

Scaling in Computer Network Traffic

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Report Documentation Page

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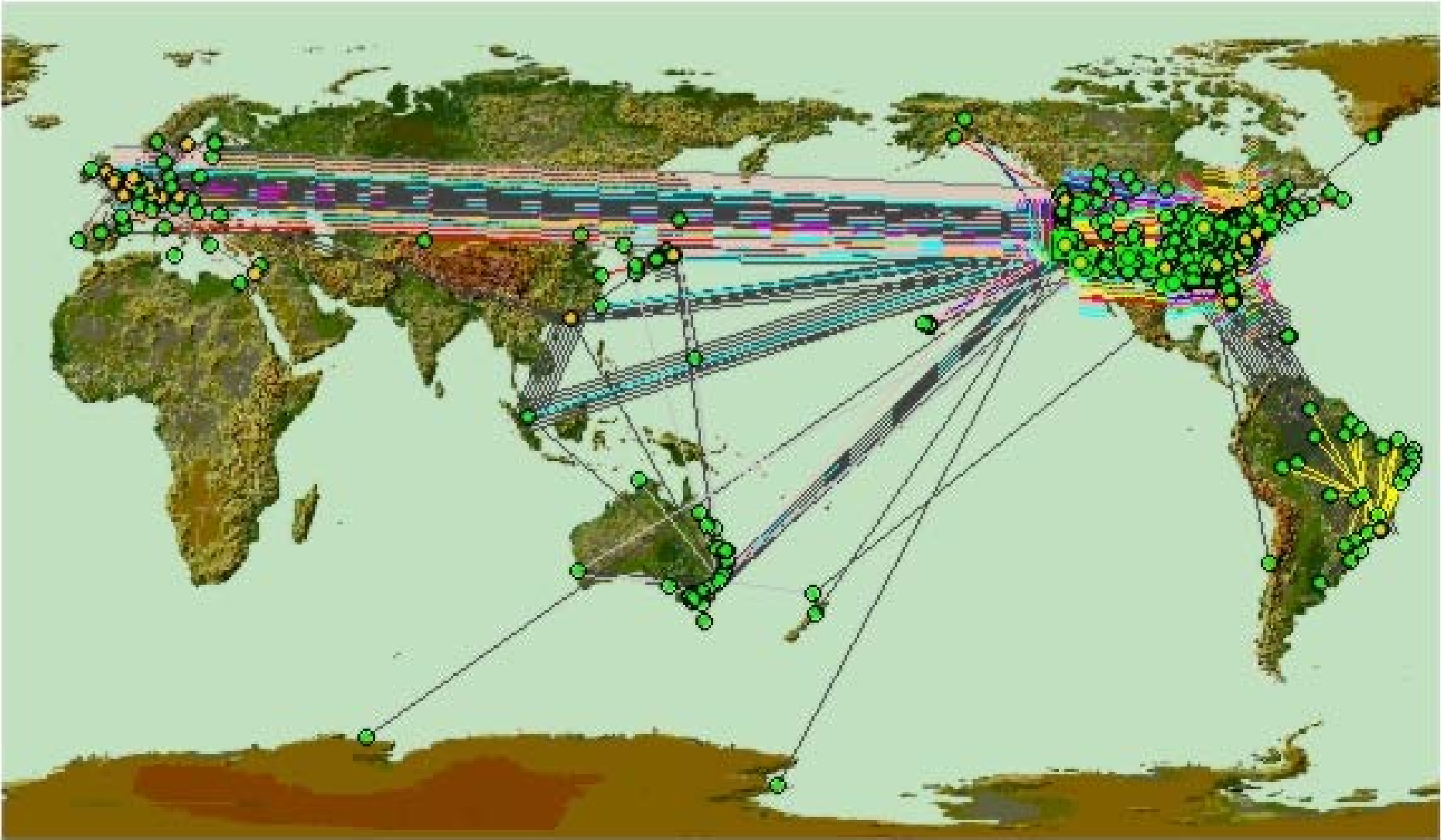
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Networks ...



Networks ... Connect



Telecommunications Networks, Traffic, & Engineering

Networks: A Deep Hierarchy of Systems

Tele-Traffic: A Turbulent River of Myriad Data Sources

Engineering: Traffic over a Network: Designing, Managing, Optimising

Networks: A Deep Hierarchy of Systems

- Connectivity (node organisation, placement, topology).
- Physical layer technology (devices, timing, coding, error recovery..).
- Circuit vs **Packet Switched** Paradigms.
- Connection-oriented vs connectionless philosophy.
- Protocol hierarchy and encapsulation, eg: Ethernet [IP [**TCP**[HTTP]]].
- Operation (routing, signaling, admission control, congestion control).
- **Inter-Net**working (Autonomous systems, domain routing, addressing, gateways, protocol translation).

Tele-Traffic: A Turbulent River of Myriad Data Sources

- 'Geographic' Complexity

- At network edge (distribution of sources, destinations, nodes)
- Internally (multiplexing and de-multiplexing of streams)

- Offered Traffic Complexity

- User 'sessions' (durations, arrivals, number of clicks..)
- Applications used (browser, napster..)
- Underlying protocols (TCP, HTTP..)
- Underlying data objects (files, video, audio..)
- Shaping by network elements

- Temporal Complexity:

- Human driven (diurnal, coffee breaks, think times..)
- Source driven (real-time constraints, file sizes..)
- Network driven (topology, protocols..)
- Technology driven (link rates, switching rates)

→ **Time scale rich:** ns to months, 1kbps to Terabits/s

→ **Burstiness:** temporal (scaling), amplitude (non-G), spatial (capacity diversity)

TeleTraffic Engineering: the traditional program

- Collect traffic measurements and measure characteristics
 - Select traffic model
 - Solve switch performance problems
 - Solve network performance problems
 - Design network to given quality of service at minimal cost
 - Solve admission control problems
 - Run network
 - Solve congestion control and routing problems
 - Improve network performance
- ← Iterate until paradigm shift

This 'scientific method' approach begins with measurements...

Papers between 1966 and 1987 (P. F. Pawlita, ITC-12, Italy)

- Queueing theory: several thousand
- Traffic measurement: around 50.

Tele-Traffic Today

Measurement Practice

- Recognition of measurement, not just routine quantification, but **discovery**.
- Widespread monitoring of LAN's, ISP networks, national infrastructures.....
- Large scale programs for Internet, from routine monitoring to ultra high resolution.
- Emergence of numerous small & large scale **active** probing efforts.
- Huge advances in measurement accuracy.

Renaissance in Modelling

- Return of science 101: **Observation** and **inspiration** before model.
- Return of verification: Evaluating usefulness against real data.
- New model paradigm as standard: Characteristic scale → **scale invariance**.
- New model classes: Source, link, network, and **closed loop**.
- New problems: **Active**, **multi-route**, and **high resolution** measurements.

Stimulus to Theory

- Statistical estimation: For time series with infinite moments and/or scaling.
- Queueing Theory: Dealing with sub-exponential (eg LRD) input processes.
- Applied Probability: Convergence results for stochastic processes.
- Algorithms: On and Off-line synthesis methods for very long time series.
- Analysis: Network feedback, and properties of new models.

Measurement Practice

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- Large scale programs, from routine monitoring to ultra high resolution.
- Emergence of numerous small & large scale **active** probing efforts.
- Huge advances in measurement accuracy.
- Router based measurements widely used.

Renaissance in Modelling

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Stimulus to Theory

- Statistical estimation: For time series with infinite moments and/or scaling.
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- Applied Probability: Convergence results for stochastic processes.
- Algorithms: On & Off-line synthesis/analysis for long time series.
- Analysis: Properties of new models, especially mixed open and closed loop.

Passive and Active Measurement

Typical Passive Aims

- “At-a-point” or “Network core”.
- Backbone link utilisation, Link traffic patterns, Server workloads.
- Long term monitoring: Dimensioning, Capacity Planning, Source modelling.
- Engineering view: **Network performance**.

Typical Active Aims

- “End-to-End” or “Network edge”.
- End-to-End Loss, Delay, Connectivity, “Discovery” and “Tomography”.
- Long and short term monitoring, “Network health” and “Route state”.
- Internet view: **Application performance and robustness**.

