Network traffic: Scaling

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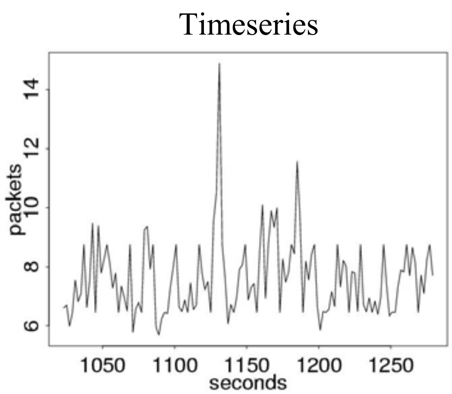
Ways of representing a time series



Timeseries: information in time domain

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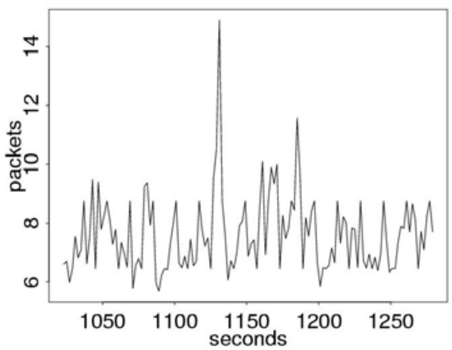
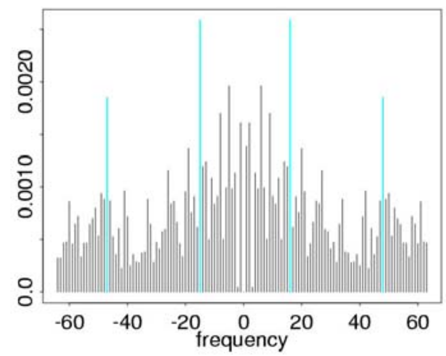
Ways of representing a time series

Timeseries



FFT

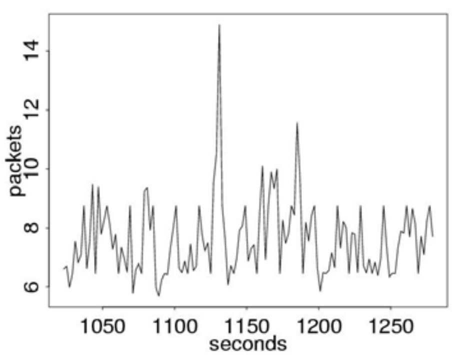


Timeseries: information in time domain

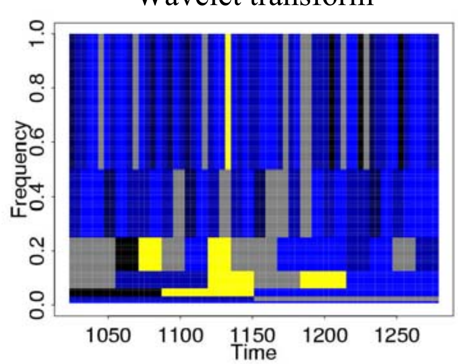
FFT: information in frequency (scale) domain

Ways of representing a time series

Timeseries



Wavelet transform



Timeseries: information in time domain

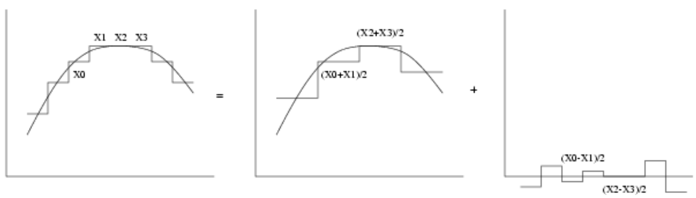
FFT: information in frequency (scale) domain

Wavelets: information in time and scale domains

Wavelet Coefficients: Local averages and differences

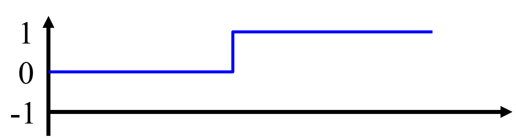
Intuition:

