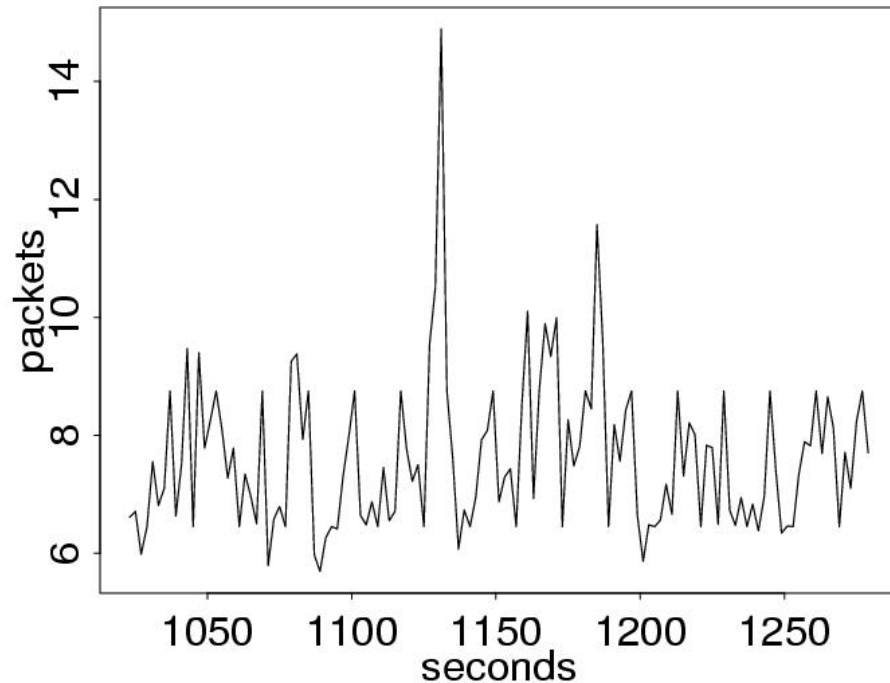


Network traffic: Scaling

Ways of representing a time series

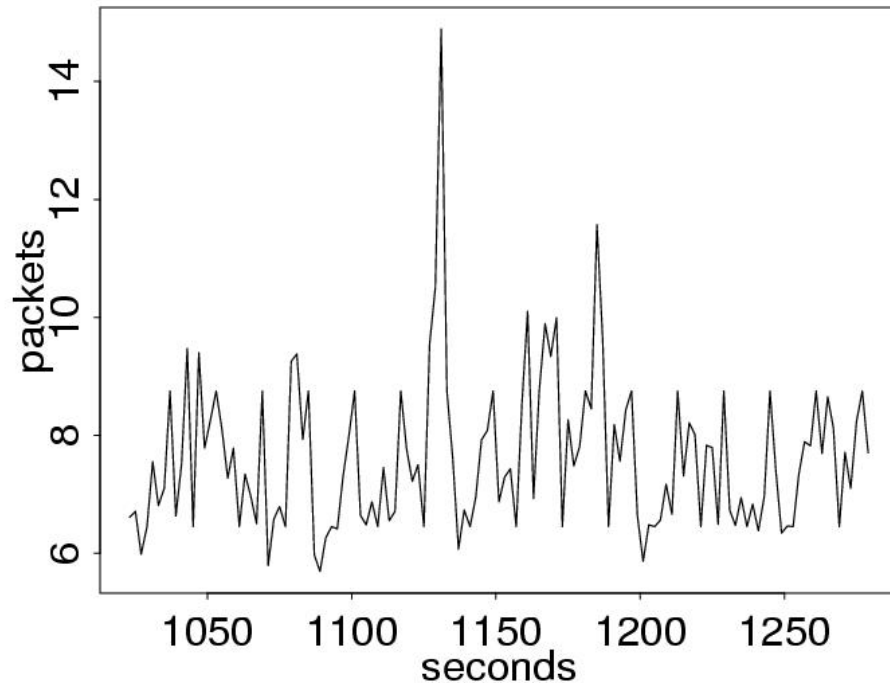
Timeseries



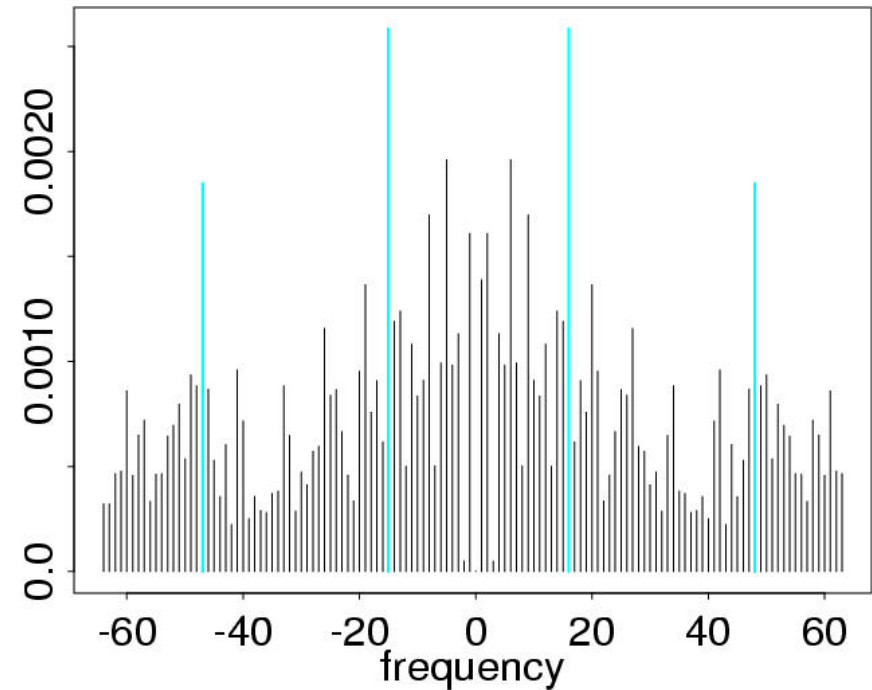
Timeseries: information in time domain

Ways of representing a time series

Timeseries



FFT

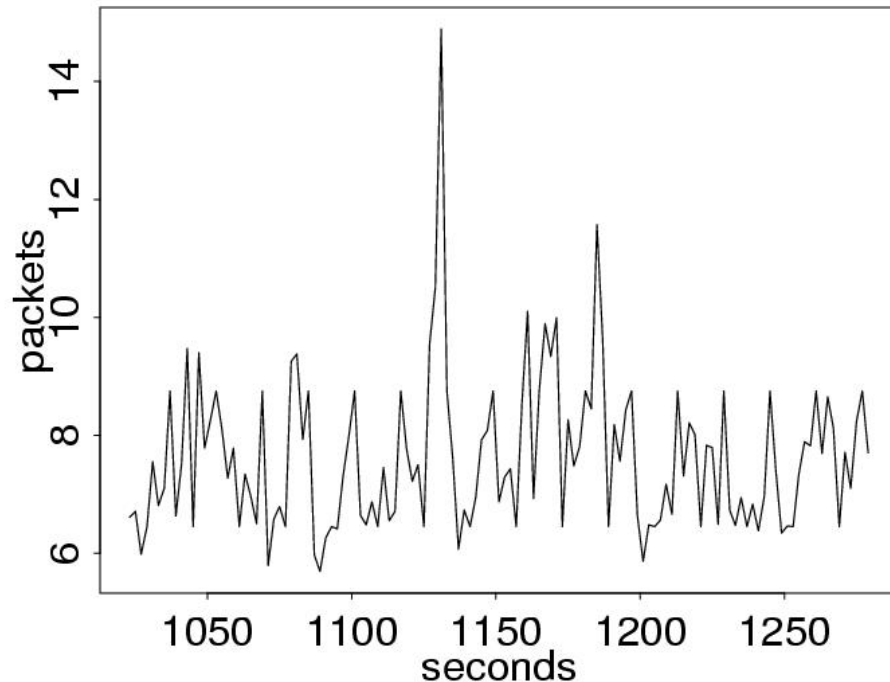


Timeseries: information in time domain

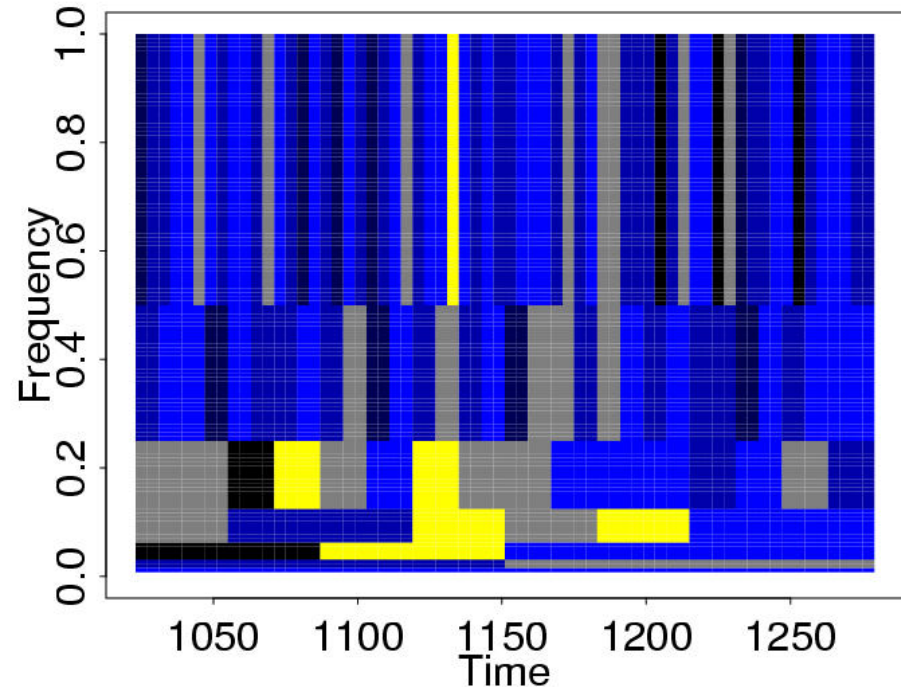
FFT: information in frequency (scale) domain