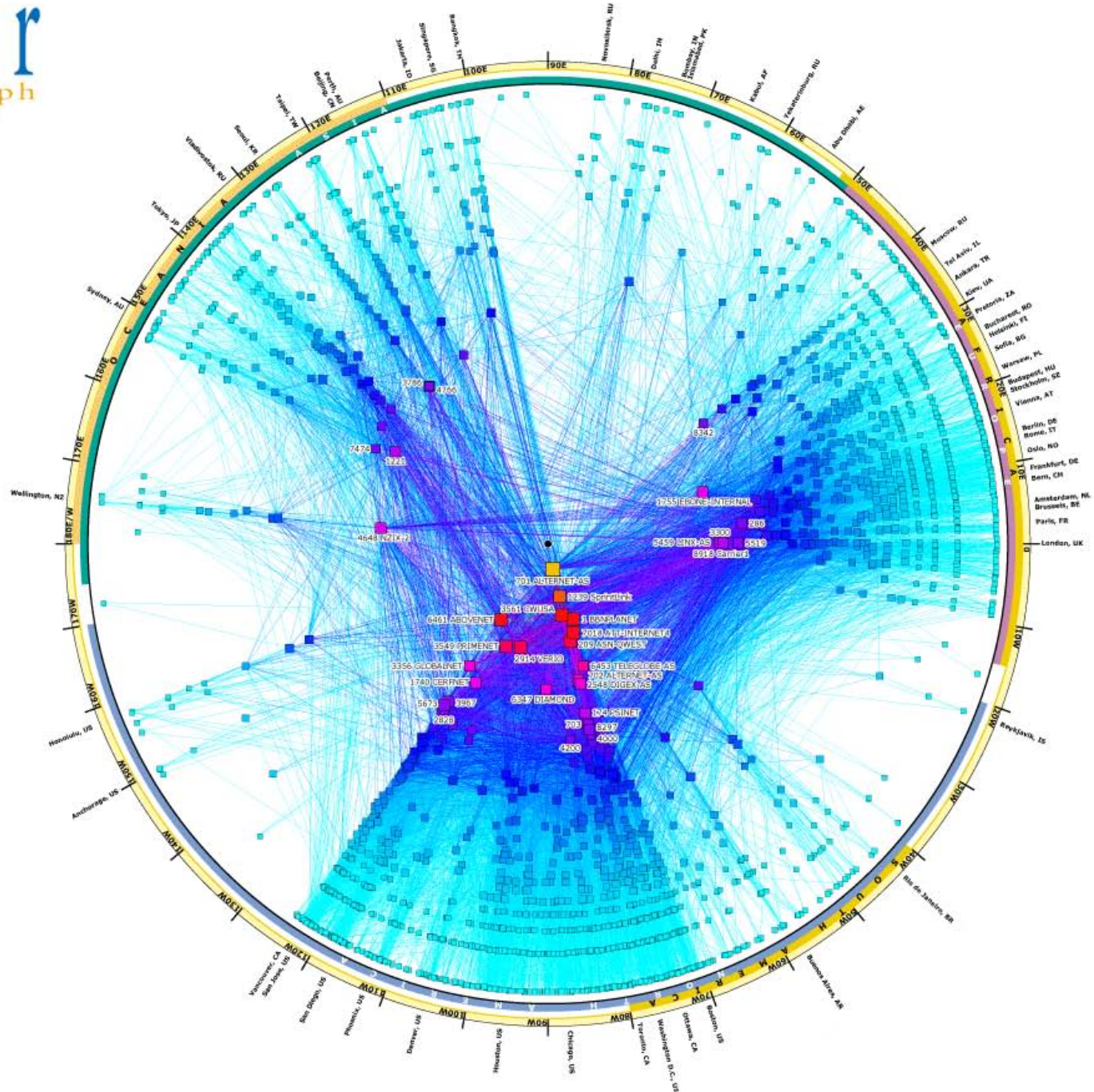
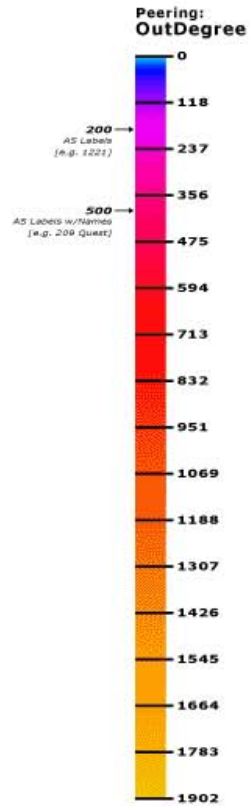
Major Measurement Programs

Passive Active Tools

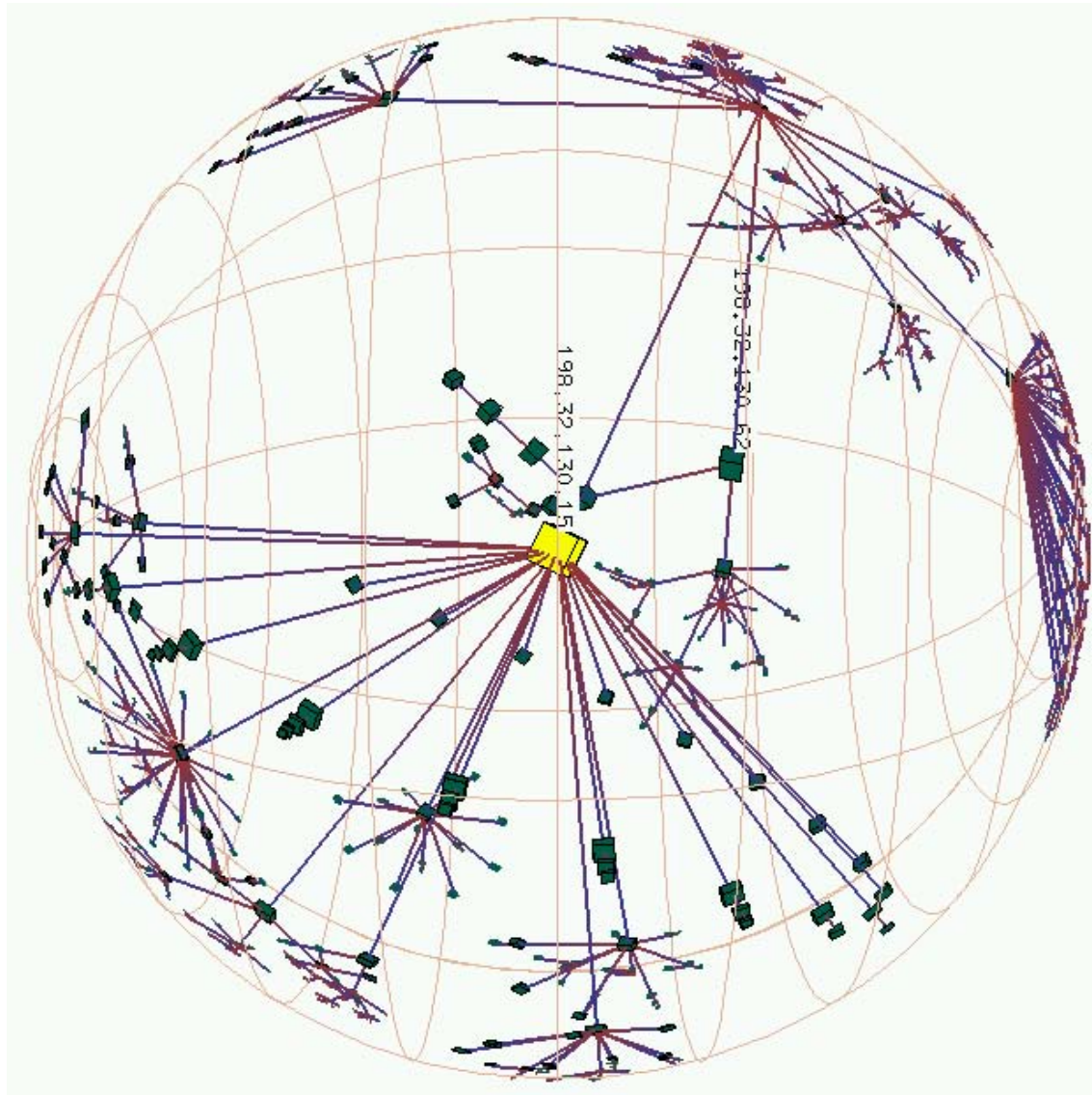
- ♡ NLANR (National Laboratory for Applied Network Research).
- ♠ CAIDA (Cooperative Association for Internet Data Analysis).
- ♡ ♠ WAND (Waikato Applied Network Dynamics [DAG cards]).
- ♡ PingER (Ping End-to-end Reporting).
- ♡ Surveyor (From Advanced Networks and Services).
- ♡ ♠ RIPE–NCC (Network Coordination Centre).
- ♠ NIMI (National Internet Measurement Infrastructure).
- ♡ ♠ AT&T NetScope.
- ♠ Cicso Netflow.
- ♠ NetraMet.