- 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

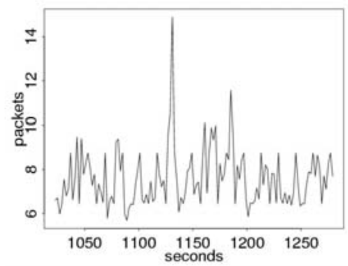
s_1	**0 0 0 0 1 1 1 1**	**0 0 0 0 0 0 0 0**	**d_1**
s_2	**0 0 1 1**	**0 0 0 0**	**d_2**
s_3	**0 1**	**0 0**	**d_3**
s_4	**1**	**1**	**d_4**

Wavelets

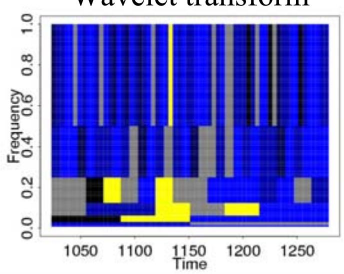
FFT: decomposition in frequency domain

Wavelets: localize a signal in both time and scale

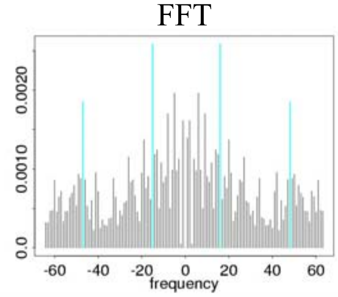
Timeseries



Wavelet transform



FFT



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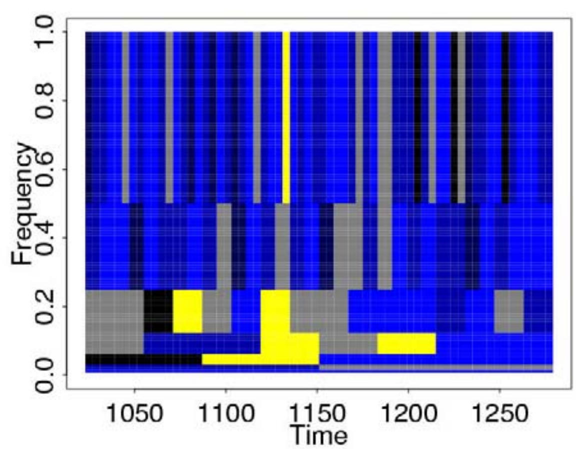
Wavelets

Wavelet coefficients $d_{j,k}$



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Discrete wavelet transform

Definition:

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

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

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

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Global scaling analysis

Methodology: Exploit properties of wavelet coefficients

- Self-similarity: coefficients scale independent of k

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

Algorithm:

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

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

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

Ref: AV IEEE Transactions on Information Theory 1998

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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????

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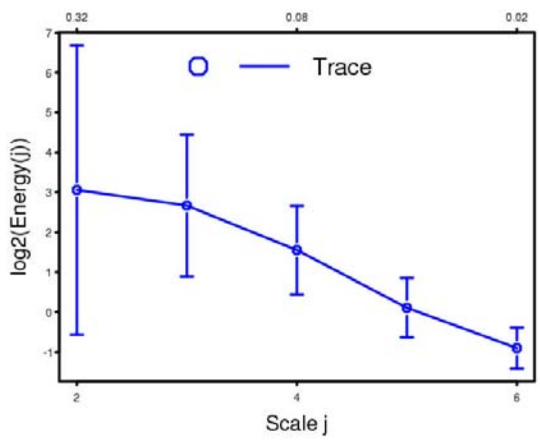
Global scaling analysis (large scales)

