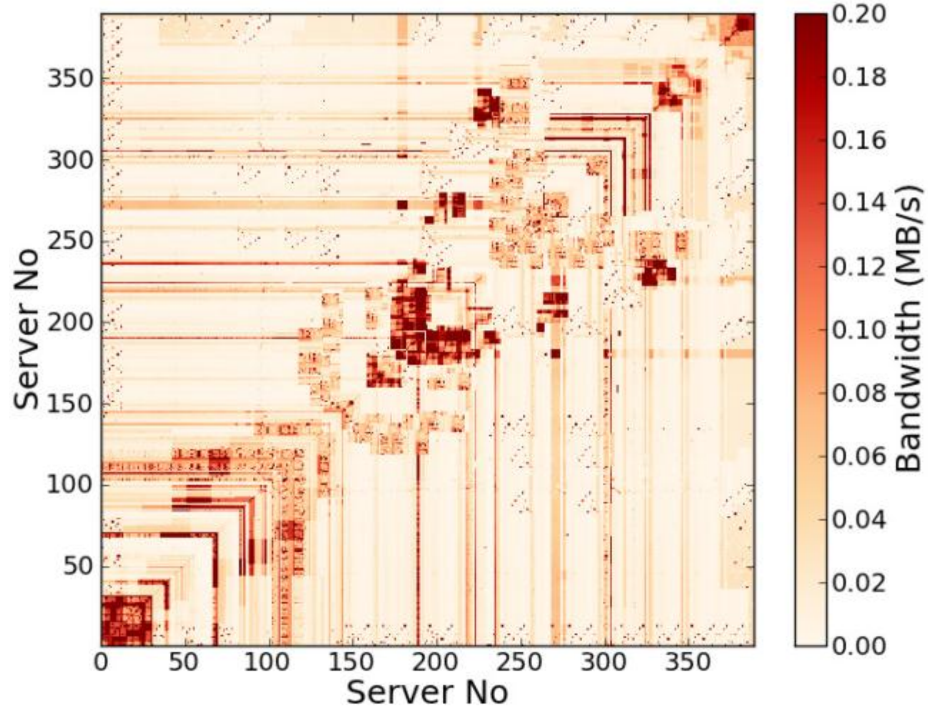
- High spatial locality → Most accesses are confined within the same rack
- The model should preserve the spatial locality (within racks & hotspots)

Spatial Patterns in Network Activity



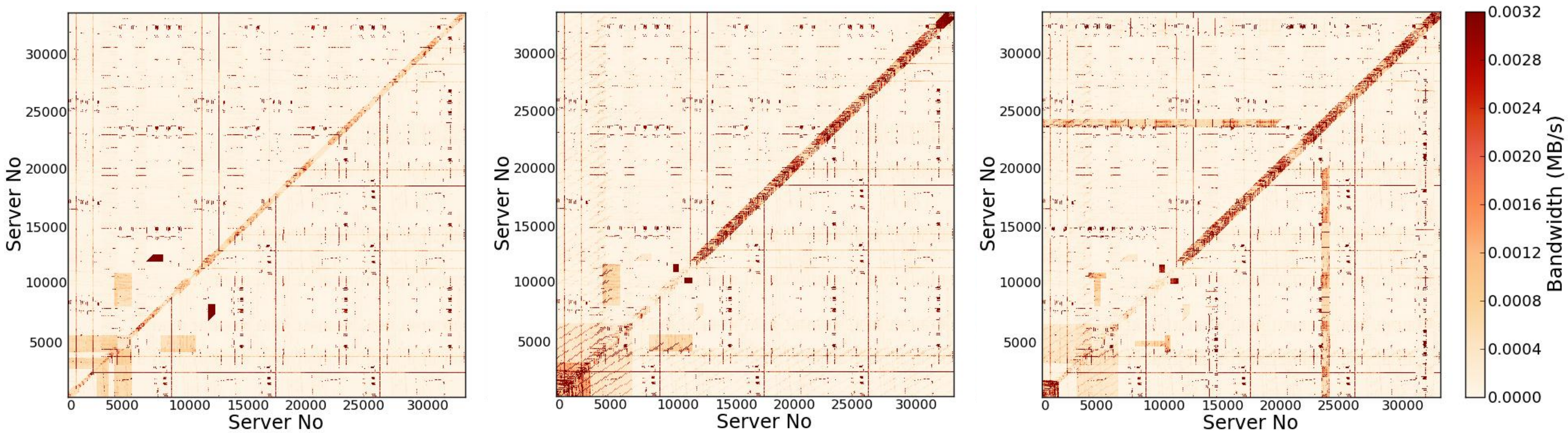
- High spatial locality → Most accesses are confined within the same rack
- The model should preserve the spatial locality (within racks & hotspots)
- A few servers communicate with most of the machines → cluster scheduler, aggregators, monitoring servers