Ways of representing a time series

Timeseries



Wavelet transform



Timeseries: information in time domain

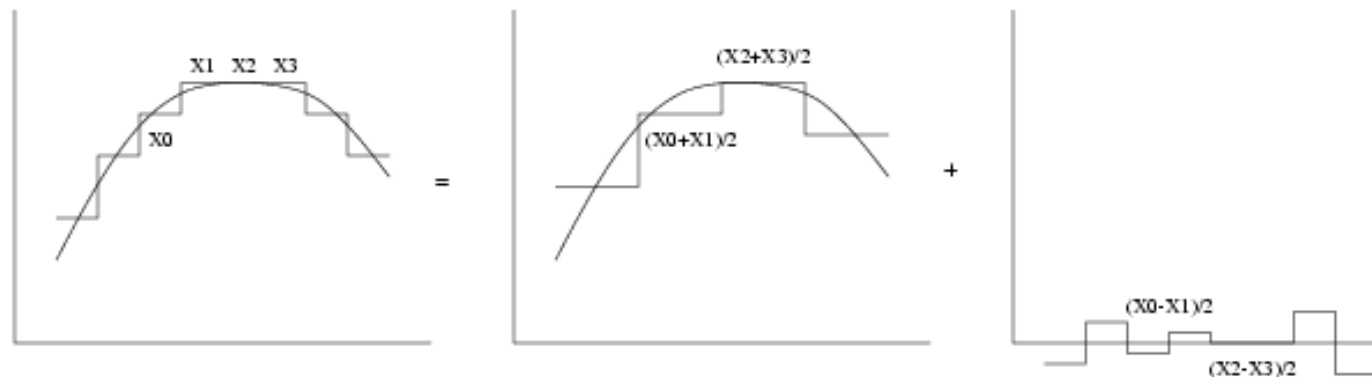
FFT: information in frequency (scale) domain

Wavelets: information in time and scale domains

Wavelet Coefficients: Local averages and differences

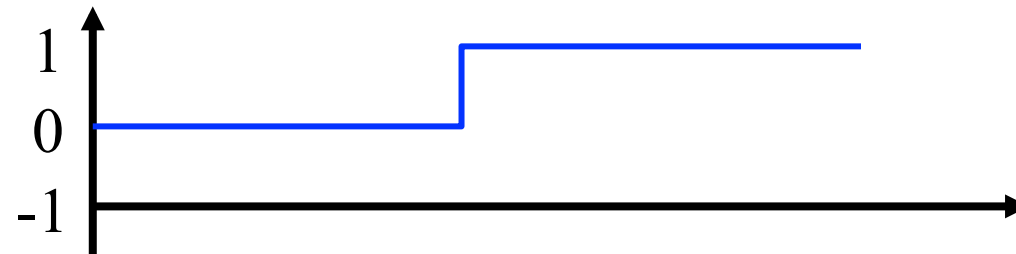
Intuition:

- Finest scale:
 - Compute averages of adjacent data points
 - Compute differences between average and actual data
- Next scale:
 - Repeat based on averages from previous step