$$Energy_j = \frac{1}{N_j}\sum_k \left|d_{j,k}\right|^2$$



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

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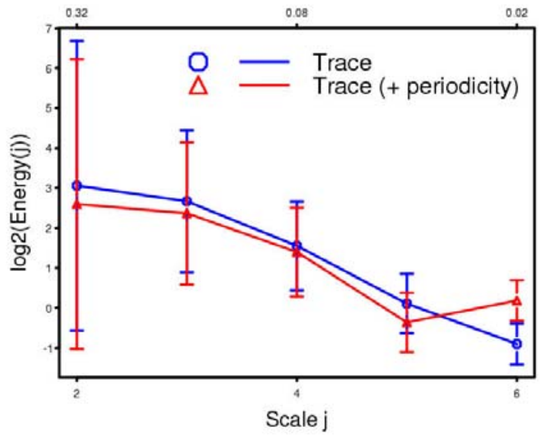
Global scaling analysis (large scales)

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



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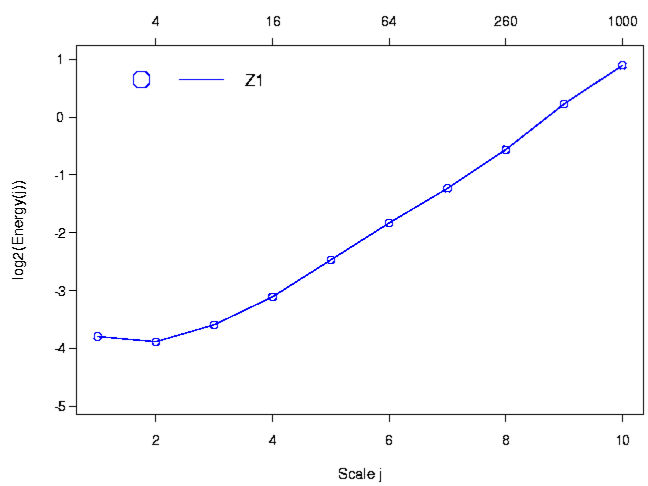
Self-similar traffic



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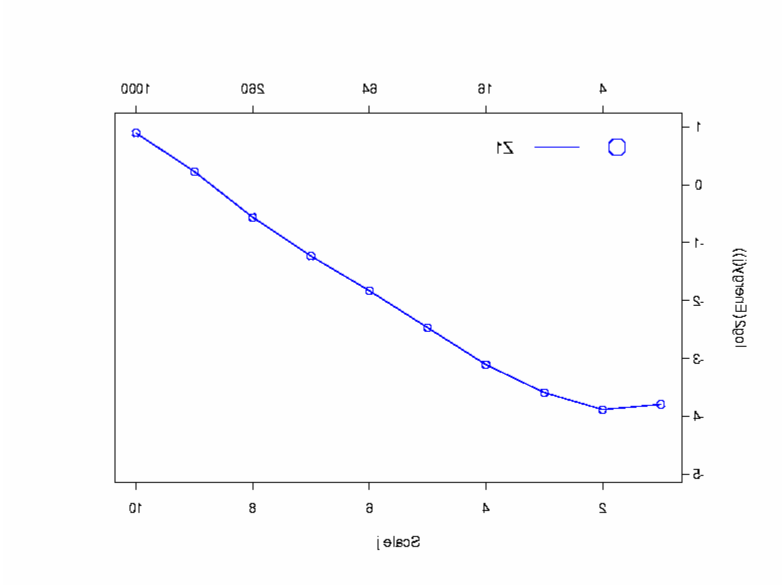
Self-similar traffic