Spatial Patterns in Network Activity



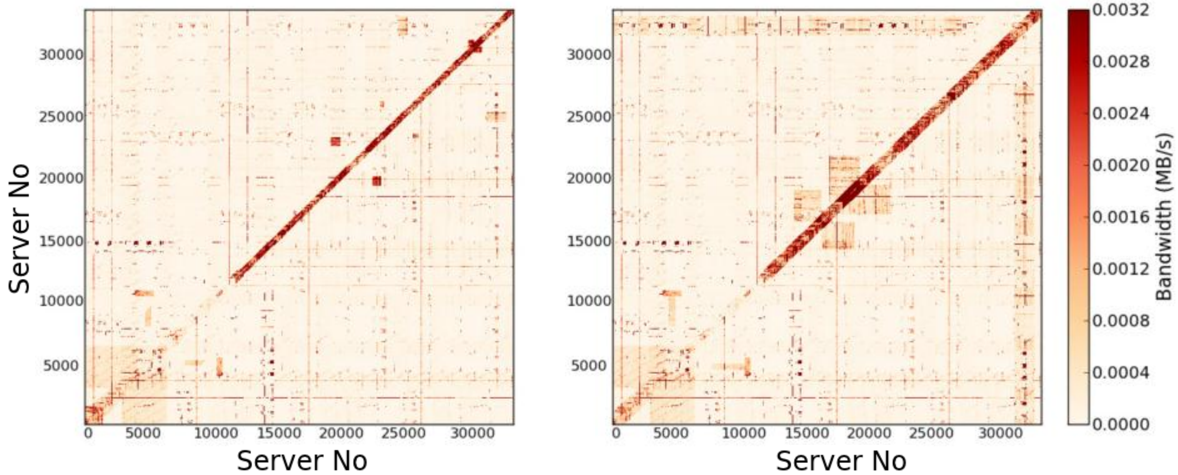
- In contrast, Combine has less spatial locality → most servers talk to many machines
- Consistent with its functionality → query aggregation

Fluctuations in Spatial Patterns



- At first glance spatial locality is very similar across months

Fluctuations in Spatial Patterns



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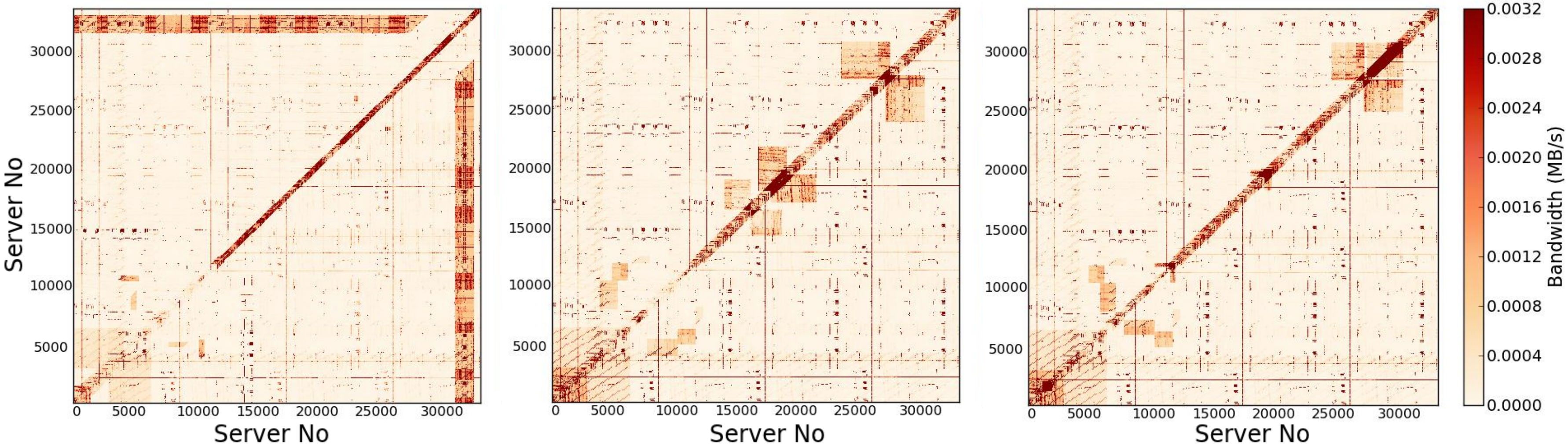
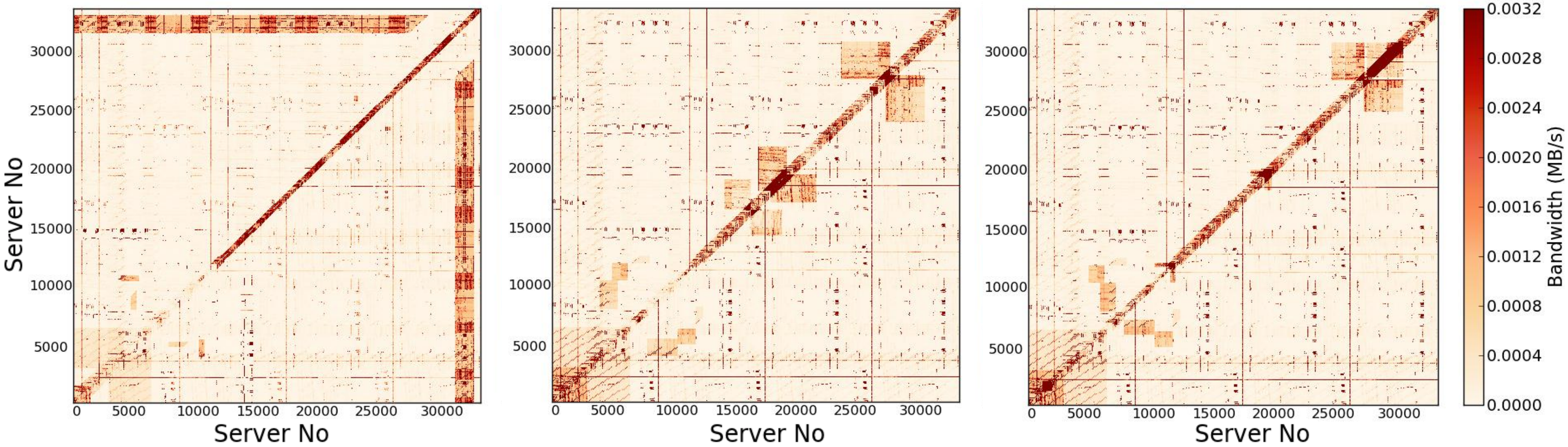
- However, at finer granularity there are differences