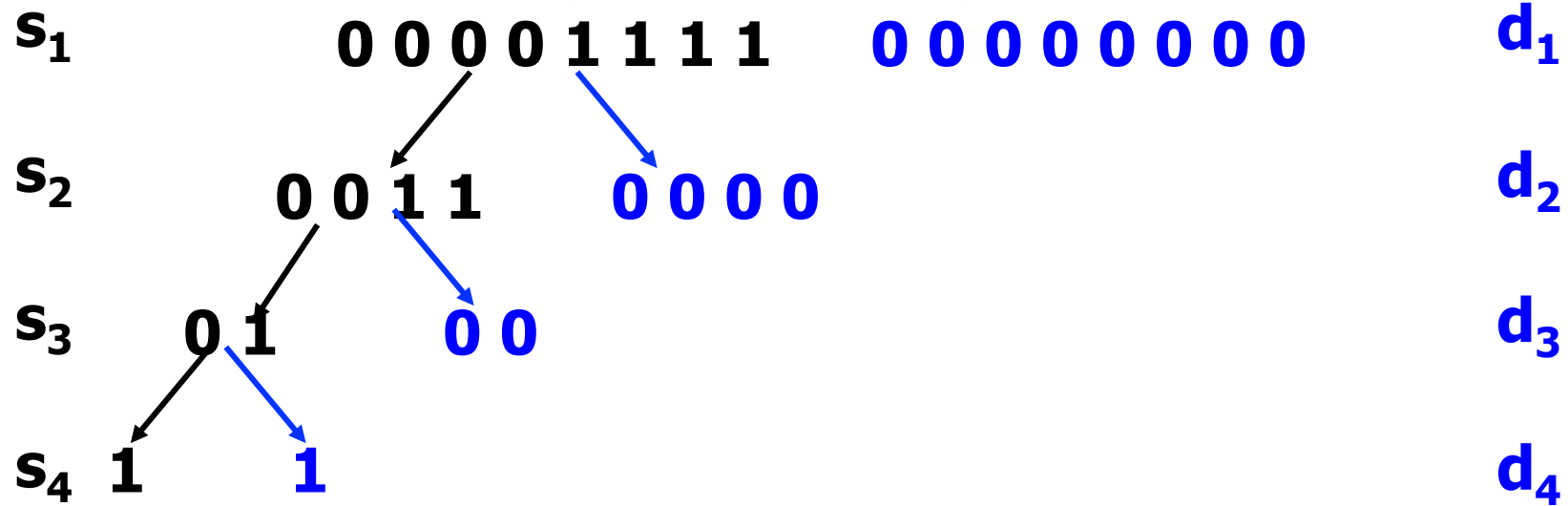


Use wavelet coefficients to study scale or frequency dependent properties

Wavelet example



00 00 00 00 11 11 11 11

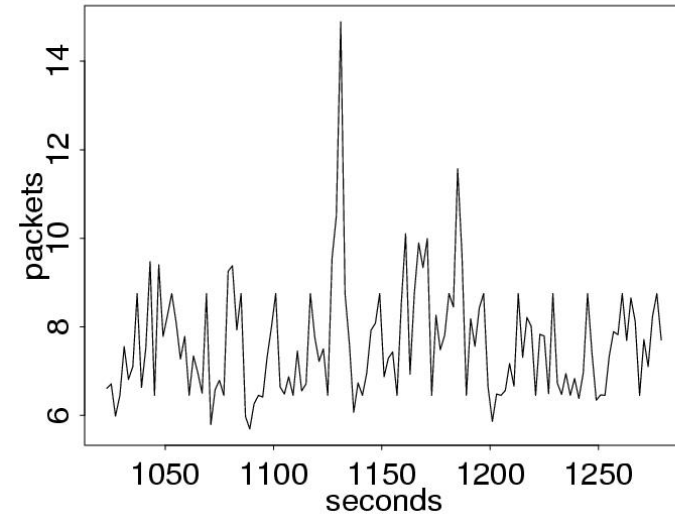


Wavelets

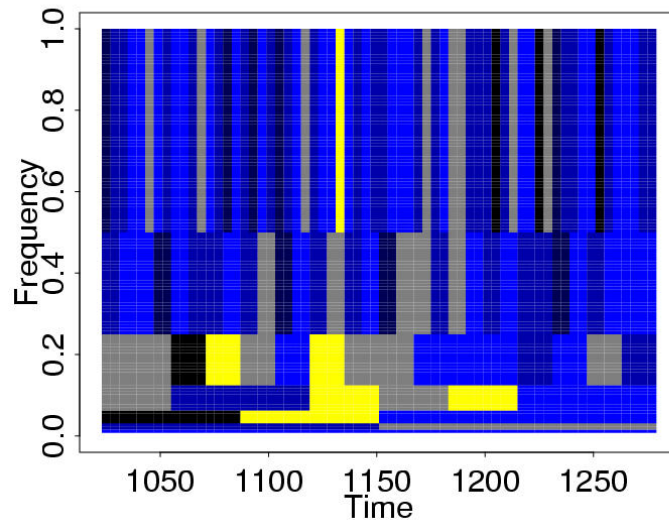
FFT: decomposition in frequency domain

Wavelets: localize a signal in both **time** and **scale**

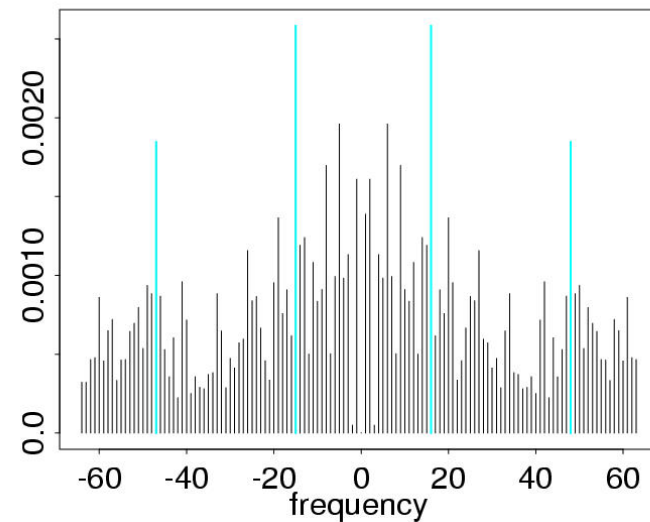
Timeseries



Wavelet transform

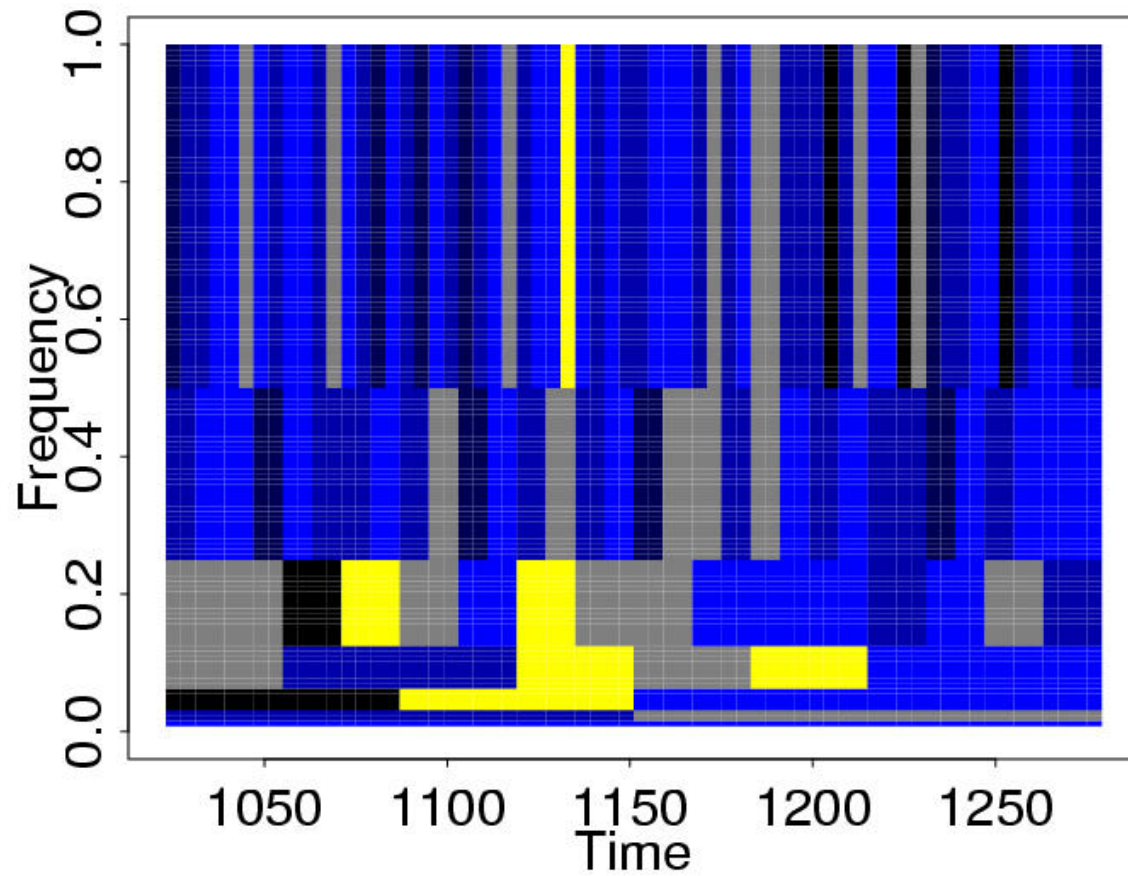


FFT



Wavelets

Wavelet
coefficients $d_{j,k}$



Discrete wavelet transform

Definition:

- From 1D to 2D: $X \leftrightarrow \{d_{j,k} : j \in \mathbb{Z}, k \in \mathbb{Z}\}$
- Wavelet coefficients at scale j and time $2^j k$

$$d_{j,k} = \int X(s) \Psi_{j,k}(s) ds, \quad j \in \mathbb{Z}, k \in \mathbb{Z}$$

- Wavelets: $\Psi_{j,k}(t) = 2^{-j/2} \Psi(2^{-j} t - k)$
- Wavelet decomposition: $X(t) = \sum_{j \in \mathbb{Z}} \sum_{k \in \mathbb{Z}} d_{j,k} \Psi_{j,k}(t)$

Global scaling analysis

Methodology: Exploit properties of wavelet coefficients

- Self-similarity: coefficients scale independent of k

$$d_{j,k} \approx 2^{j(1+2H)} \text{ for all } j$$

Algorithm:

- Compute Discrete Wavelet Transform
- Compute energy of wavelet coefficients at each scale

$$\log_2 E_j = \log_2 \left(\frac{1}{N_j} \sum_k |d_{j,k}|^2 \right) \approx -j(1+2H)$$

- Plot $\log_2 E$ versus scale j
- Identify scaling regions, break points, etc.
- Hurst parameter estimation

Motivation

Scaling

- How does traffic behave at different aggregation levels

Large time scales: User dynamics => self-similarity

- Users act mostly independent of each other
- Users are unpredictable: Variability in
 - Variability in doc size, # of docs, time between docs

Small time scales: Network dynamics

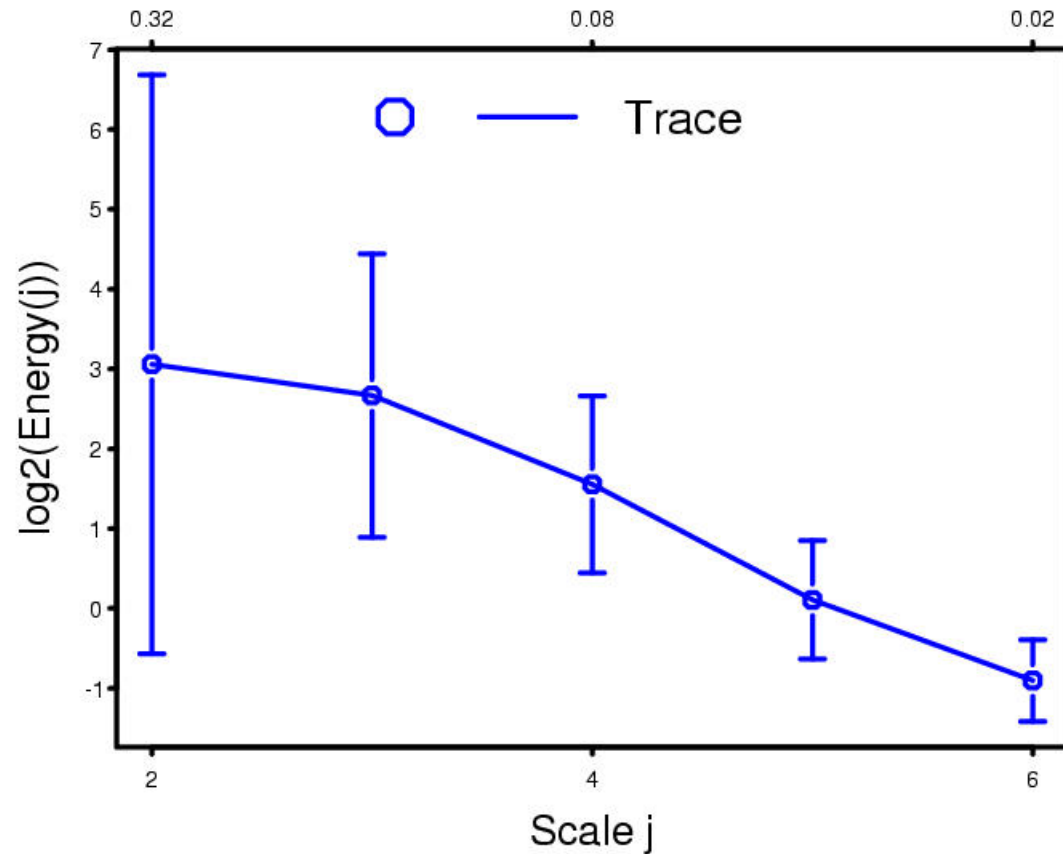
- Network protocols effects: TCP flow control
- Queue at network elements: delay
- Influences user experience

How do they interact????