skitter

AS internet graph



Tracing Network Nodes

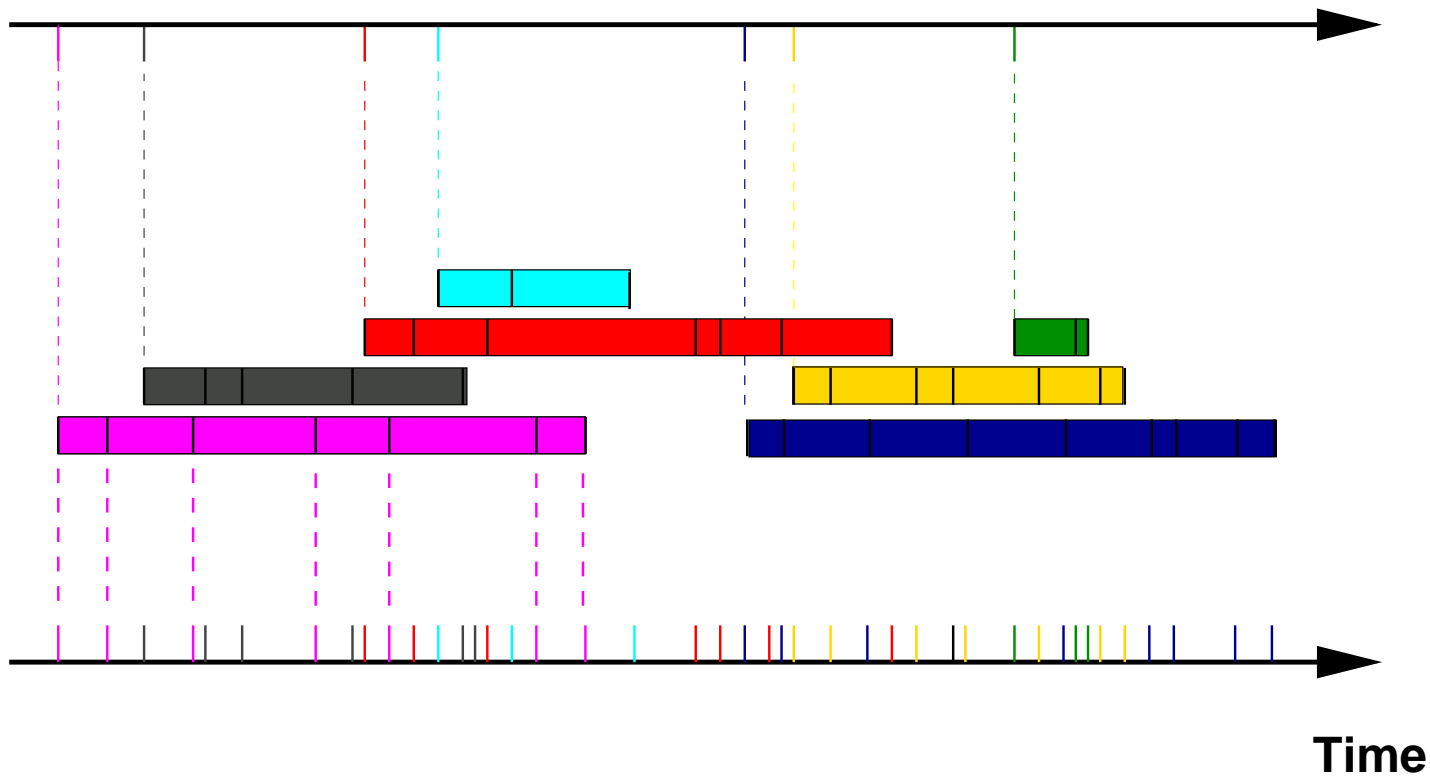


Reproduced with permission of CAIDA, © 2001 CAIDA/UC Regents. Mapnet Author: Bradley Huffaker.

Flows and Packets

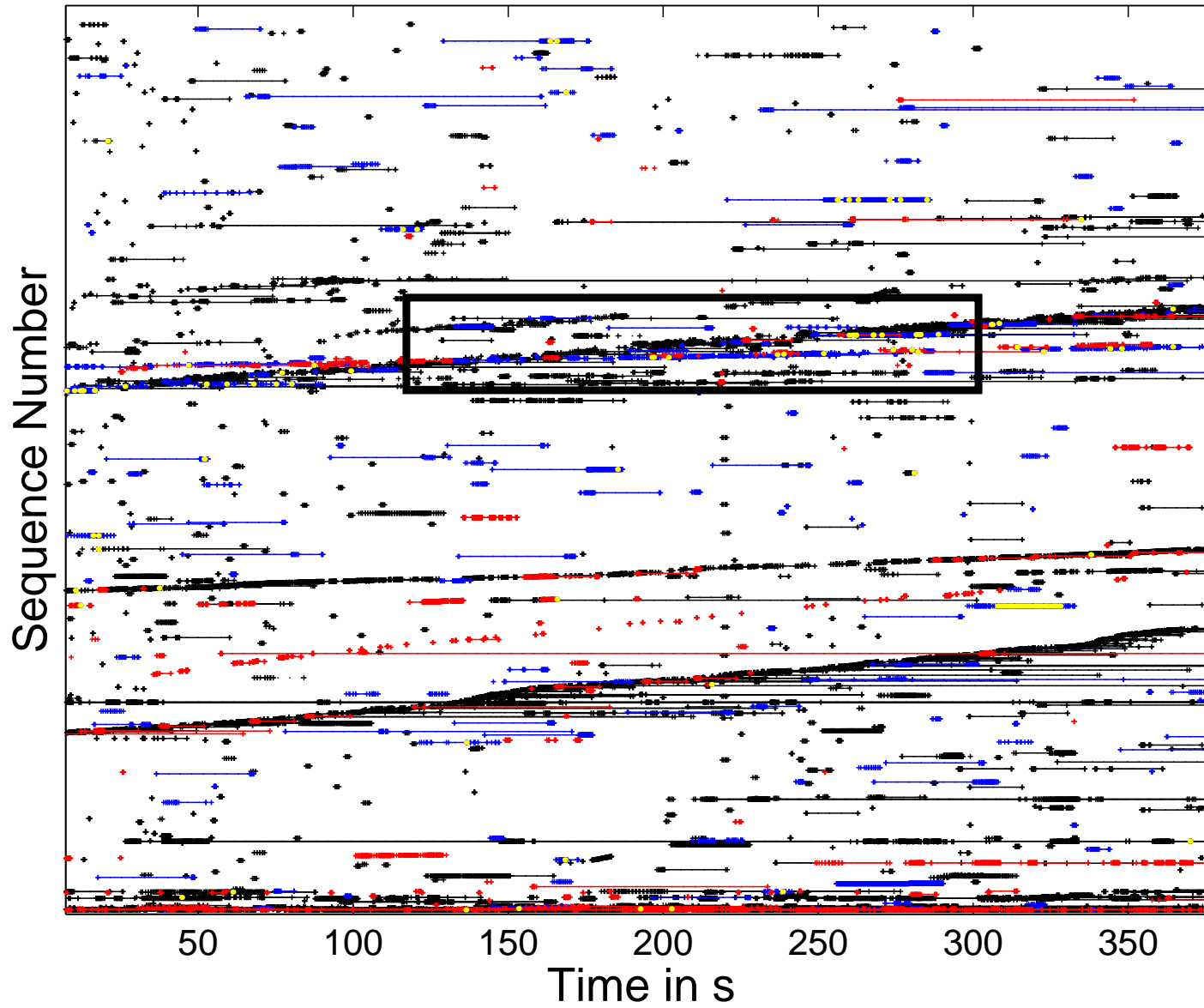
Flows are sets of packets associated to the same data transfer.