Fluctuations in Spatial Patterns



- At first glance spatial locality is very similar across months
- However, at finer granularity there are differences
  - Software updates
  - Changes in traffic due to user load
  - Background processes (e.g., garbage collection, logging, etc.)

Fluctuations in Spatial Patterns



- At first glance spatial locality is very similar across months
- However, at finer granularity there are differences
  - Software updates
  - Changes in traffic due to user load
  - Background processes (e.g., garbage collection, logging, etc.)
- Fine-grain patterns important for studies focused on specific hours of the day

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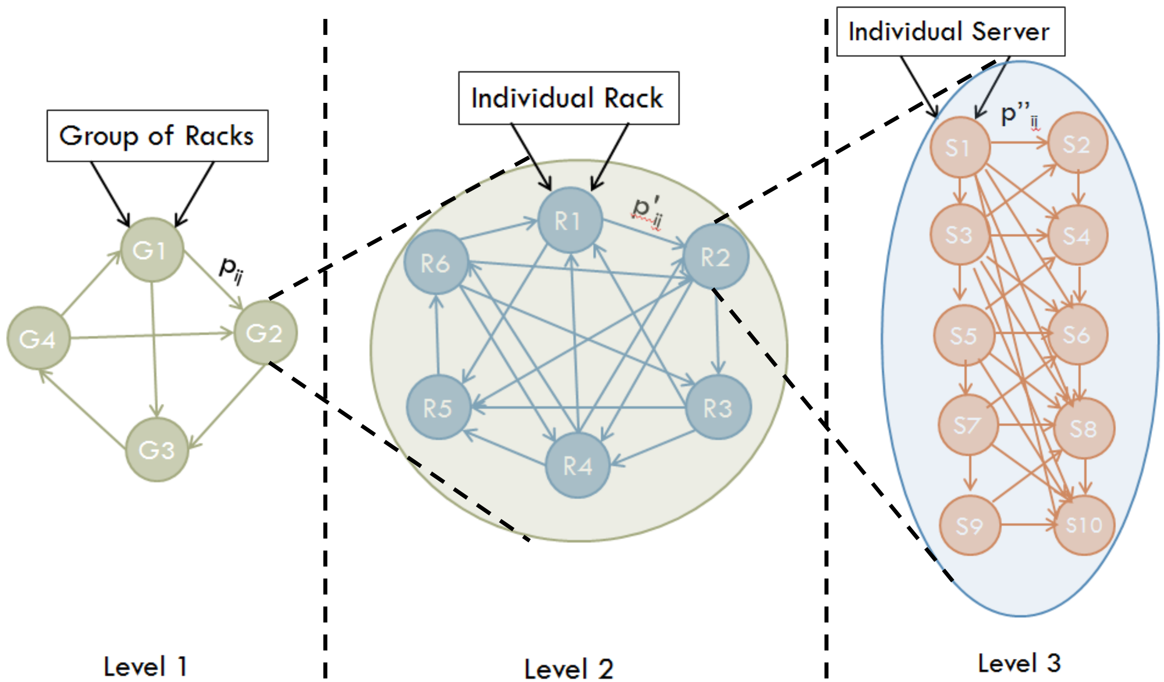
Model Requirements

Don't just model a node. Model the whole DC!