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Adding periodicity

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

10 00 00 00 10 00 00 00

s_1 1 0 0 0 1 0 0 0   1 0 0 0 1 0 0 0 d_1

s_2 1 0 1 0   1 0 1 0 d_2

s_3 1 1   1 1 d_3

s_4 1   0 d_4

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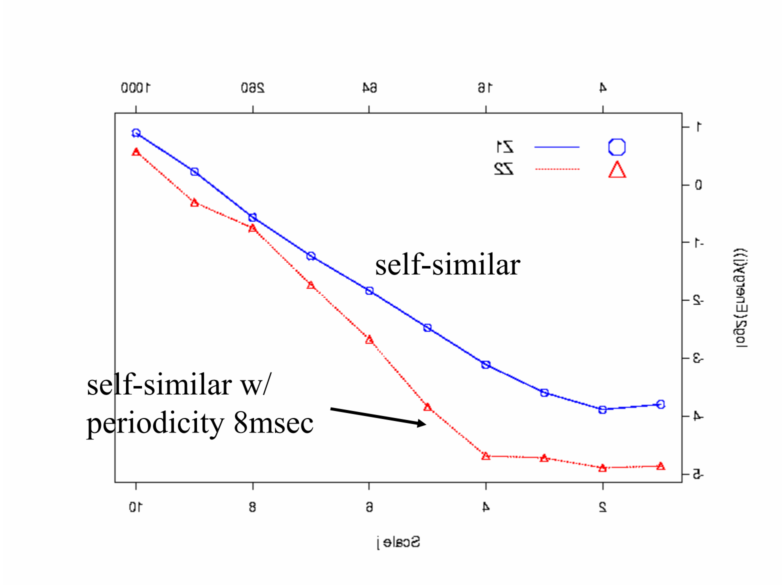
Effect of Periodicity



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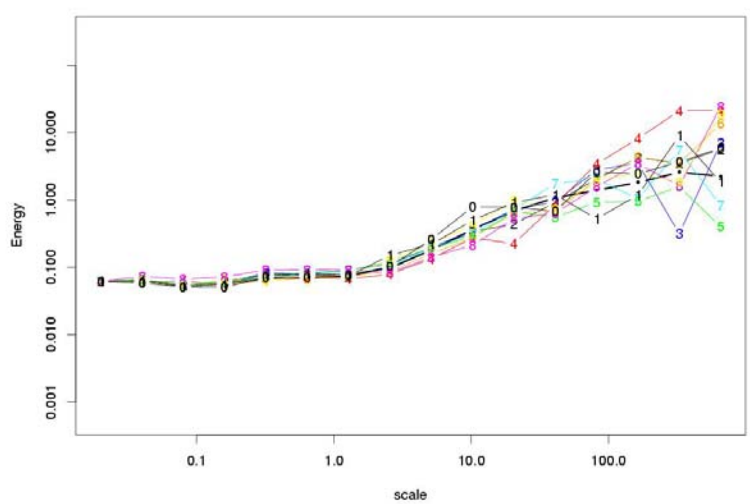
Actual traffic: Different time periods



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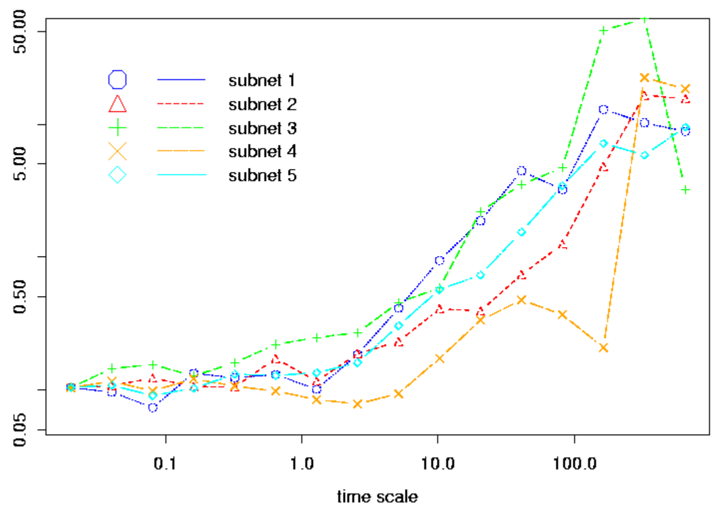
Actual traffic: different subnets