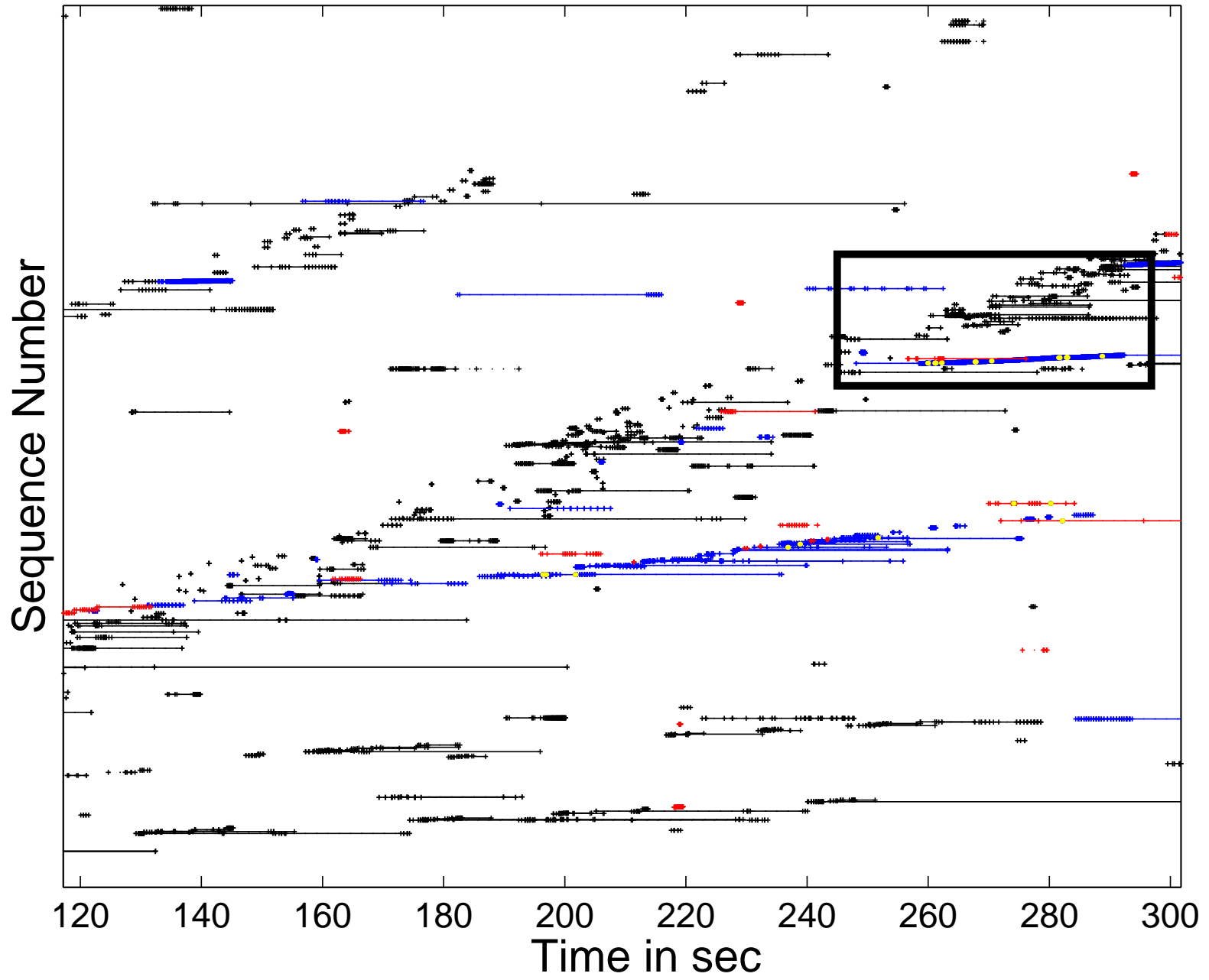
Flow arrivals: $Y(t)$

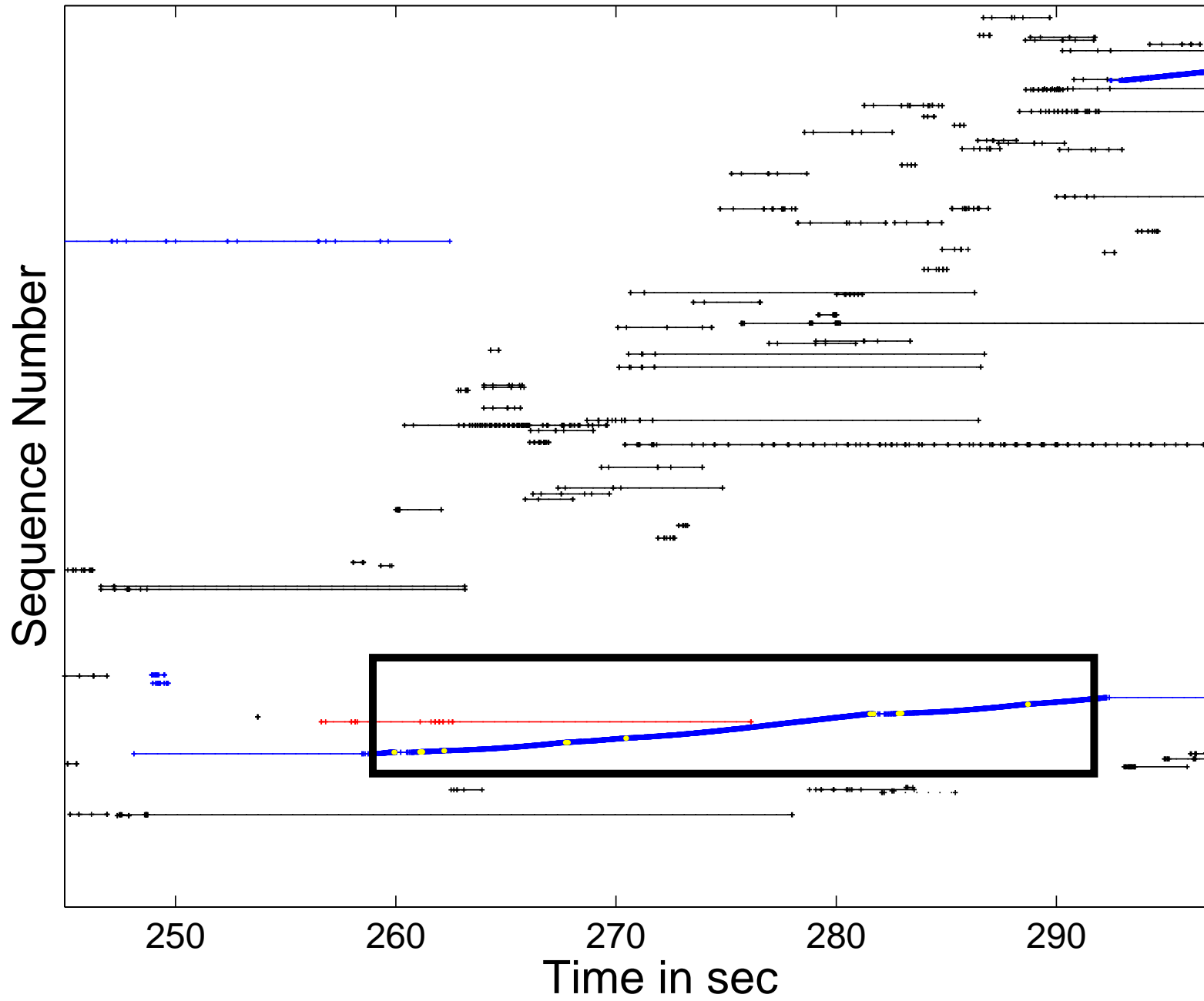


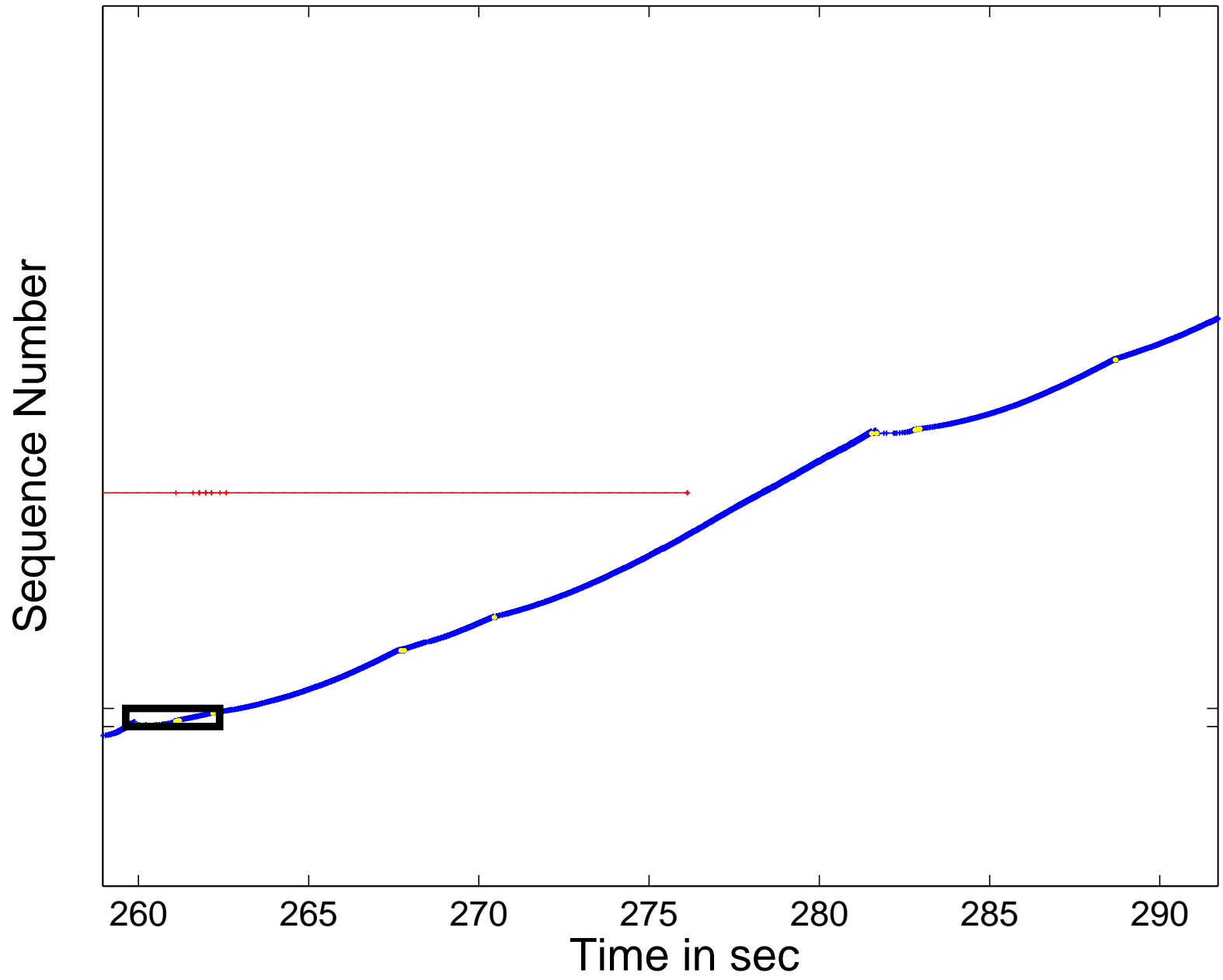
Packet arrivals: $X(t)$

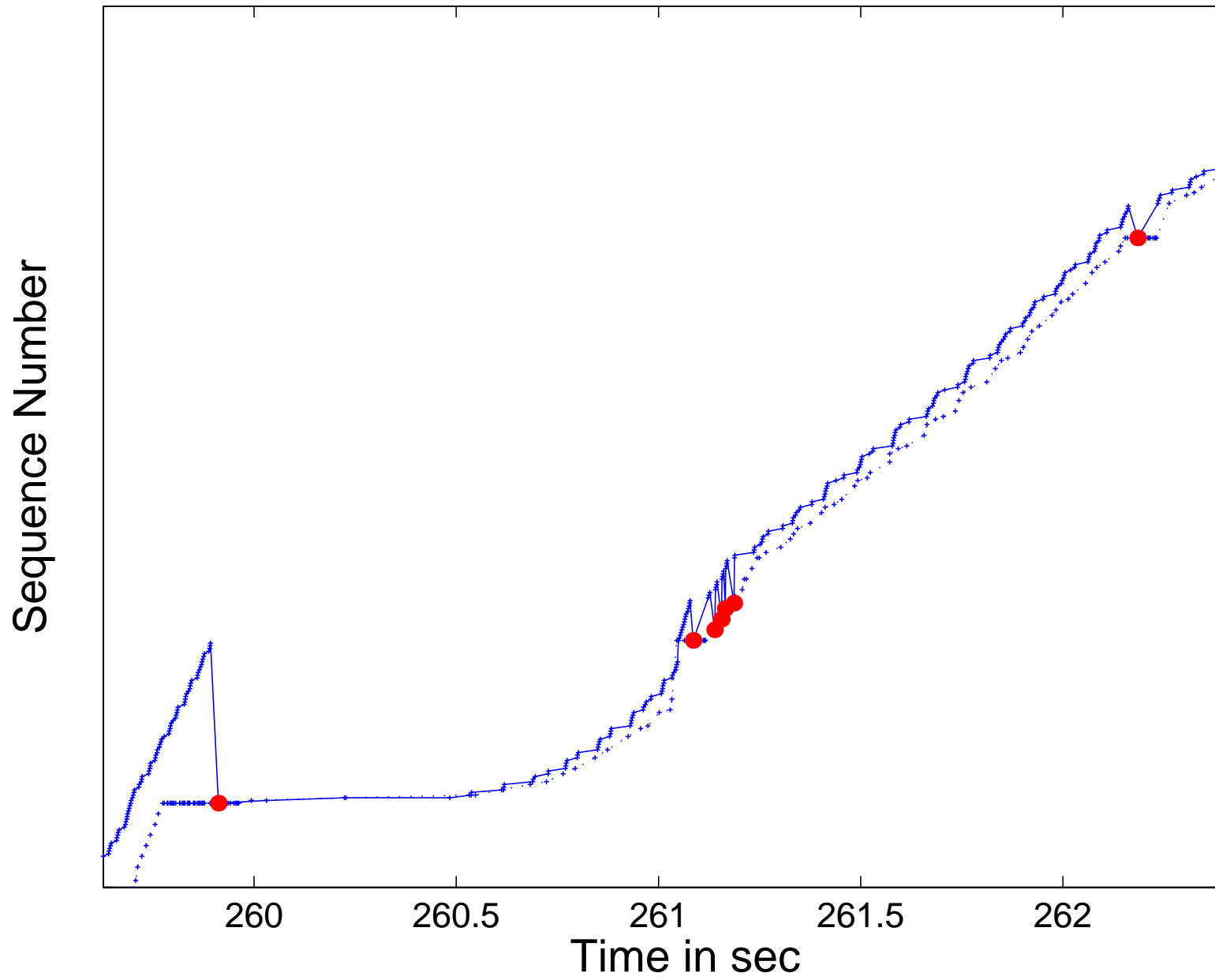
Zooming on a Single Link









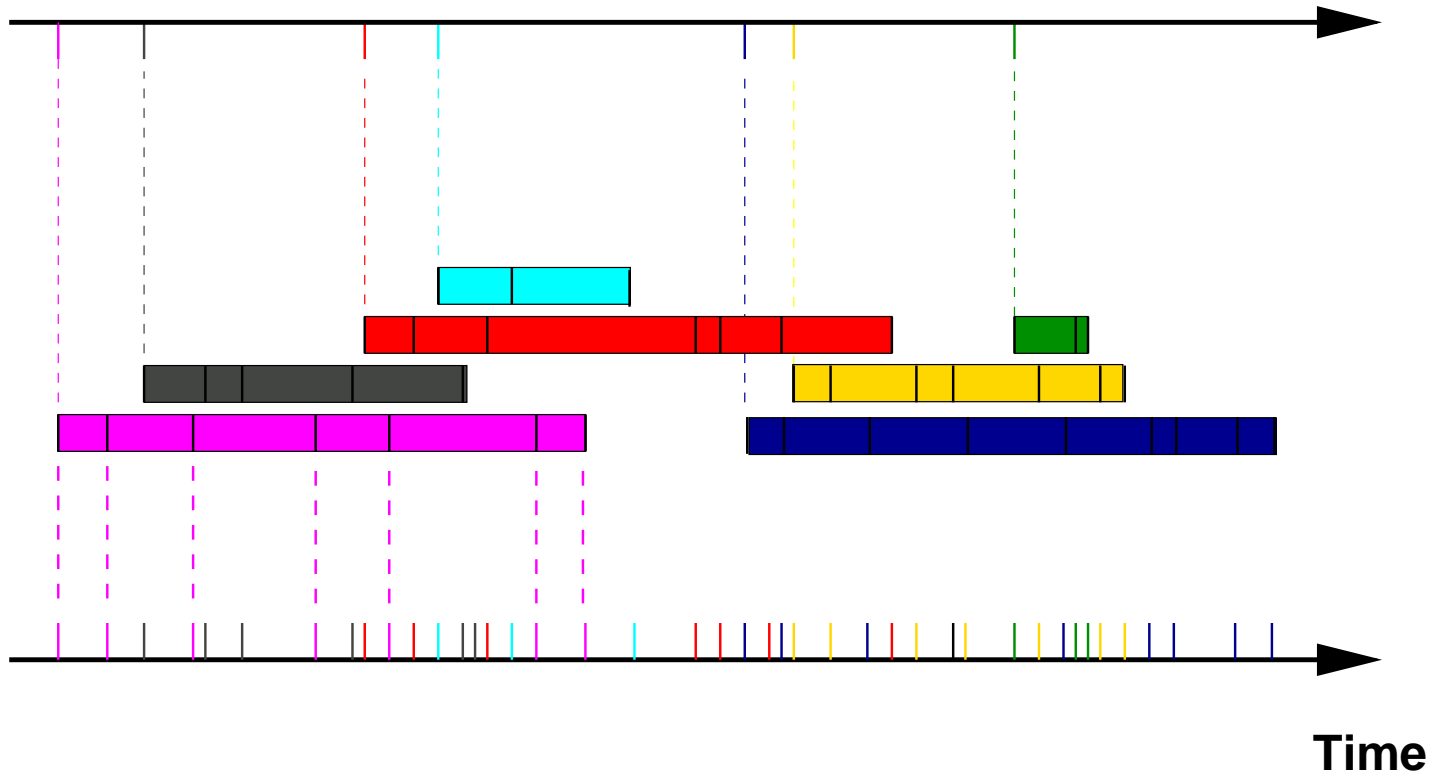


What are we Measuring?

- *Internet Protocol* (IP) packets, the unit of transport across networks.
- Data split into packets, with: **header**, **payload**.
- Payload carries higher layer protocols: **TCP, UDP, ICMP**.
- Protocols support services & applications, more protocols:
 - **TCP**: HTTP, FTP, SNMP, ... (for reliable data)
 - **UDP**: VoIP, DNS, NTP,... (for real time)
- For each packet:
 - Could filter based on criteria (address, type, size, ...)
 - Could capture all or part (e.g. just the header).
 - Must **timestamp**.
- Key concept, a **flow** (collection) of packets.

Two Point Processes from Traffic

Flow arrivals: $Y(t)$



Packet arrivals: $X(t)$

Most common time series extracted are **packets or bytes per bin**

Prelude to a Paradigm

Seeing Packet Traffic

- 1991: ISDN (Hellstern, Wirth, Yan, Hoeflin) – infinite moments.
- 1991: Ethernet (Leyland, Wilson) – bursts at all time scales.
- 1993: Ethernet (Erramilli, Willinger) – fractal properties.