Requirements:

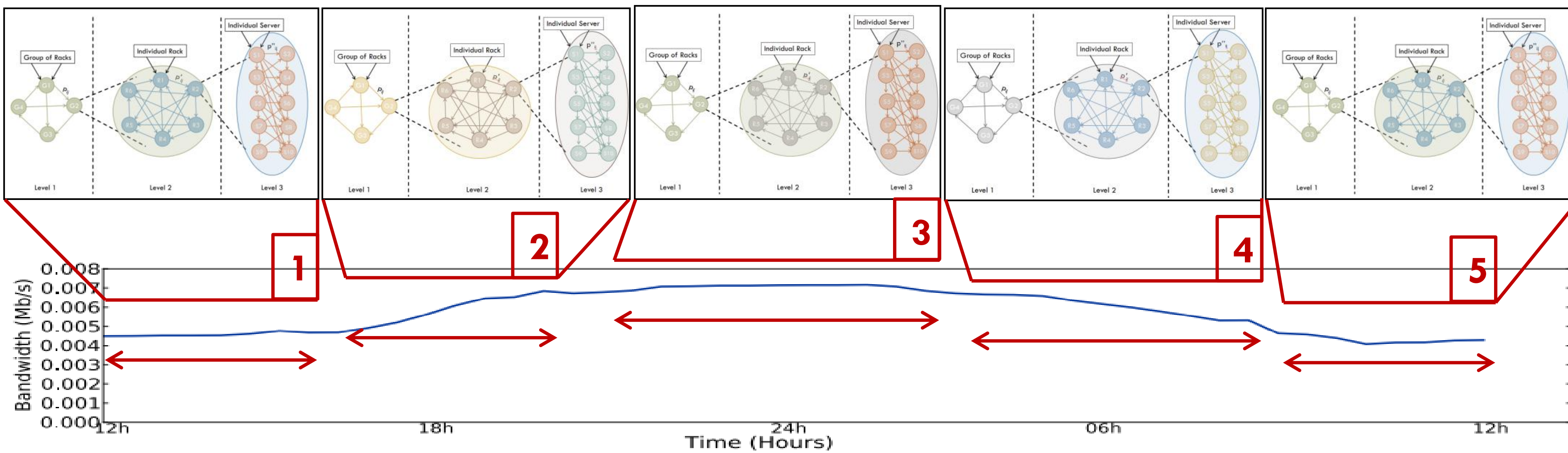
1. Average activity over time and space
2. Per-server activity fluctuation over time
3. Spatial patterns in network traffic
4. Individual server-to-server communication

Model Design – Spatial Aspects



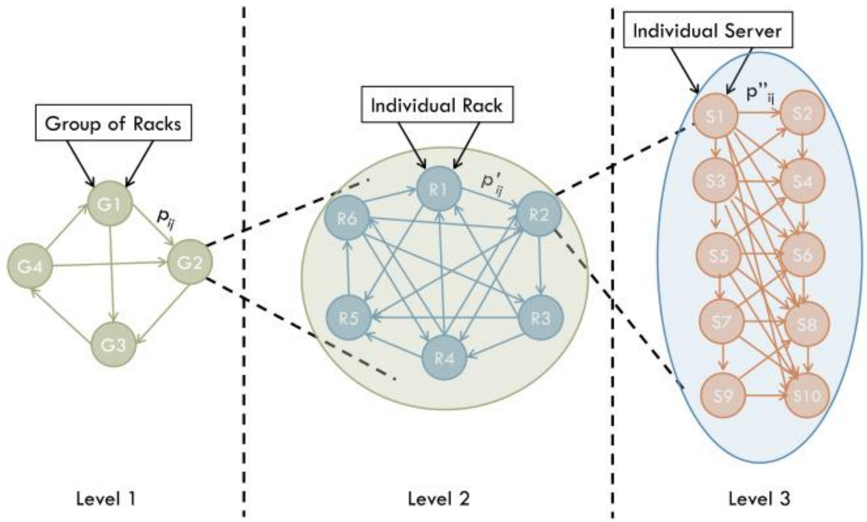
- Hierarchical Markov Chain: groups of racks → racks → individual servers
- Configurable granularity based on app/study requirements
- Captures spatial patterns in network traffic: fine-grain transitions are explored within each coarse state → most locality confined within a rack

Model Design – Temporal Aspects

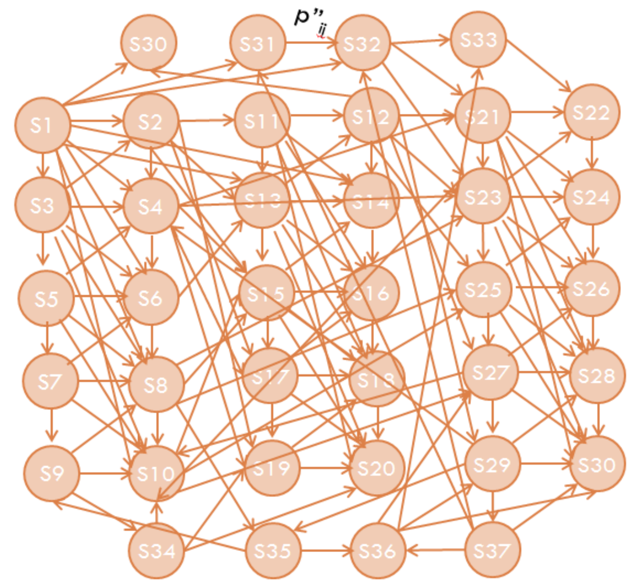


- Captures temporal patterns in network traffic → multiple models used over time
- Number of models is a function of the workload's activity fluctuations
- Switching between models allows compression in replay → fast experimentation