Global scaling analysis (large scales)

$Energy_j =$

$$\frac{1}{N_j} \sum_k |d_{j,k}|^2$$

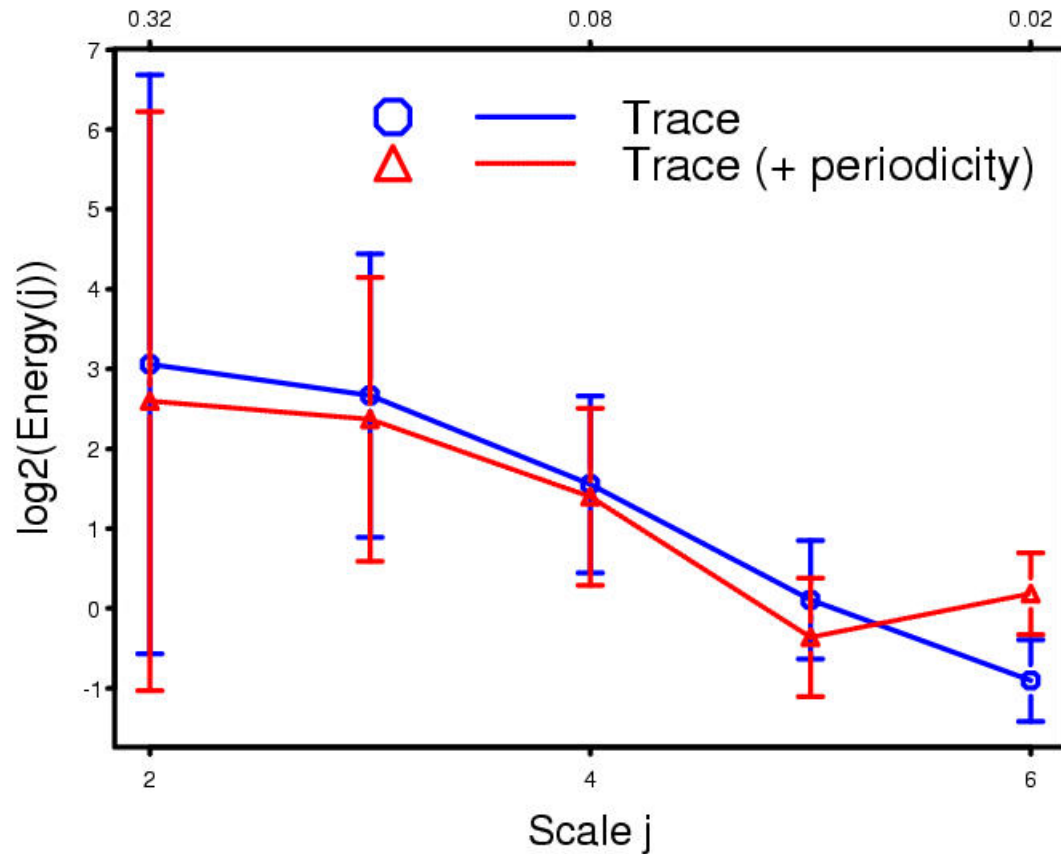


- Trivial global scaling == horizontal slope (large scales)
- Non-trivial global scaling == slope > 0.5 (large scales)

Global scaling analysis (large scales)