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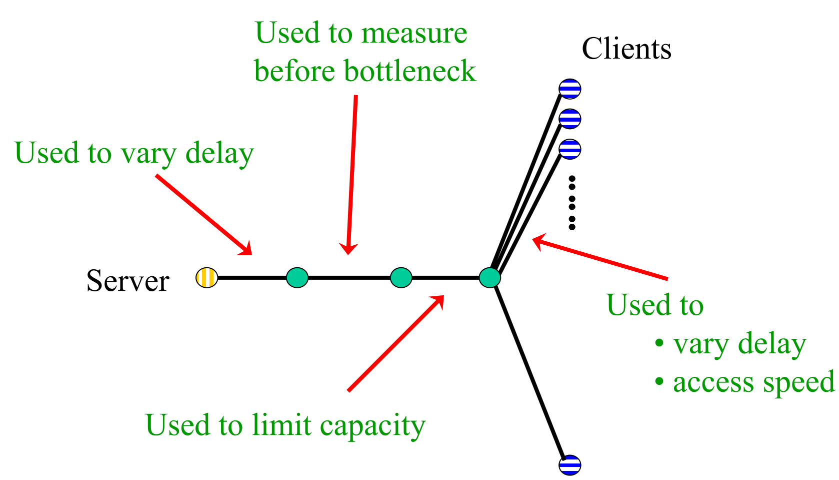
A simple topology



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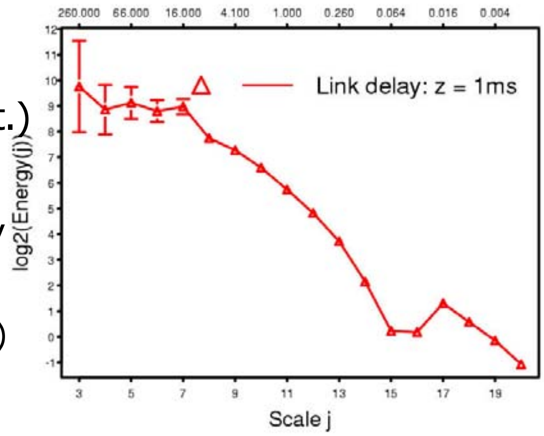
Impact of RTT on global scaling

- 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



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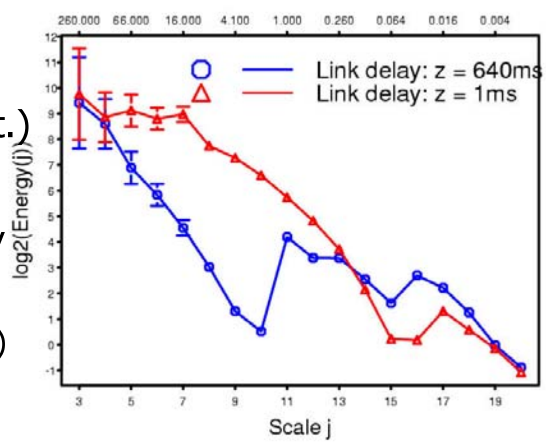

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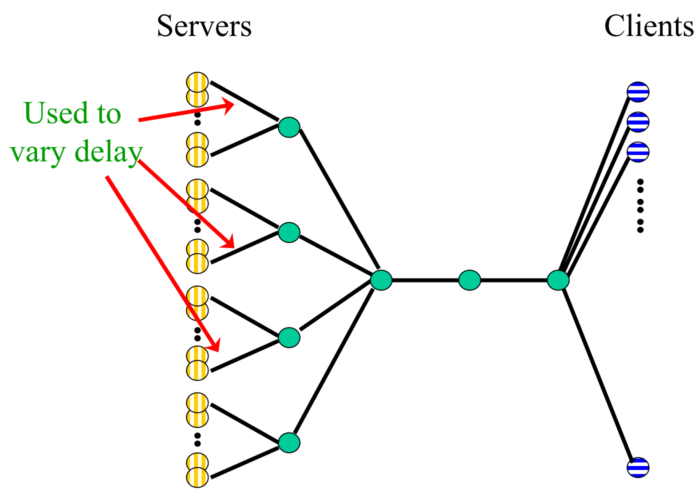
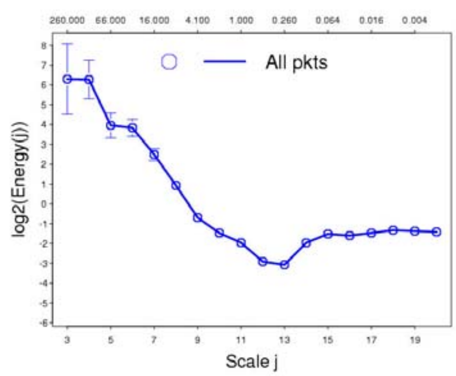
A more complex topology