Hierarchical vs. Flat Model

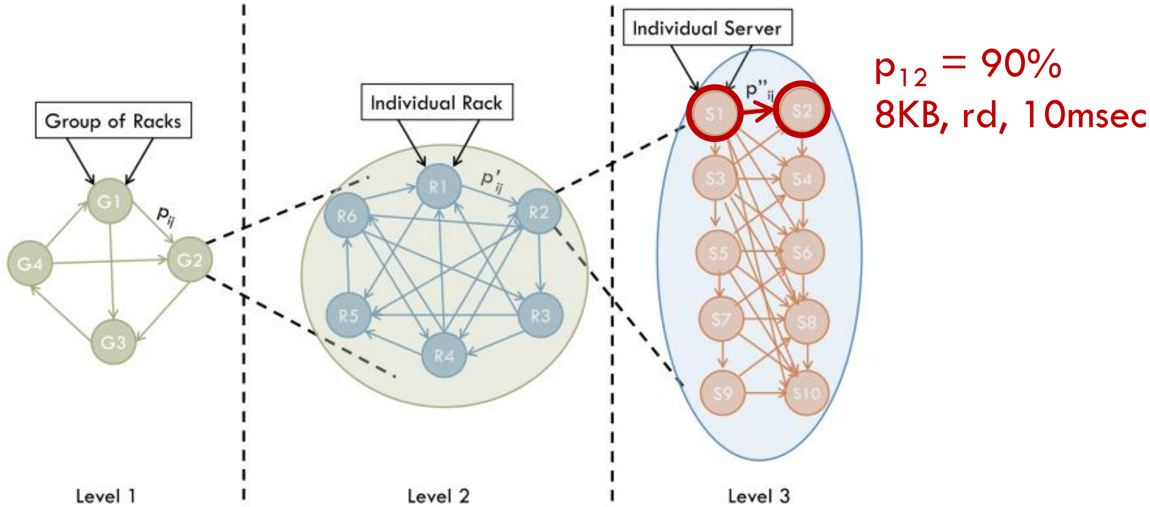


vs



- Hierarchical: explore fine grain transitions within coarse states
- Flat: explore all fine grain states → exponential increase in transition count
- Even for problems with a few hundred servers the model becomes intractable
- No loss in accuracy with the hierarchical model since locality is mostly confined within racks

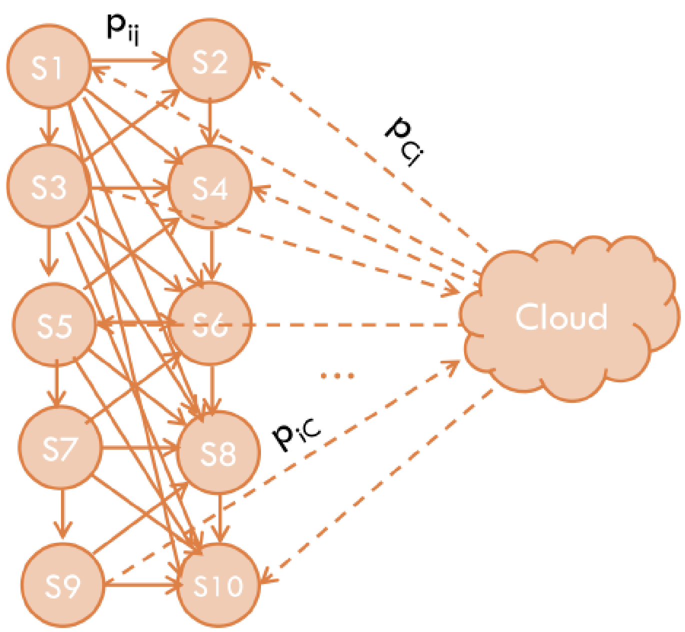
Model Construction



- Collect system-wide network activity traces
- Cluster network requests based on
  - Sender/receiver server IDs
  - Type (rd/wr) and size of request (MB)
  - Inter-arrival time between requests (ms)
- Compute transition probabilities between states (e.g., S1→ S2: 90% 8KB read requests, 10msec inter-arrival time)

Cloud Node: Modeling Server Subsets

- Focus on specific interesting activity patterns → Validating the model in server subsets (a few hundred servers)
- Network activity is not necessarily self-contained in those server subsets
- Cloud Node: Emulate all network activity to and from servers external to the studied server subset
- Maintains accuracy of per-server load while enabling more fine-grain validation