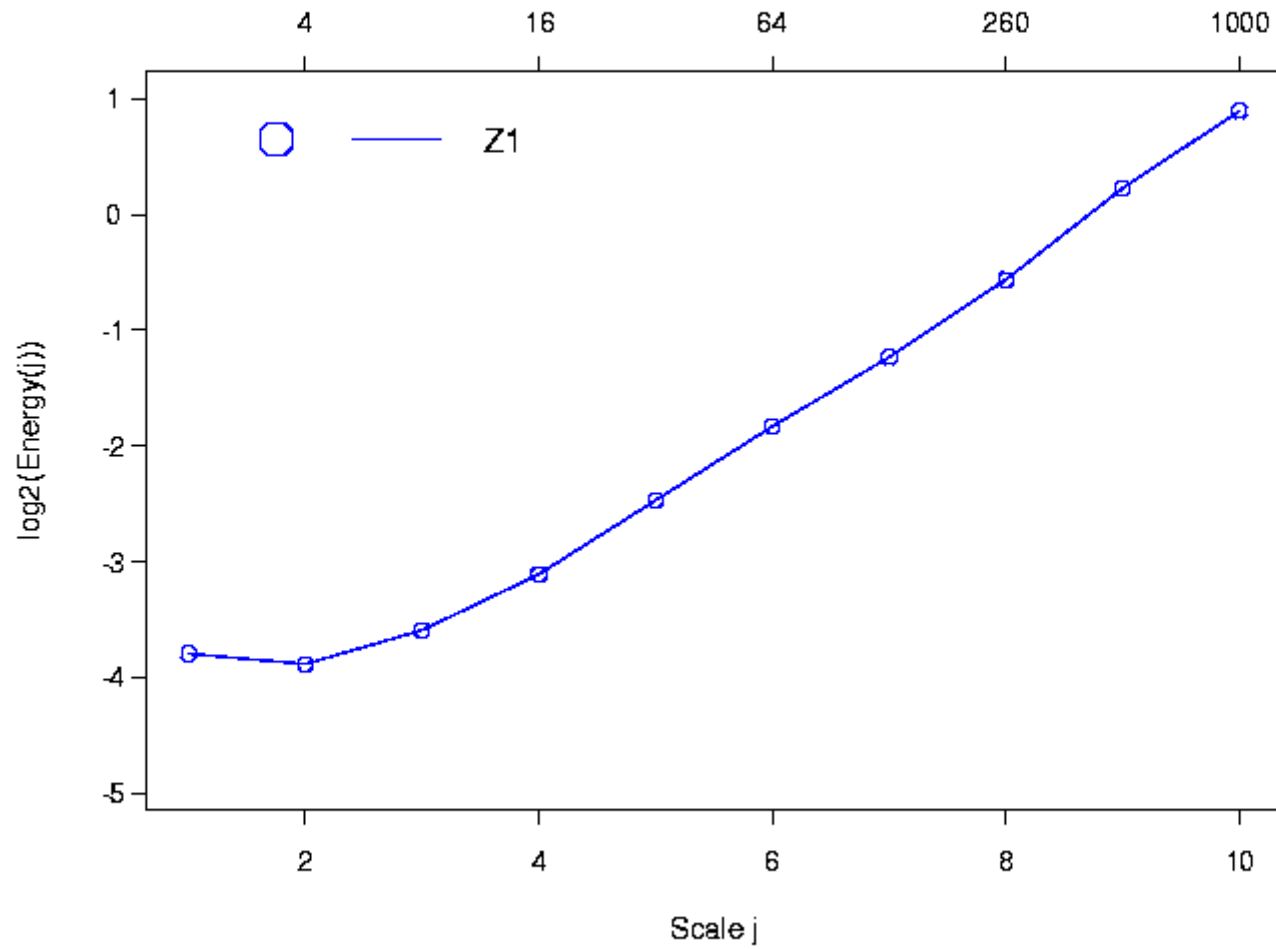
$Energy_j =$

$$\frac{1}{N_j} \sum_k |d_{j,k}|^2$$

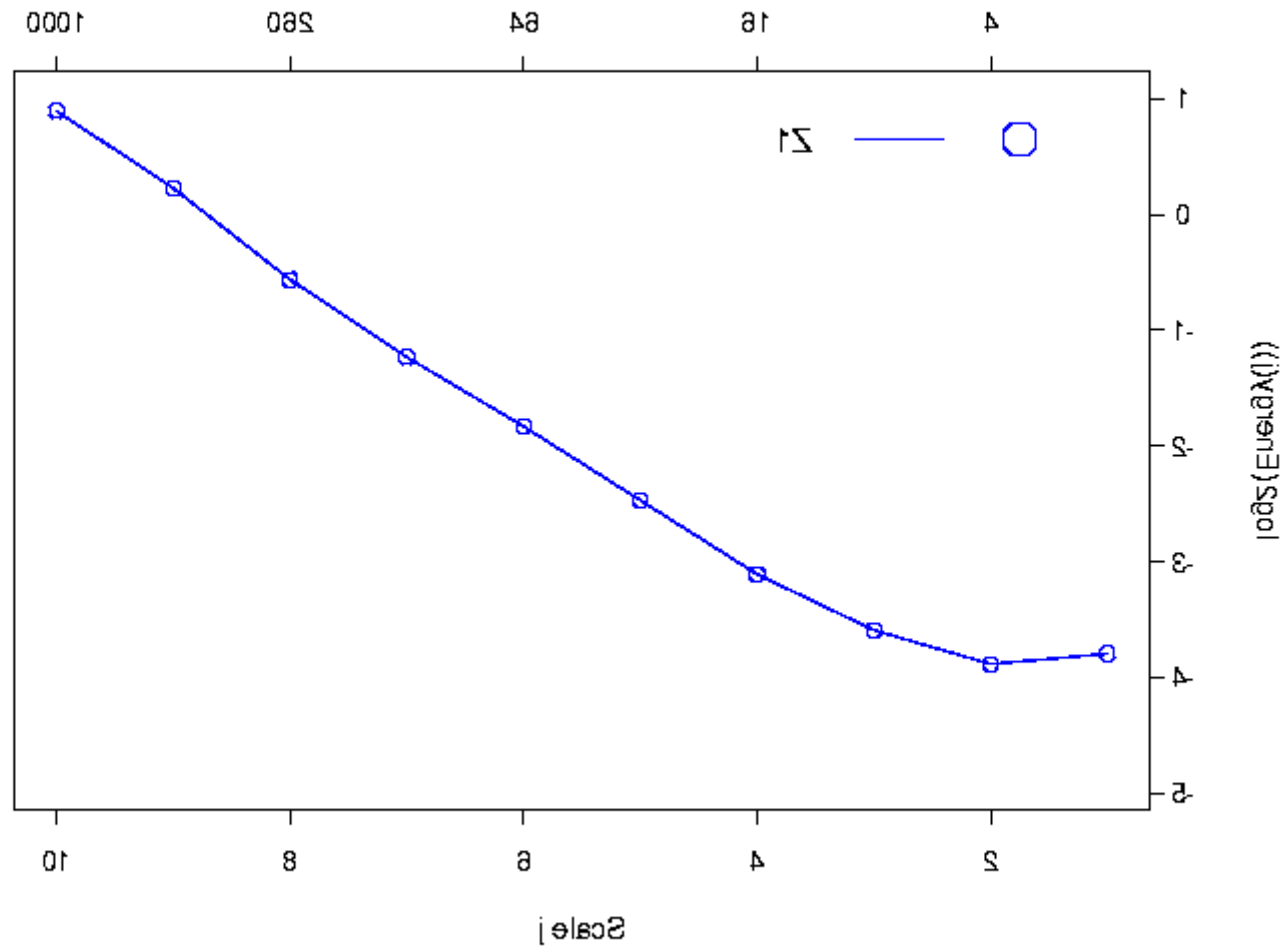


- Trivial global scaling == horizontal slope (large scales)
- Non-trivial global scaling == slope > 0.5 (large scales)

