Network traffic: Scaling
Ways of representing a time series

Timeseries: information in time domain
Ways of representing a time series

Timeseries: information in time domain
FFT: information in frequency (scale) domain
Ways of representing a time series

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
Wavelets

**FFT**: decomposition in frequency domain

**Wavelets**: localize a signal in both time and scale
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 \( k \)

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

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

Ref: AV IEEE Transactions on Information Theory 1998
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)

\[ \text{Energy}_j = \frac{1}{N_j} \sum_k |d_{j,k}|^2 \]

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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

self-similar

self-similar w/ periodicity 8msec
Actual traffic: Different time periods
Actual traffic: different subnets
A simple topology

- Server
- Clients
- Used to limit capacity
  - Used to vary delay
  - Used to measure before bottleneck
- Used to vary delay
- Used to
  - vary delay
  - access speed
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

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- **Conclusion**
  - Dip at smallest time scale bigger than RTT
A more complex topology

Used to vary delay
Impact of different RTTs on global scaling

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

Servers

Clients

Unlimited capacity

Used to limit capacity
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

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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:

\[ \# \text{ of packets in } [t_0, t_0 + \delta t] \]

**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