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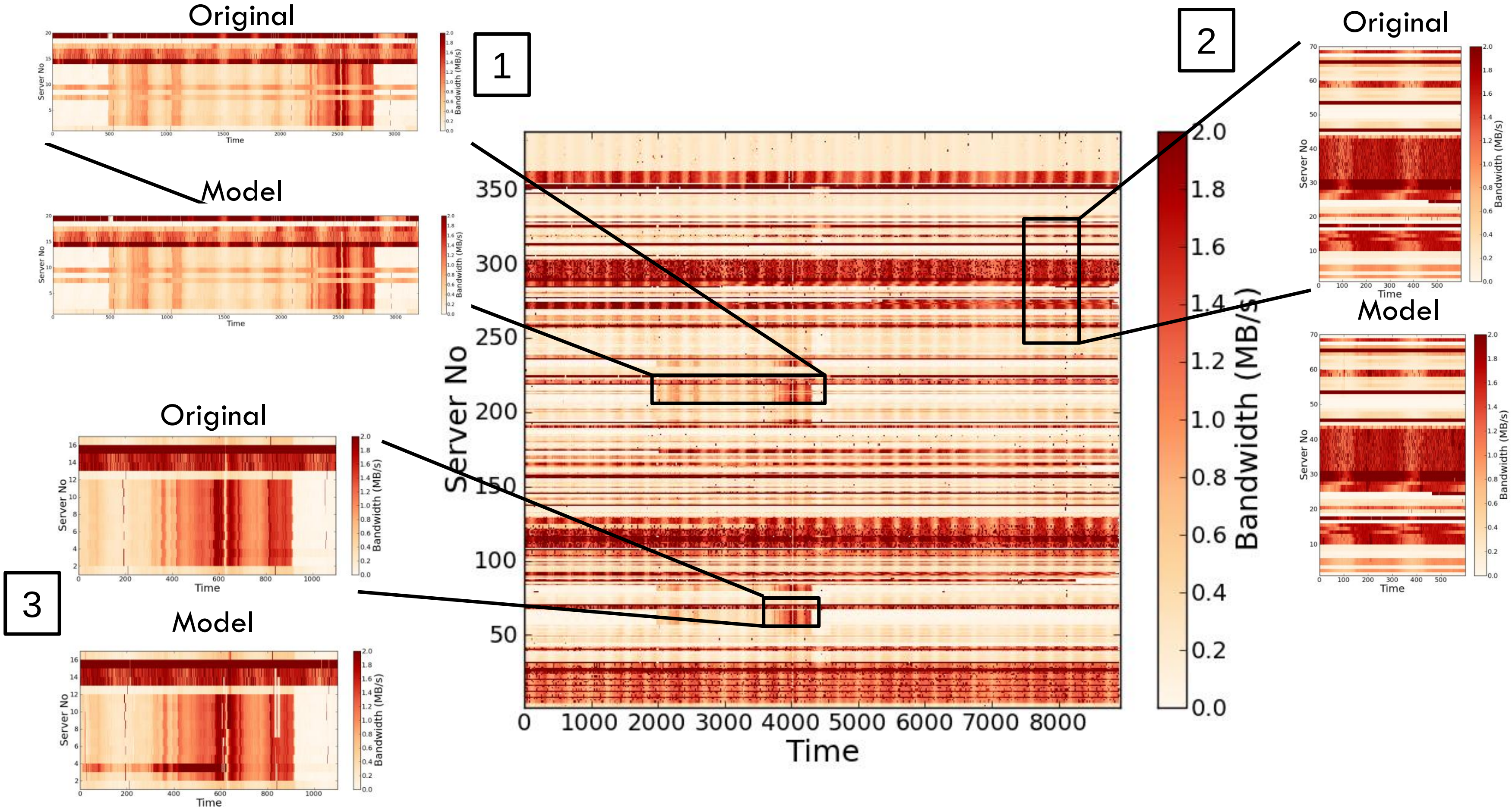
Validation