Self-similar traffic

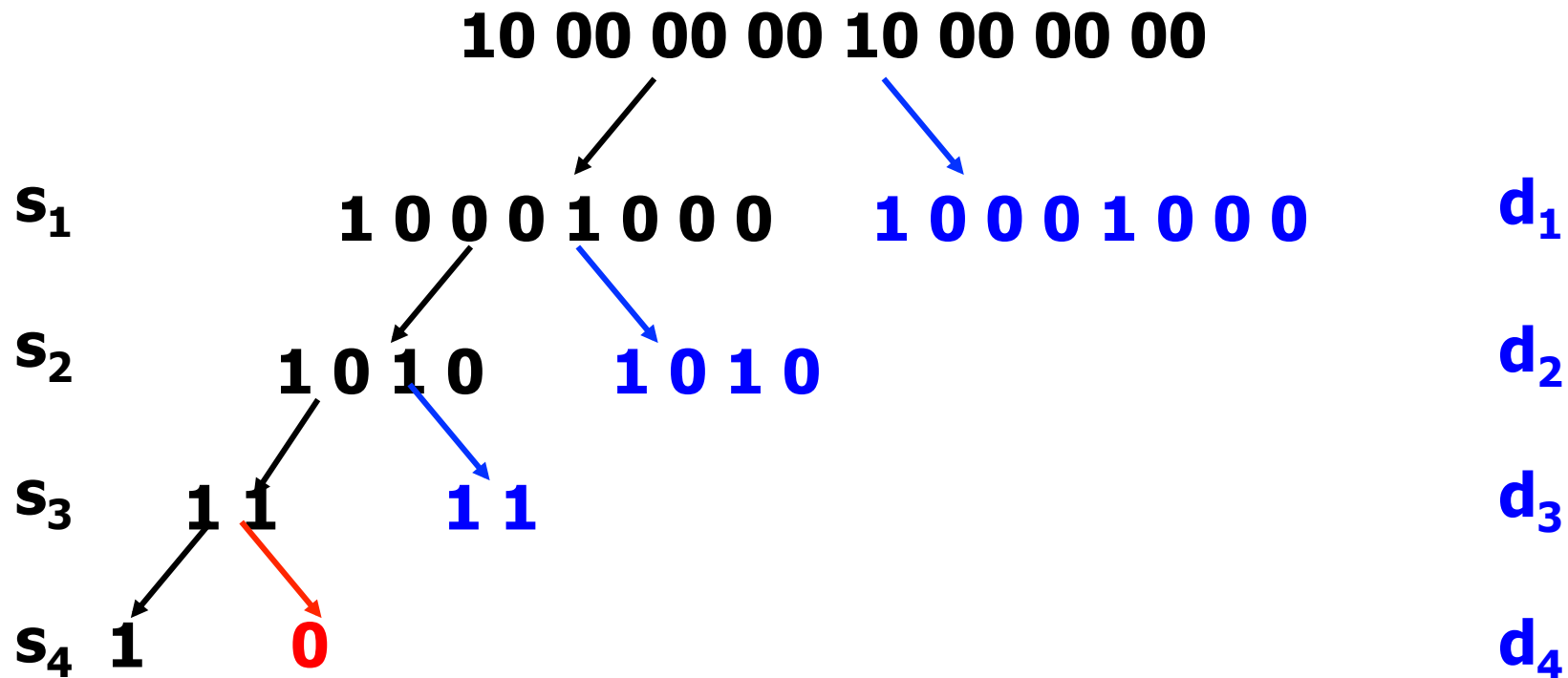


Self-similar traffic

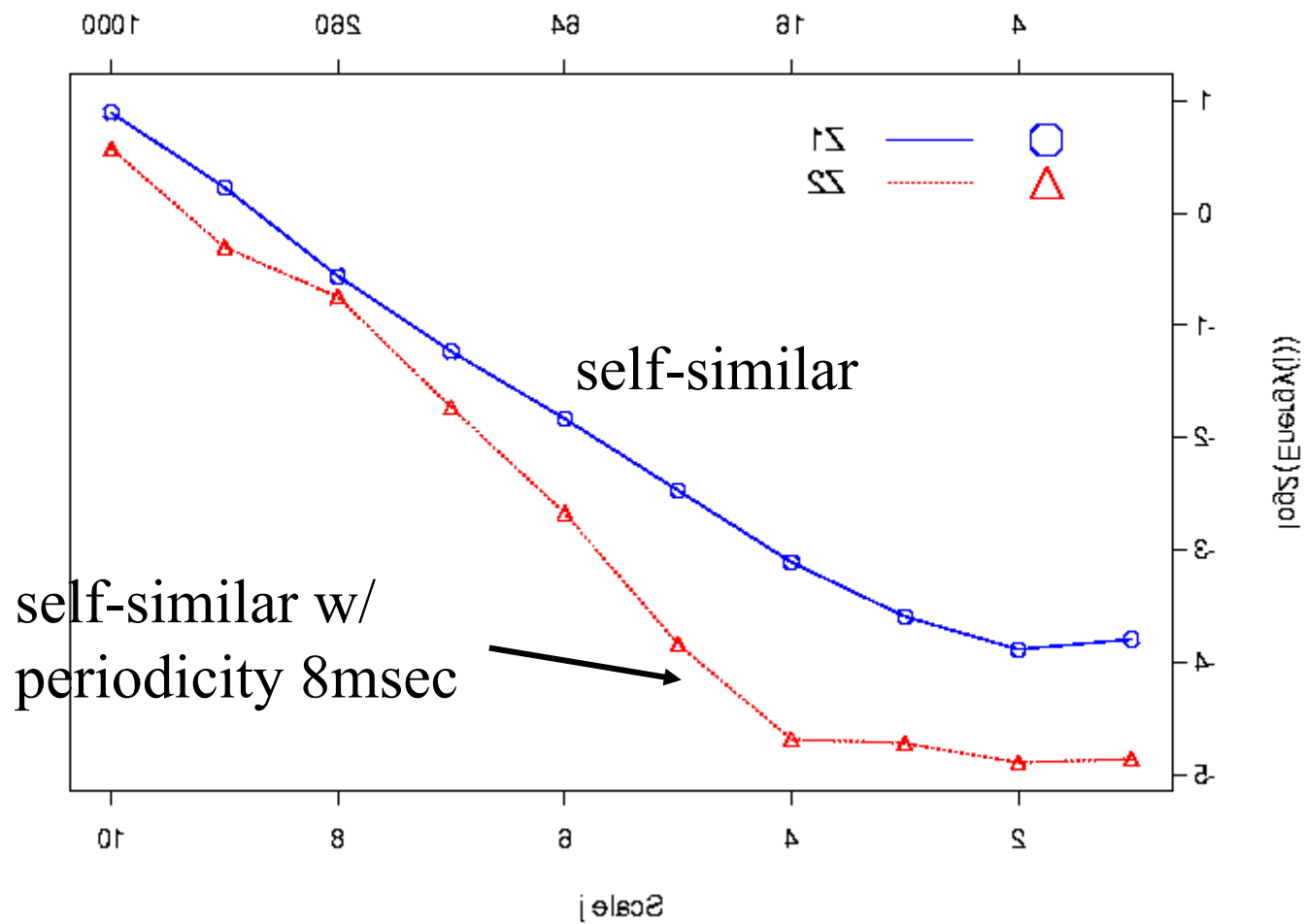


Adding periodicity

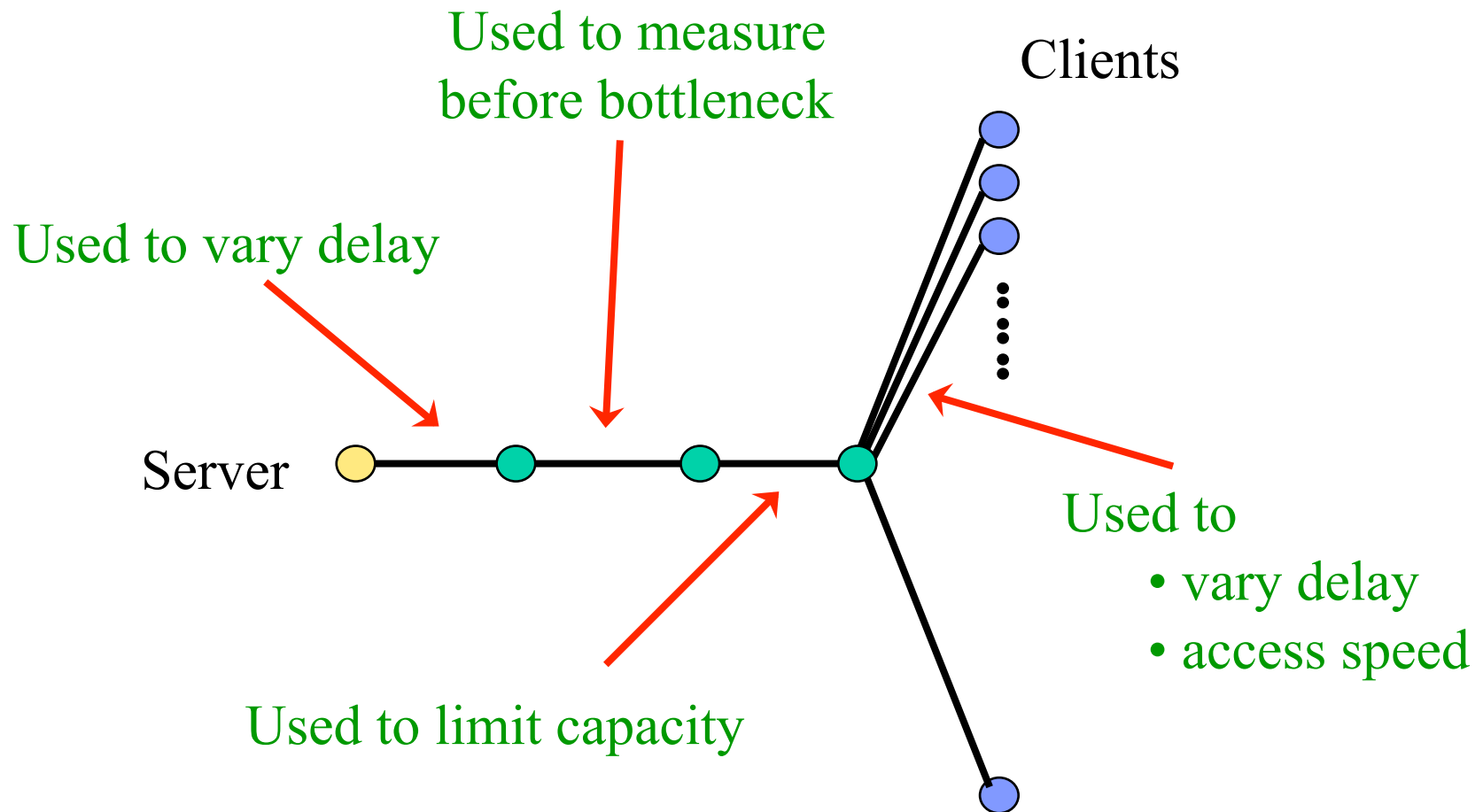
- ❑ Packets arrive periodically, 1 pkt/ 2^3 msec
- ❑ Coefficients cancel out at scale 4



Effect of Periodicity



A simple topology



Impact of RTT on global scaling

□ Workload

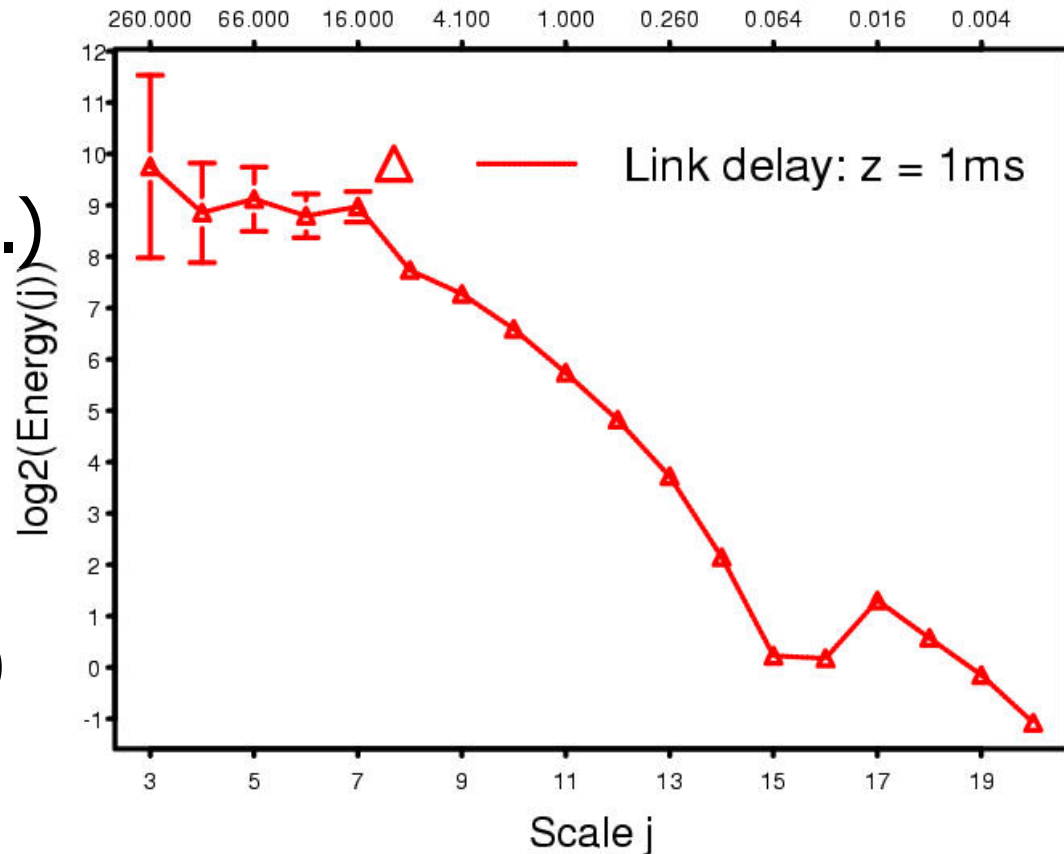
- Web (Pareto dist.)

□ Network

- Single RTT delay
- Examples
 - scale 15 (24 ms)
 - scale 10 (1.3 s)

□ Conclusion

- Dip at smallest time scale bigger than RTT



Impact of RTT on global scaling

□ Workload

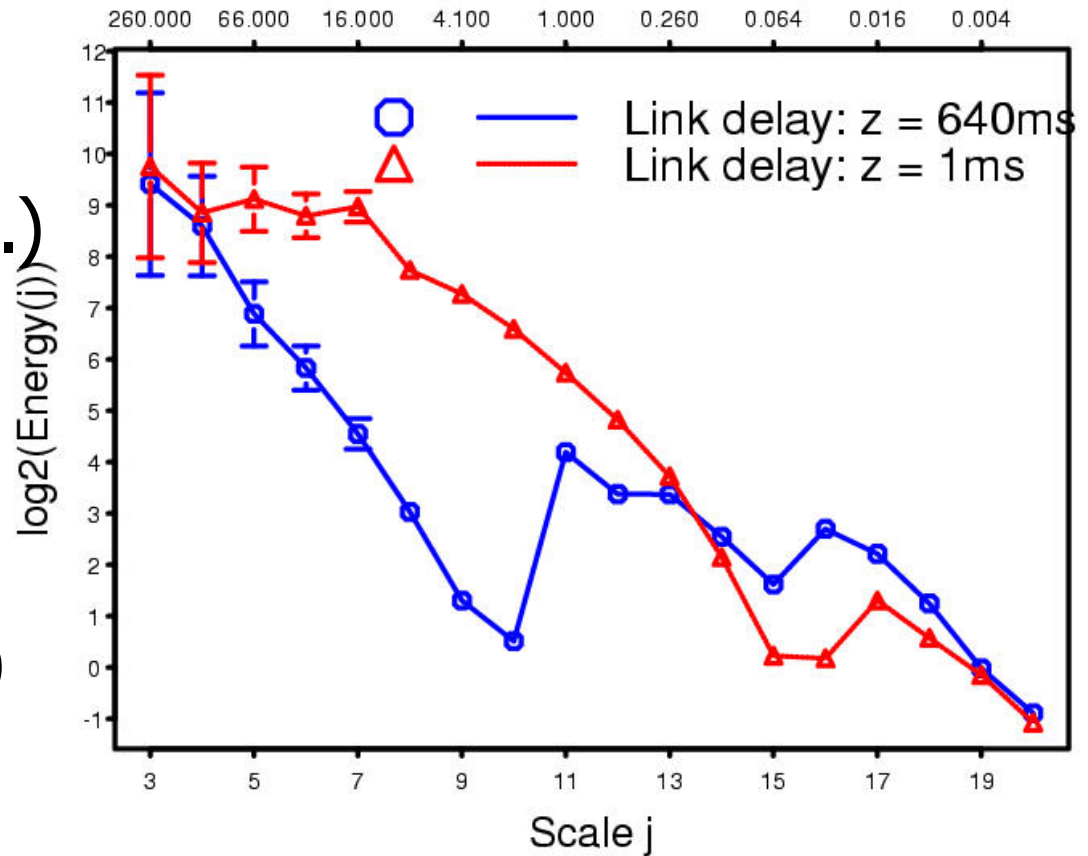
- Web (Pareto dist.)