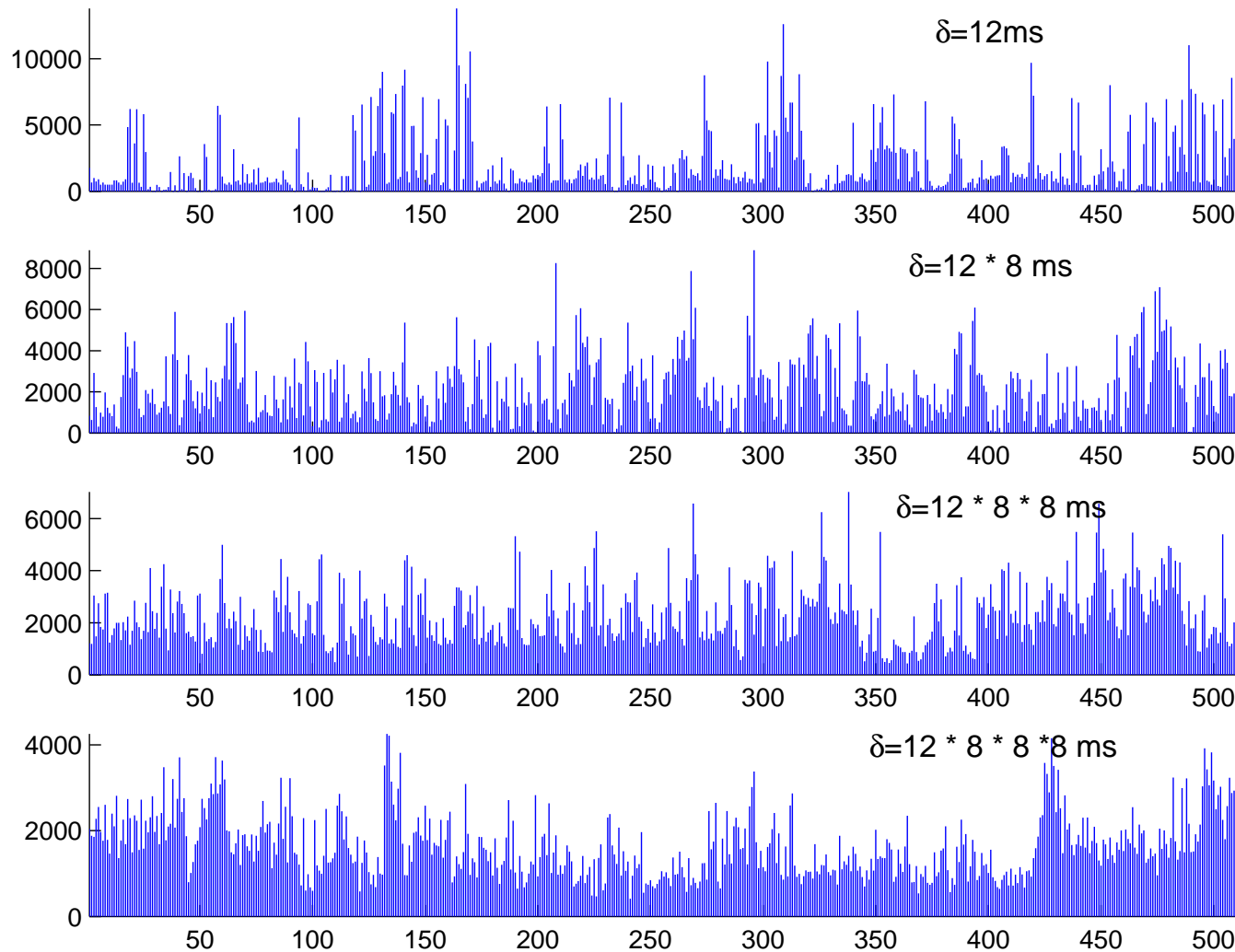
The Arrival of Fractal Traffic

Believing Packet Traffic

- 1993: Ethernet (Leyland, Taqqu, Willinger, Wilson) – **Self-Similar Traffic.**
- 1994: CCSN/SS7 (Duffy, McIntosh, Rosenstein, Willinger) – **Self-Similar.**
- 1994: Internet (Paxson, Floyd) – **Failure of Poisson modelling.**
- 1994 → ... LAN's across the world see – **Self-Similarity.**
- 1994: Web docs (Cunha, Bestavros, Crovella) – **Heavy tailed file sizes.**
- 1995: Video (Beran, Sherman, Taqqu, Willinger) – **roughly Self-Similar.**

The Self-Similarity of Ethernet Traffic

The reference Bellcore trace, 'pAug', is close to *Fractional Gaussian Noise*.



Measuring the Exponent using Wavelets

Wavelet coefficients of our traffic process:

$$d_X(j, k) = \langle X, \psi_{j,k} \rangle.$$

Spectral definition of LRD is

$$\Gamma_X(\nu) \sim c_f |\nu|^{-\alpha}, \quad |\nu| \rightarrow 0, \quad \text{with } \alpha \in (0, 1).$$

In this case, provided $N \geq 1$ vanishing moments:

$$\mathbf{E}|d_X(j, k)|^2 \sim c_f C(\alpha) 2^{\alpha j}, \quad j \rightarrow +\infty$$

Estimating the LHS from data using

$$S_2(j) = \frac{1}{n_j} \sum_k |d_X(j, k)|^2,$$

where n_j is the number of $d_X(j, k)$ available at octave j (scale $a = 2^j$),

We use ‘*Logscale Diagram*’ to refer to the log-log plot:

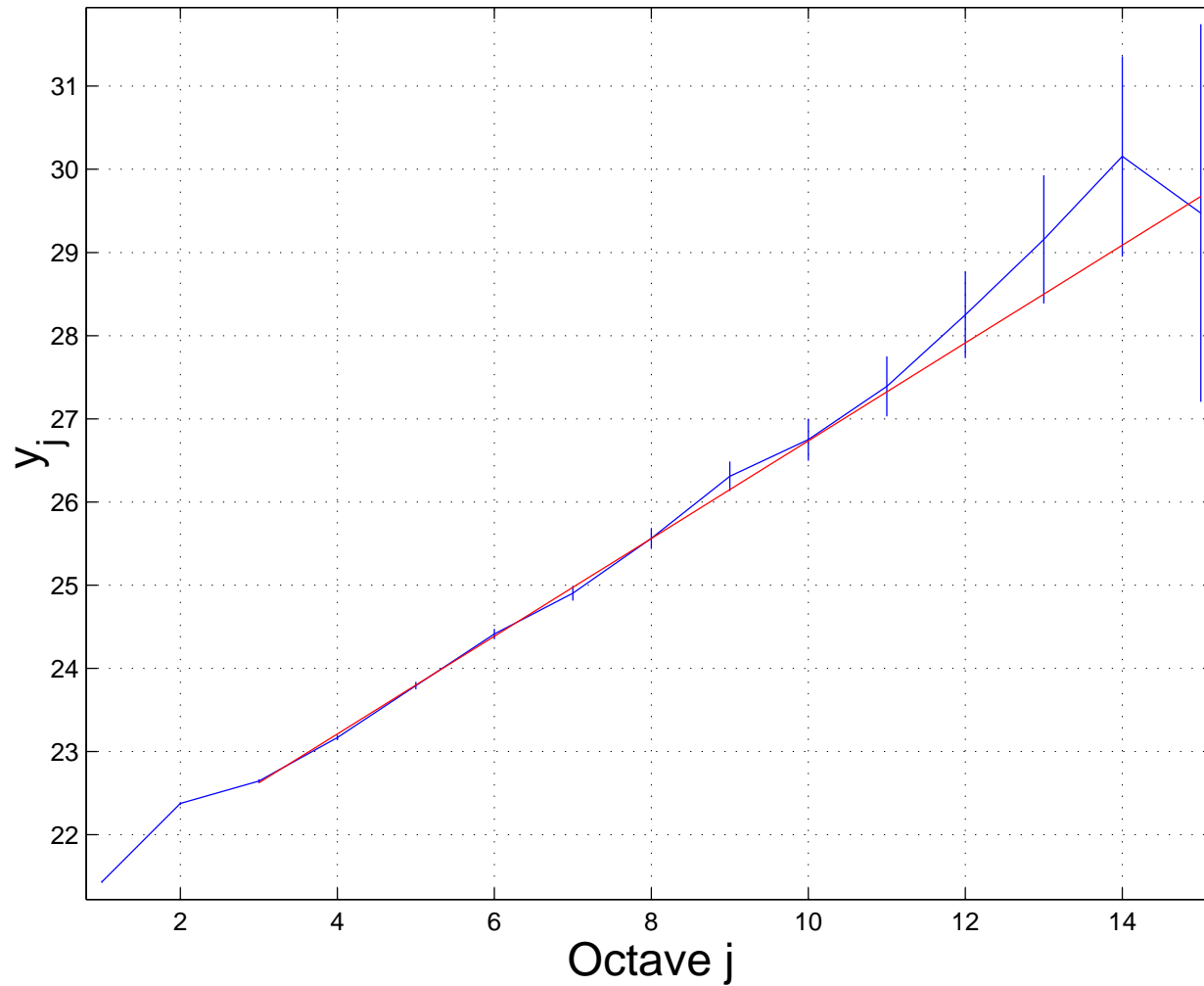
$$\text{LD : } \log_2 S_2(j) \text{ vs } j,$$

in which straight lines are evidence for scaling, **slope** = α .

Analysis of Trace 'pAug'

ETHERNET: bytes per 12ms bin.

Logscale Diagram, $N=2$ $[(j_1, j_2) = (3, 15), \alpha\text{-est} = 0.59, Q = 0.011384], D\text{-init}$



An Old Story for Science and Nature

What does it mean?

- **No** characteristic time-scale controlling the dynamics / statistics.
- **Statistically**, All scales (in a range) are **equivalent**, under a renormalisation.
- Radical **temporal burstiness**: no natural burst scale.
- Key parameters no longer special scales, but relations **across** scales.
- Absolute quantities → scale dependent quantities.
- Affects **system description, behaviour, measurement**

The Self-Similar Traffic Model

Fractional Gaussian Noise (fGn) and Fractional Brownian Motion (fBm)

The unique Gaussian processes which are

$$\text{Stationary; Cov } [X_H](k) = \frac{1}{2} \left[(k-1)^{2H} + 2k^{2H} + (k+1)^{2H} \right]$$

$$\text{Stationary Increments; Var } [Z_H(k)] = k^{2H}$$

Corresponding traffic models:

$$\text{Rate: } R(t) = \mu + \sigma X_H(t)$$

$$\text{Total Traffic: } W(t) = \mu t + \sigma Z_H(t)$$

$$\text{where } Z_H(t) = \sum_{i=1}^t X_H(i), \quad W(t) = \sum_{i=1}^t R(i).$$

The Long-Range Dependent (LRD) Traffic Models

LRD definition: a slowly decaying covariance

$$\Gamma_X(k) \sim c_r k^{-\beta}, \quad 0 < \beta < 1,$$

where $(\beta = 2 - 2H)$.

Corresponding traffic rate model:

$$R(t) = \mu + \sigma X_{\beta, c_r, k^*}(t).$$

LRD more general than H-SS:

- **Second order** description only, not necessarily Gaussian!
- Has been called **second order asymptotically self-similar** (but careful!)
- Heavy tail **'begins'** only after some cutoff scale k^* .
- Tail may be **'thin'**, low mass (small c_r), independent of variance!
- Small scale structure **unspecified**.
- At a minimum, **three** correlation parameters, not just H .