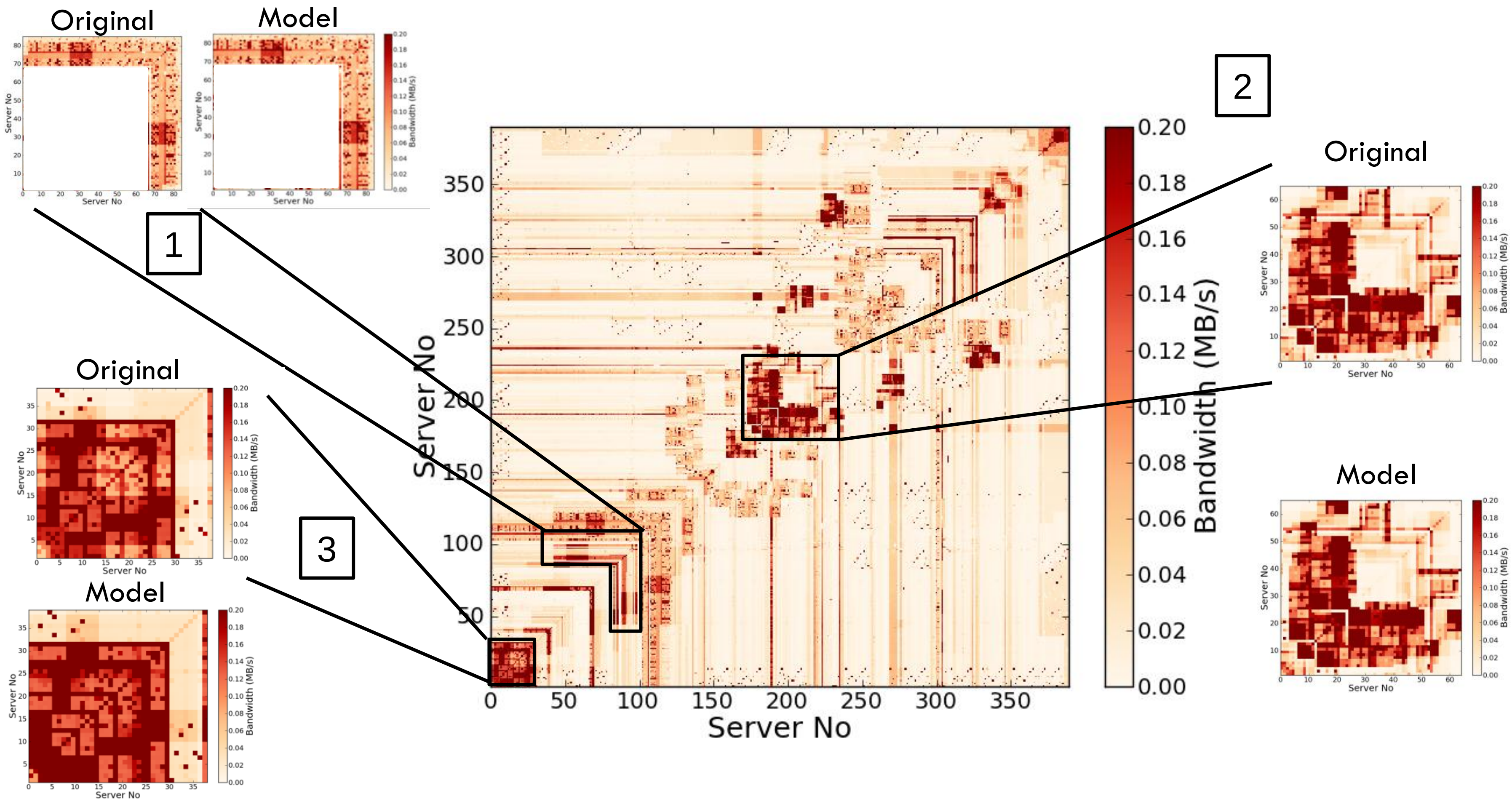
1. Temporal variations of network activity
2. Spatial patterns of network activity
3. Individual server interactions (one-to-one communication patterns)

Validation – Temporal Patterns



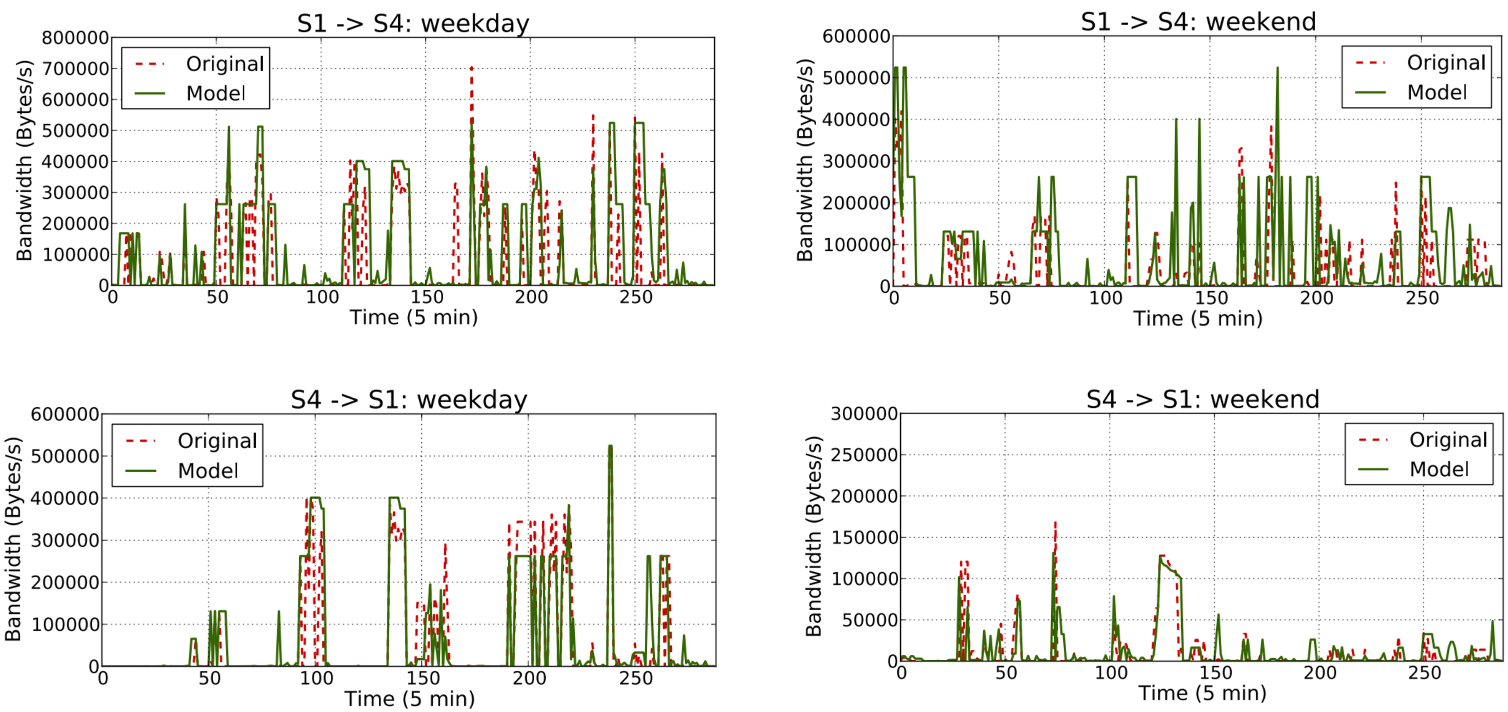
- Less than 8% deviation between original and synthetic workload, on average across server subsets