□ Network

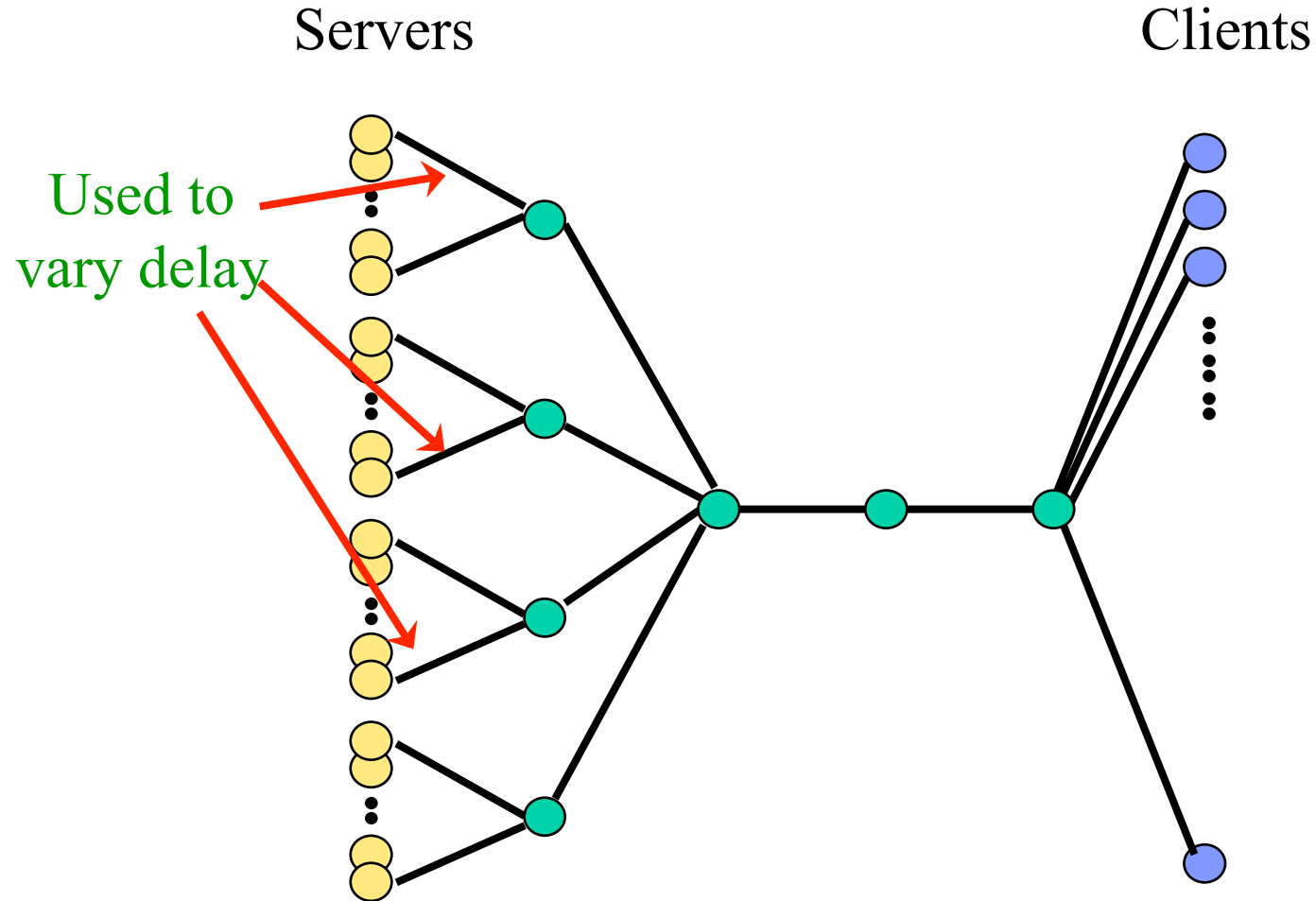
- Single RTT delay
- Examples
 - scale 15 (24 ms)
 - scale 10 (1.3 s)

□ Conclusion

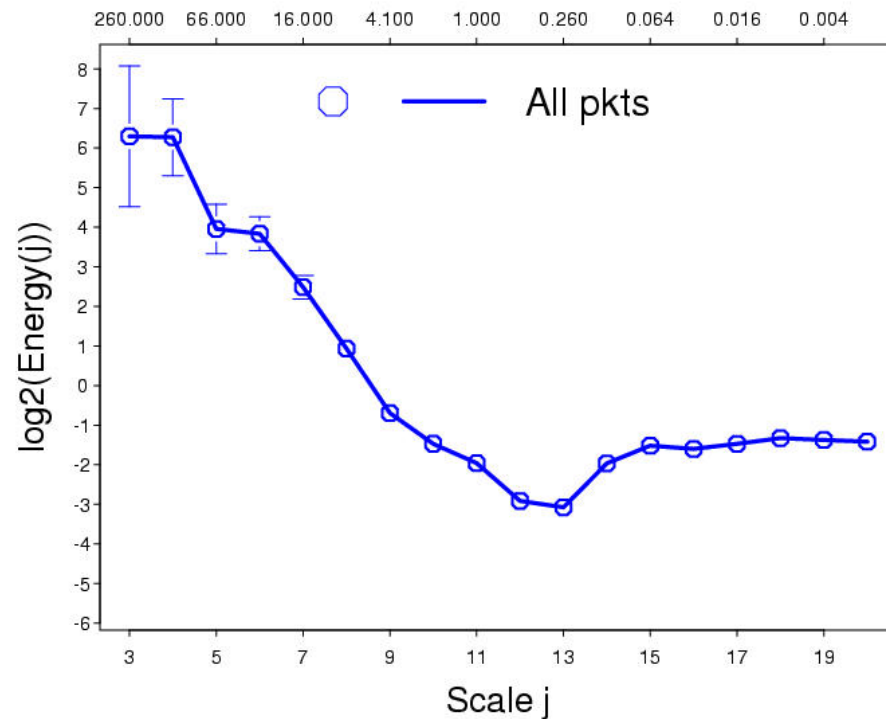
- Dip at smallest time scale bigger than RTT



