# The Changing Nature of Network Traffic: Scaling Phenomena


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## *Outline*

- **Background**
- **Self-Similarity and Wavelets**

  Wavelet-based scaling analysis

  Example: FGN
- **Scaling Phenomena**

  Packet-level WAN traces

  WAN traffic at the transport layer (TCP connections)
- **Implications for Structural Modeling Approaches**

  Cox's and Kurtz's construction

  Multifractals

## *Some Background*

- **LAN Environments and Self-similarity**
  - Aggregate LAN traffic is consistent with *exact self-similarity*
  - Re-examine traffic characteristics at the level of individual source-destination pairs: *Heavy-tailed* ON/OFF periods
  - Standard reference: *Leland, Taqqu, Willinger, Wilson, 1994*
- **WAN Environments and Self-Similarity**
  - Aggregate WAN traffic is consistent with *asymptotic self-similarity* or *long-range dependence*
  - Re-examine traffic characteristics at application layer: *Heavy-tailed* session sizes and/or durations
  - Standard reference: *Paxson and Floyd, 1995*

## *Some Background (cont.)*

- **Re: Traffic Measurements**
  - Properties: High-quality, high-volume, diversity
  - Challenges: Constantly changing networking environments
  - New developments: Switched Ethernet, Gigabit Ethernet, IPv6, ATM
- **Statistical Inference Techniques**
  - Properties: Trade-offs between speed, accuracy and size of data set
  - Challenges: Scientific inference vs. statistical inference
  - New development: Wavelet-based methods

## *Wavelet-Based Scaling Analysis*

- **Wavelets**
  - Tool for time-frequency localization
  - Wavelet transform divides a signal into different frequency components
  - Each frequency component is analyzed at a resolution matched to its scale
  - Use the coefficients of a wavelet decomposition to directly study scale- or frequency-dependent properties of the signal

## *Wavelet-Based Scaling Analysis (cont.)*

- **Wavelet decomposition of a signal $X$**

$$X = \sum_{j \in \mathbf{Z}} \sum_{k \in \mathbf{Z}} \langle X, \psi_{j,k} \rangle \psi_{j,k} = \sum_{j \in \mathbf{Z}} \sum_{k \in \mathbf{Z}} d_{j,k} \psi_{j,k}$$

where

$$\psi_{j,k}(t) = 2^{-j/2} \psi(2^{-j} t - k)$$

are rescaled and translated copies of the wavelet $\psi$.

$d_{j,k} = \langle X, \psi_{j,k} \rangle,\ k \in \mathbf{Z}$ are called the wavelet coefficients of $X$ for scale $j$

## *Wavelet-Based Scaling Analysis (cont.)*

- **Scaling Analysis**
  - Use wavelet coefficients of signal to investigate scale or frequency dependent properties of the signal
  - $|d_{j,k}|^2$ measures amount of energy in the signal about time $2^j k$ and frequency $2^{-j}\lambda_0$
  - $E_j = \frac{1}{N_j}\sum_k |d_{j,k}|^2$ measures energy in $X$ that lies within bandwidth $2^{-j}$ about a frequency $2^{-j}\lambda_0$.

## *Wavelet-Based Scaling Analysis (cont.)*

- **Self-Similarity and Wavelets**
  - A covariance-stationary process $X$ is *(asymptotically) second-order self-similar* if and only if $X$ exhibits *long-range dependence*
  - If $X$ is long-range dependent process, Hurst parameter $H \in (1/2, 1)$, then its spectral density is given by

$$f(\lambda) \sim c_f |\lambda|^{1-2h} \quad , \text{as } \lambda \to 0$$

## *Wavelet-Based Scaling Analysis (cont.)*

- **Self-Similarity and Wavelets (cont.)**
  - If $X$ is long-range dependent with $H \in (1/2, 1)$, then for each scale $j$, the energy $E_j$ of $X$ satisfies

$$\mathbf{E}[E_j] = c_f |2^{-j}\lambda_0|^{1-2H} \int |\lambda|^{1-2H} |\hat{\psi}(\lambda)|^2 \, d\lambda,$$

that is,

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

## *Wavelet-Based Scaling Analysis (cont.)*

- **Scaling Heuristics**
  - Compute $\log_2 E_j = \log_2(\frac{1}{N_j} \sum_k |d_{j,k}|^2)$
  - Plot $\log_2 E_j$ versus scale $j$
  - Identify scaling regions, breakpoints, and "non-scaling" behavior
  - Beware of non-stationarity effect (via vanishing moments)
- **Example: FGN as Reference Point**
  - Fractional Gaussian Noise (FGN) is exactly self-similar
  - Same non-trivial scaling for all scales
  - By-product: Hurst parameter estimation technique (Abry and Veitch, 1997)