Non-Gaussian LRD – the On/Off Source

- Alternating renewal process: $\{A_i\}$ i.i.d. $\{B_i\}$ i.i.d.
- LRD if A or B heavy tailed:
 - If $\Pr(B > x) \sim c x^{-\alpha}$, $\beta_{\text{LRD}} = 3 - \alpha$, $c_r = \frac{c(1-\lambda)^3}{(\alpha-1)\mathbf{E}[A]}$.
 - Efficient generation ($O(1)$ computation and state)

Corresponding traffic rate models:

- as active/silence sources.
- as building blocks for a compound source, eg.
 - $N \uparrow$, $p = \Pr(\text{On}) \rightarrow 0$, $\lambda = \text{const}$, $h = \text{const}$: \rightarrow M/G/ ∞
 - $N \uparrow$, $p = \text{const}$, $\lambda = \text{const}$, $h \rightarrow 0$: \rightarrow fGn

Impacts on Traffic Modelling

Statistics

- Difficult estimation of almost everything.
- Difficult model choice: Non-stationarity confusions and others.
- Large confidence intervals (need more data).
- Wavelets can help kill LRD, mitigate NS, in many cases. Complexity only $O(n)$ and can be done on-line.

Queueing

- Larger buffer sizes, lower utilisation at given QoS.
- ‘Buffer insensitivity’ (bigger won’t help much).
- Impact depends a lot on the **amplitude burstiness**:
 - fBm storage (Norros) – Weibullian tail.
 - large peak On/Off superpositions – Regularly varying tails, infinite mean (Cohen; Boxma; Whitt).
- Service discipline is important – can reinstate finite mean (Boxma et al.)
- Critical time scales can exist, but value depends on full structure.

Lessons for Network Performance

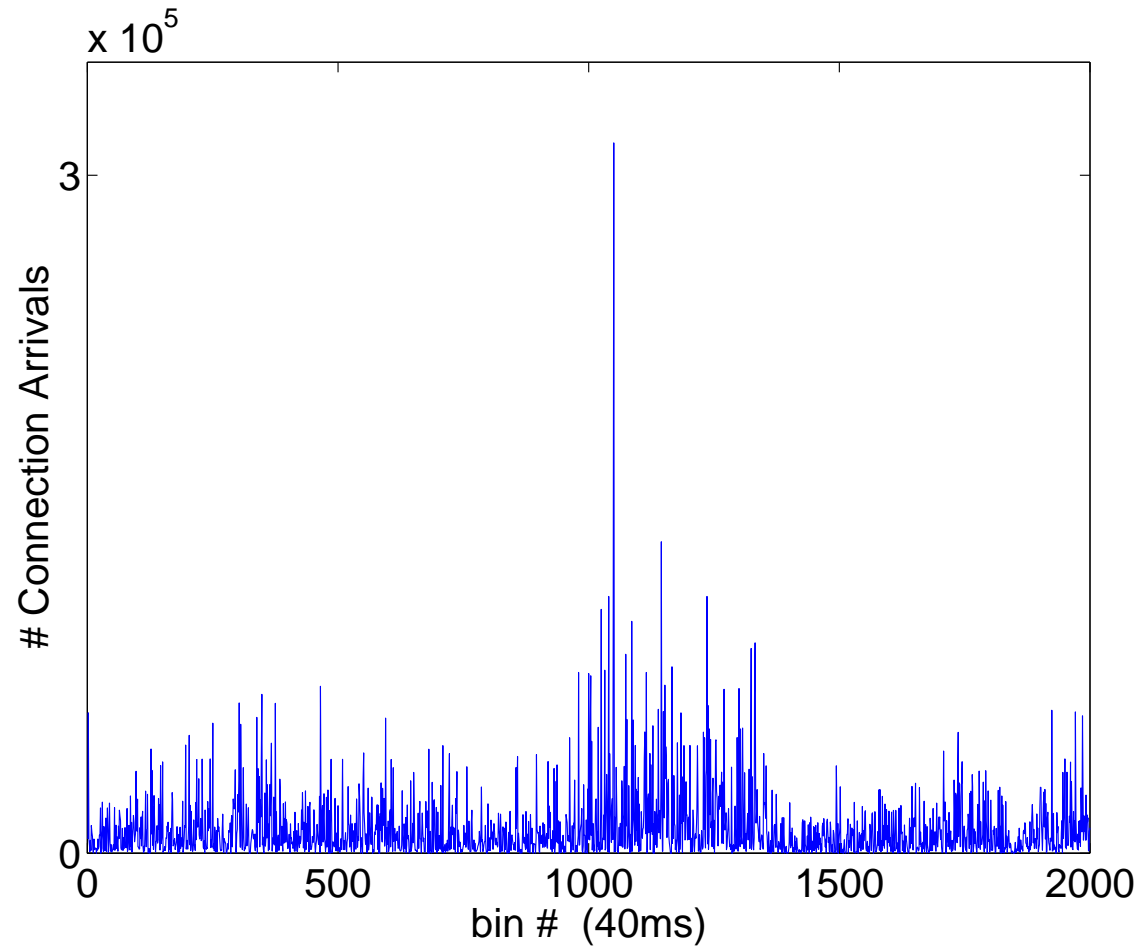
- Heavy tails can be thinned, but not cut off.
- Smoothing the beast will not tame it.
- **Statistical Multiplexing** works as ever – recommended.
- Processor Sharing helps the individual, but not the society.
- Hi Peak rates can kill.
- Power-laws are very persistent, if you can't kill it:
 - Make sure it is irrelevant, or
 - Make it work for you, or
 - Understand it, calm it down, then live with it.
- LRD not everything, obviously: *variance, marginal.*

BUT: Internet, TCP, Small Scales, and Non-Gaussianity

The 'Self-Similarity' model has limits

- Only really asymptotic: true for 'large scales', $\approx > 1$ second.
- Really requires Gaussianity – often far from the case!
- Range of scales where valid may not be crucial for engineering purposes.
- At small scales, feedback **can** mold the beast.

High Amplitude Burstiness at Small Scale



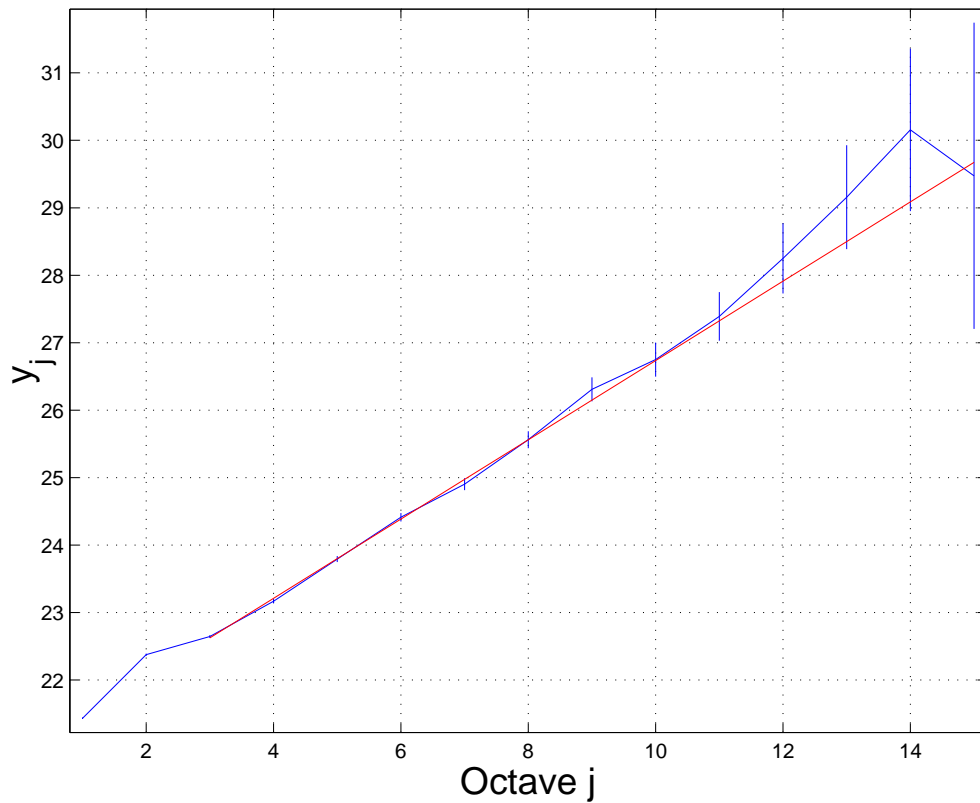
So small scales are much harder ...

Examples of Scaling in Traffic: 2nd Order Wavelet Analysis

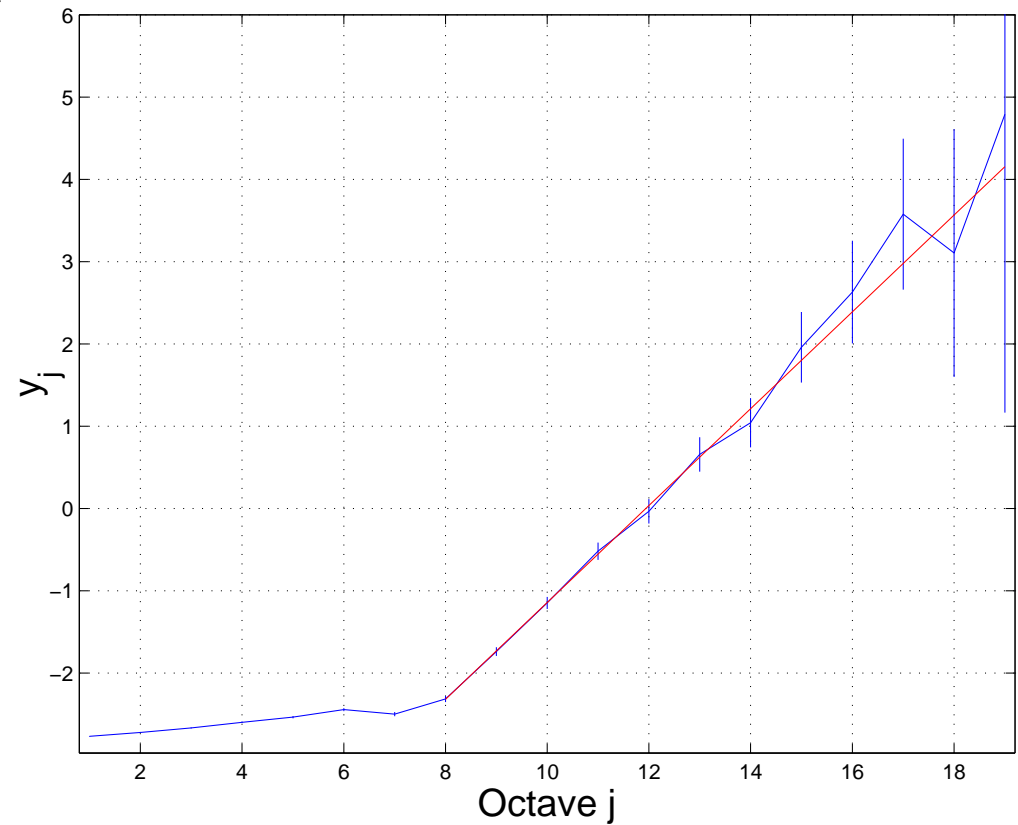
ETHERNET: bytes per 12ms bin.