A more complex topology

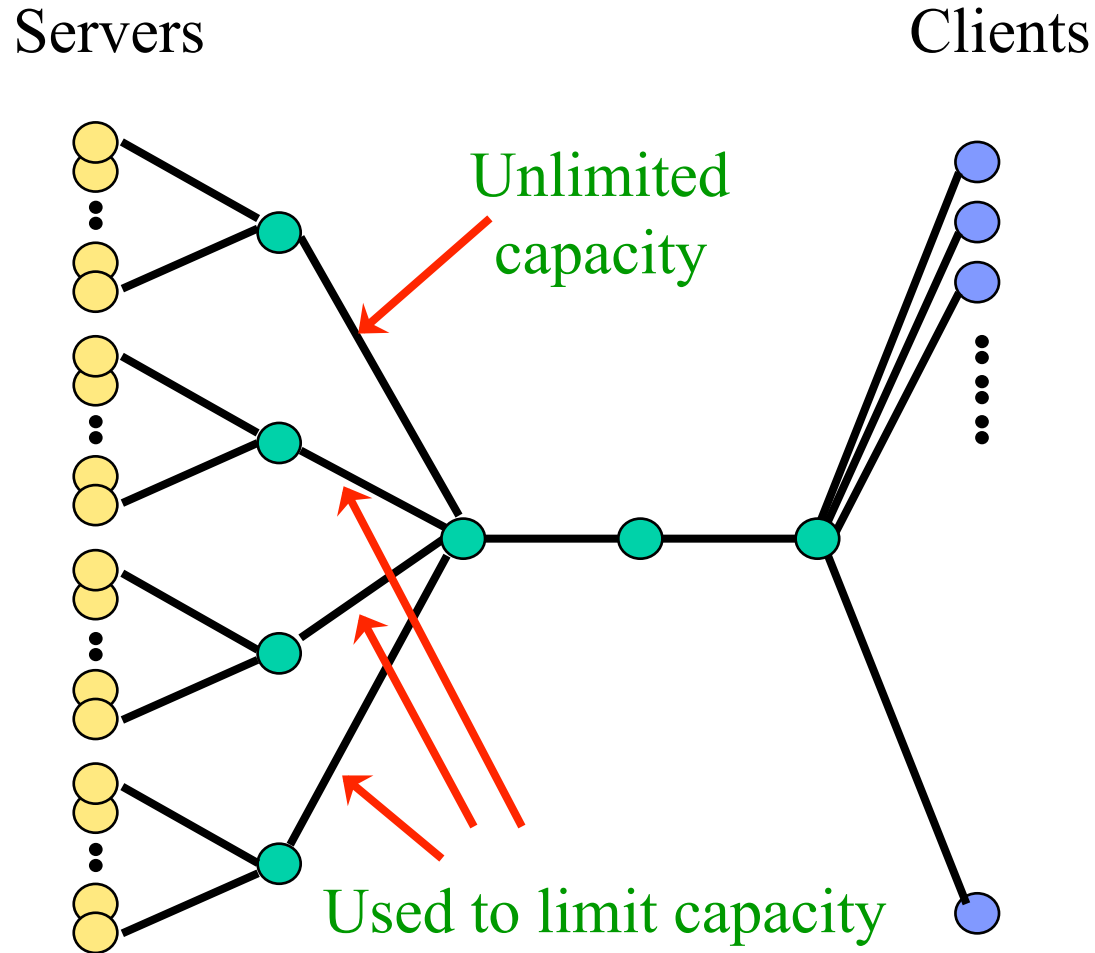


Impact of different RTTs on global scaling

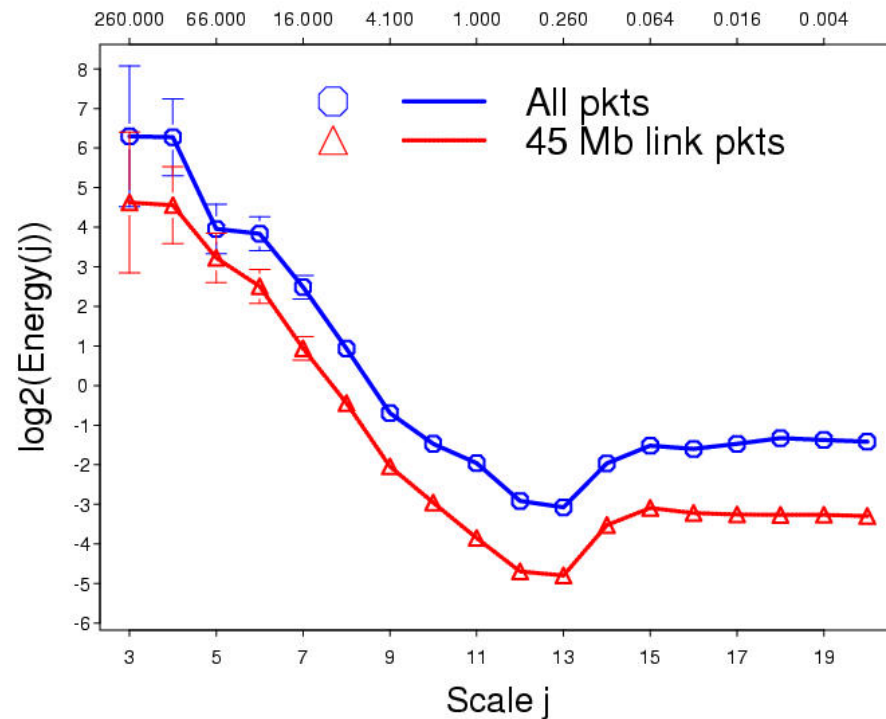


- ❑ Network variability (delay) \Rightarrow wider dip
- ❑ Self-similar scaling breaks down for small scales

A more complex topology

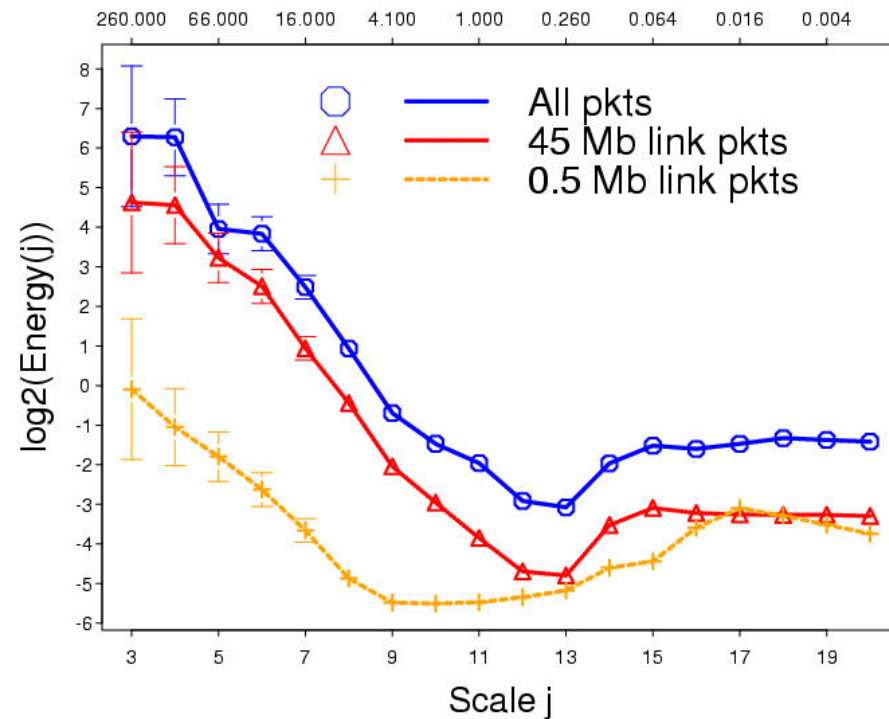


Impact of different bottlenecks on global scaling



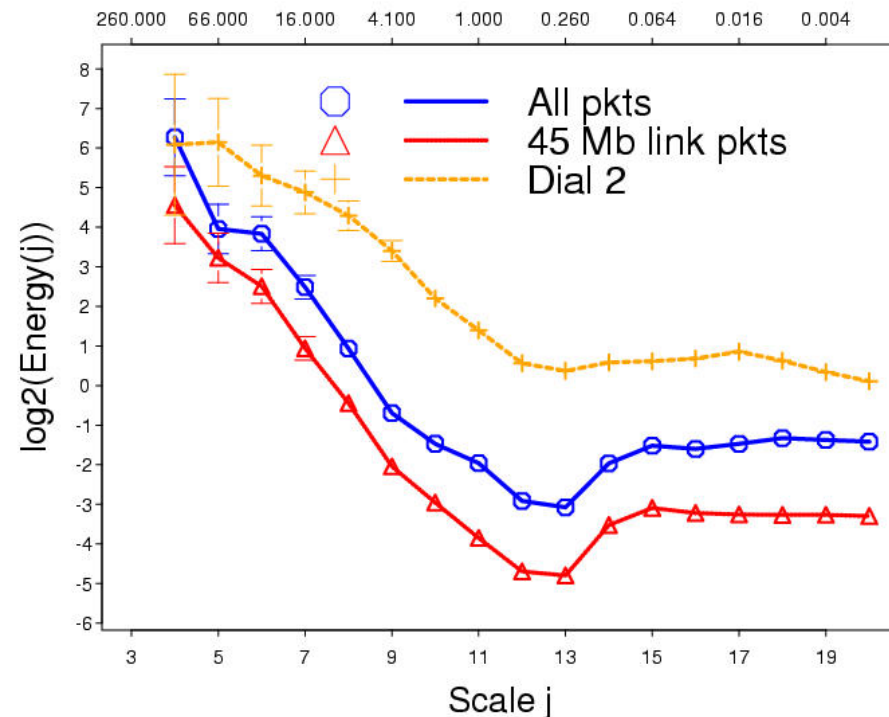
- ❑ Network variability (delay) => wider dip
- ❑ Network variability (congestion) => wider dip
- ❑ Simulation matches traces without explicit modeling

Impact of different bottlenecks on global scaling



- ❑ Network variability (delay) => wider dip
- ❑ Network variability (congestion) => wider dip
- ❑ Simulation matches traces without explicit modeling

Impact of different bottlenecks on global scaling



- ❑ Network variability (delay) => wider dip
- ❑ Network variability (congestion) => wider dip
- ❑ Simulation matches traces without explicit modeling

Small-time scaling - multifractal

Wavelet domain:

Self-Similarity: coefficients scale **independent of k**

Multifractal: scaling of coefficients **depends on k**
local scaling is **time dependent**

Time domain:

Traffic rate process at time t_0 is:

of packets in $[t_0, t_0 + \delta t]$

Self-Similarity: traffic rate is like $(\delta t)^H$

Multifractal: traffic rate is like $(\delta t)^{\alpha(t_0)}$

Conclusion

Scaling

- Large time scales: self-similar scaling
 - User related variability
- Small time scales: multifractal scaling
 - Network variability
 - Topology
 - TCP-like flow control
 - TCP protocol behavior (e.g., Ack compression)

Summary

- ❑ Identified how IP traffic dynamics are influenced by
 - User variability, network variability, protocol variant
- ❑ Scaling phenomena
 - Self-similar scaling, breakpoints, multifractal scaling
- ❑ Physical understanding guides simulation setup
 - Moving towards right “ball park”
- ❑ Beware of homogeneous setups
 - Infinite source traffic models