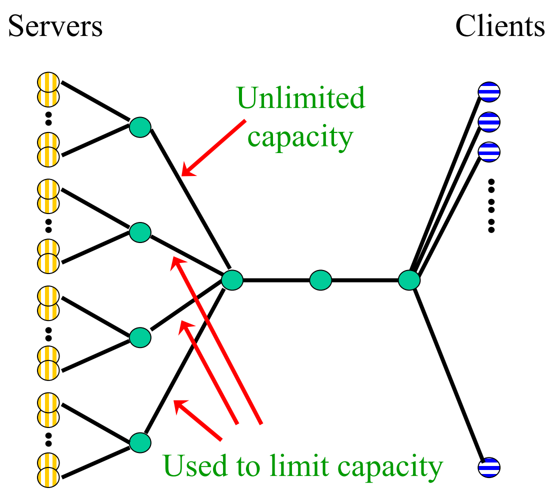


Impact of different RTTs on global scaling



- Network variability (delay) => wider dip
- Self-similar scaling breaks down for small scales

A more complex topology



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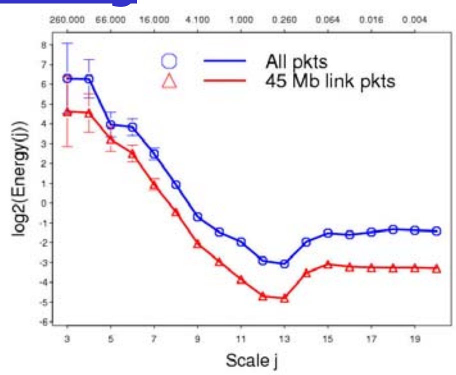
Impact of different bottlenecks on global scaling



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

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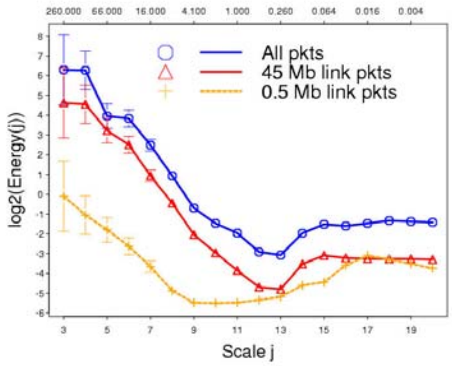
Impact of different bottlenecks on global scaling



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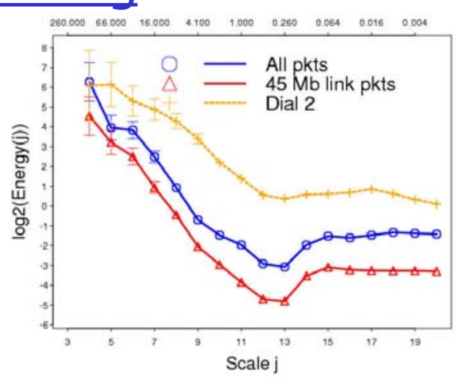
Impact of different bottlenecks on global scaling



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

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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 $(\delta t)^{\alpha(t_0)}$

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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)

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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

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