Validation – Spatial Patterns



- Less than 10% deviation between original and synthetic workload, on average across server subsets

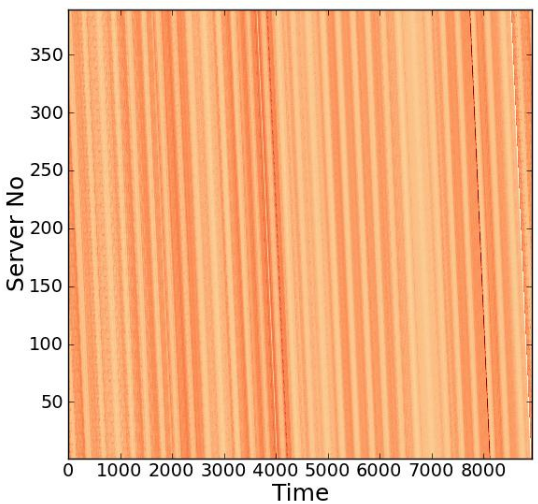
Validation – Indiv. Server Interactions



- 12% deviation between original and synthetic for a weekday
- 9% deviation between original and synthetic for a day of the weekend

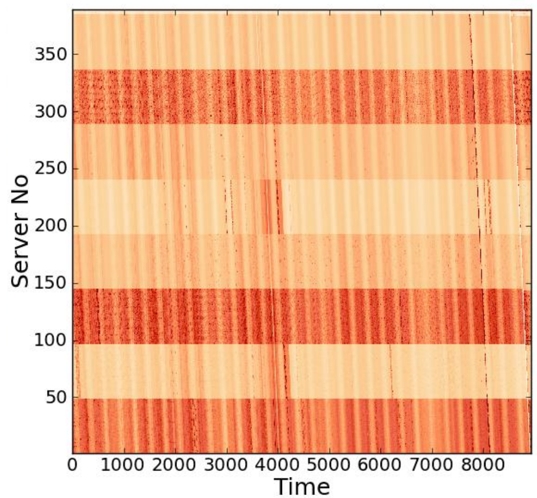
Validation – Benefits of Hierarchy

1 Level



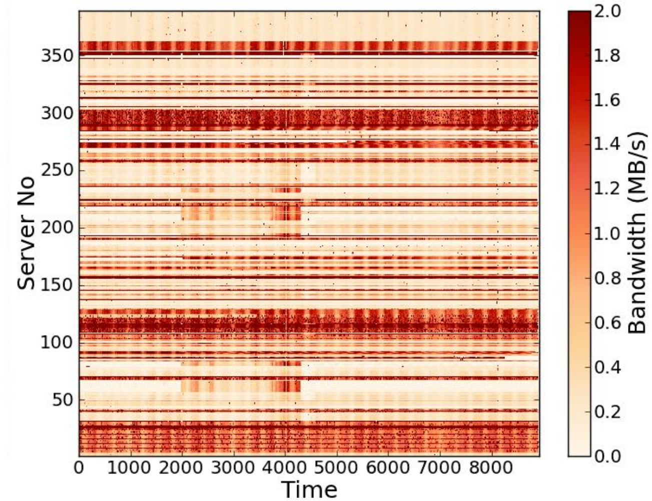
28% deviation

2 Levels



9.1% deviation

3 Levels



4.4% deviation

Motivation: Revisited

- Scalable Topologies ✓
  - Dragonfly, Fat tree, Clos, hotspot detection & elimination
- Flow Control ✓
  - Load balancing
  - Speculative flow control, Hedera, etc.
- Network Switches Design ✓
  - High port count designs, low latency RPCs, RAMCloud, etc.
- Software-defined DC networks ✓
  - OpenFlow, Nicira, etc.
- Security attacks ✓
  - Real-time deviation from modeled behavior
- Retraining for major sw updates, major system configuration changes
  - Low overhead process

Conclusions

- ECHO leverages validated analytical models to capture the temporal and spatial access patterns in DC network activity
- It preserves the intensity and characteristics of DC network traffic
- It adjusts the granularity of representation to the app/study demands
- It is scalable and lightweight
- Decouples network system studies from access to large-scale applications

Future work

- Use ECHO for network system studies without the requirement for full application deployment
- Expand similar concepts to other subsystems.

Questions??

Thank you