## *Scaling Phenomena – Packet-Level*

- **Packet-Level Data**
  - 5 hour-long packet-level traces
  - From 4 different locations
  - WAN traces from 1990, 1994, 1997
  - Traces cover "interesting" times ...
  - Emergence of WWW as "killer application" on the Internet
  - Time series: Number of packets/bytes per 10 milliseconds

## *Scaling Phenomena – Packet-Level (cont.)*

- **Results of Scaling Analysis**
  - Pre-Web: Scaling for all scales
  - Today: Large-time *and* small-time scaling regions
  - Question 1: Why large-time scaling?
  - Question 2: Why small-time scaling?
  - Question 3: Why are they different?

## *Scaling Phenomena – Packet-Level (cont.)*

- **Structural Modeling of WAN Traffic I**
  - Explain packet-level via application-layer characteristics
  - $M/G/\infty$ model (immigration birth process; Cox, 1984)
  - Poisson arrivals, heavy-tailed holding times, constant rate during connection
  - Large-time scaling via high variability
  - Limitations: Source-centered view, inflexible

## *Scaling Phenomena – Packet-Level (cont.)*

- **Empirical Validation of Cox's construction**
  - Pre-Web WANs: TELNET-, FTP-sessions (Paxson and Floyd, 1995)
  - Today's WANs: What about WWW-session characteristics?
- **Statistical Characteristics of WWW-sessions**
  - Obtain WWW-session information via modem call records
  - Arrivals: Consistent with (non-homogeneous) Poisson
  - Session sizes/durations: Consistent with heavy tails with infinite variance

## *Scaling Phenomena – TCP Connection-Level*

- **Connection-Level Data**
  - 5 hour-long connection-level traces
  - 4 different locations
  - Traces from 1993, 1995, 1997
  - Increasing portion of TCP connections have become WWW-related
  - Time series: Number of TCP connection arrivals per second

## *Scaling Phenomena – TCP Connection-Level (cont.)*

- **Results of Scaling Analysis**
  - Pre-Web (TELNET and FTP control): trivial scaling
  - Pre-Web (everything): appearance of large-time scaling
  - Today (HTTP-related): self-similarity (Feldmann, 1995)
- **Explaining TCP Connection-level Self-Similarity**
  - Session sizes (in terms of number of TCP connections per session) are heavy-tailed with infinite variance
  - TCP connection arrivals within sessions: ???

## *Scaling Phenomena – TCP Connection-Level (cont.)*

- **Structural Modeling of WAN Traffic II**
  - Inadequacy of Cox's construction: Small-time scaling, TCP scaling
  - Kurtz's construction (Kurtz, 1996): $M/G/\infty$-type model
  - Poisson arrivals; heavy-tailed holding times; allows for very flexible "within-session" structure
  - Large-time scaling via high variability
  - Limitations: Currently known limiting regimes do not account for observed small-time scaling phenomenon

## *Implications for Structural Modeling*

- **Large-Time scaling**
  - Robust under the observed changes
  - Well understood (constructions of Cox, Kurtz)
  - Well-known application-level characteristics
  - Infinite variance phenomenon, heavy-tailed distributions
  - Paxson and Floyd, 1995; Crovella and Bestavros, 1996
  - Expected to be present in future WAN traffic
  - But be aware of: Internet Pricing schemes, new protocols

## Implications for Structural Modeling (cont.)

- **Small-Time Scaling**
  - Cox's construction: inadequate; inflexible
  - Kurtz's construction: has potential; flexibility
  - Multifractals (Evertsz and Mandelbrot, 1992)

    Recent empirical evidence: Riedi and Levy-Vehel, 1997

    Structural modeling: via random cascades

    Cascade models: impact of the network on the traffic

    Connection to Kurtz's construction

# Conclusions

- **"Operational" view of self-similarity**
  - Has been main focus in the past
  - Self-similarity as mathematical property
  - Self-similar processes as "black boxes"
  - "Black boxes" as network traffic models
- **"Phenomenological" view of self-similarity**
  - Self-similarity: Result of a construction
  - Construction: Result of a physical understanding of self-similarity in the network setting (subject matter expertise is crucial)
  - "Physically-based" network traffic models