INTERNET: new connections per 10ms bin.

Logscale Diagram, $N=2$ $[(j_1, j_2) = (3, 15), \alpha\text{-est} = 0.59, Q = 0.011384]$, D-init

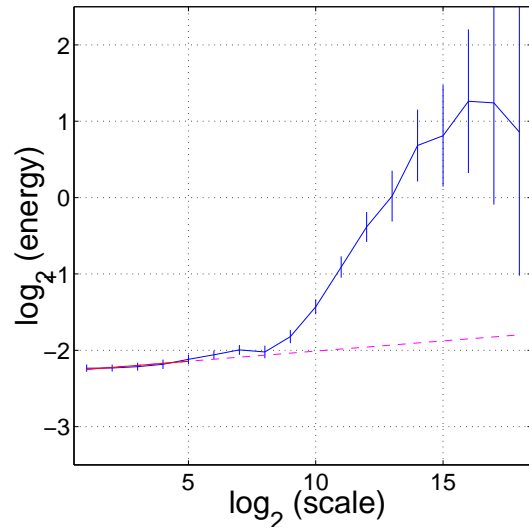


Logscale Diagram, $N=2$ $[(j_1, j_2) = (8, 19), \alpha\text{-est} = 0.59, Q = 0.81665]$

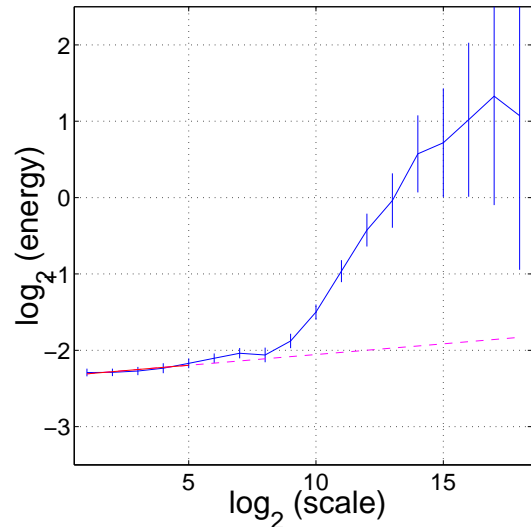


Biscaling in TCP Arrivals

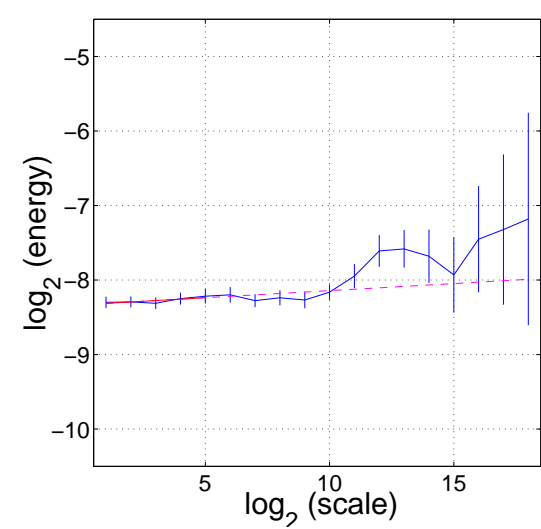
All Connections



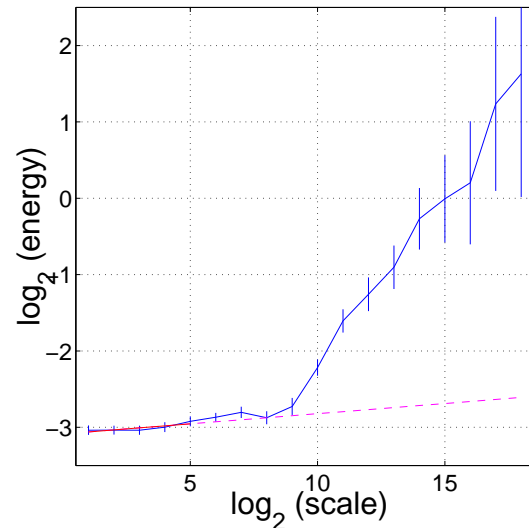
TCP



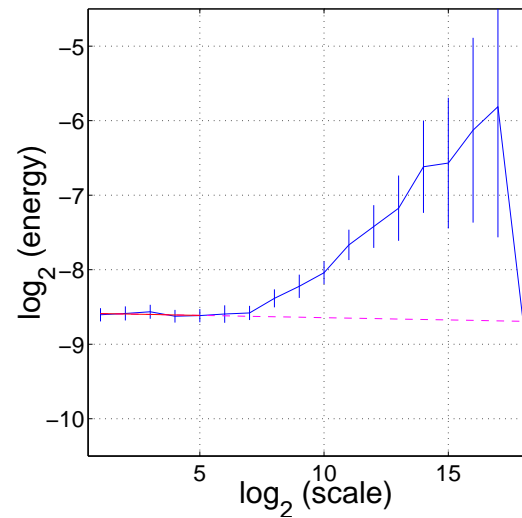
UDP



HTTP



SMTP



Collaboration with Patrice Abry and Nicolas Hohn

Evidence for Multifractality

Wavelet q th order moments: $\mathbf{E}|d_X(j, k)|^q \sim C 2^{\alpha_q j}, j \rightarrow 0.$

Estimating the LHS from data using

$$S_q(j) = \frac{1}{n_j} \sum_k |d_X(j, k)|^q,$$

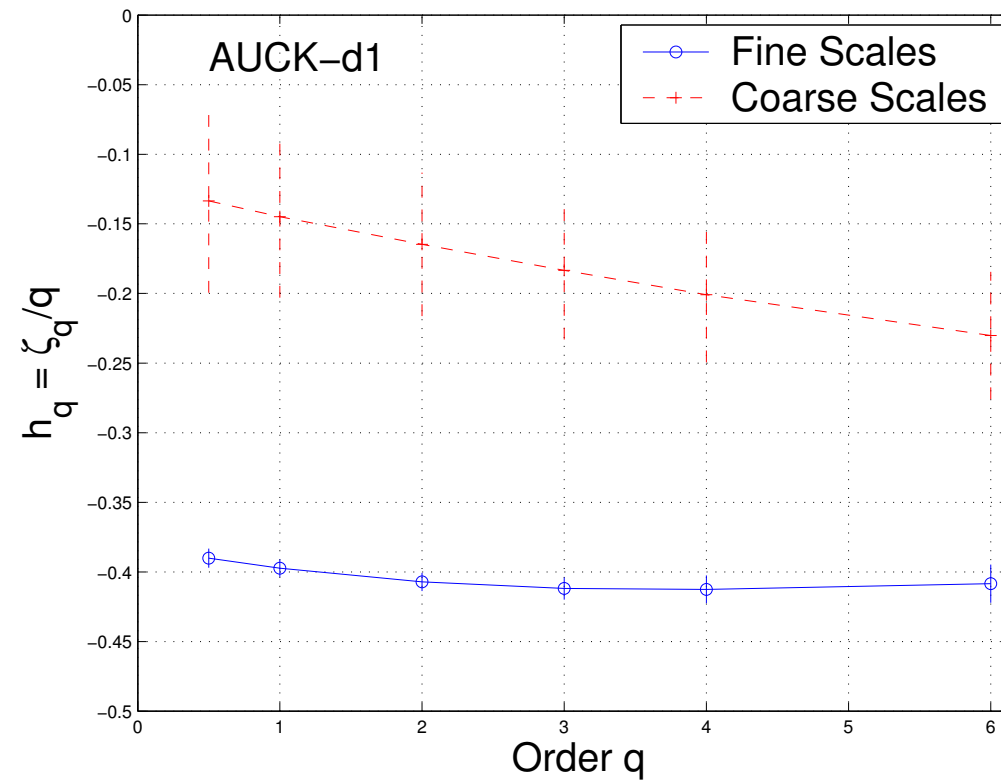
and measure the slopes $\hat{\alpha}_q = \zeta(q) + q/2$ in a log-log plot (the 'MD').

Instead of testing for linearity of $\zeta(q)$ vs q , **look for $\zeta(q)/q$ vs q constant.**

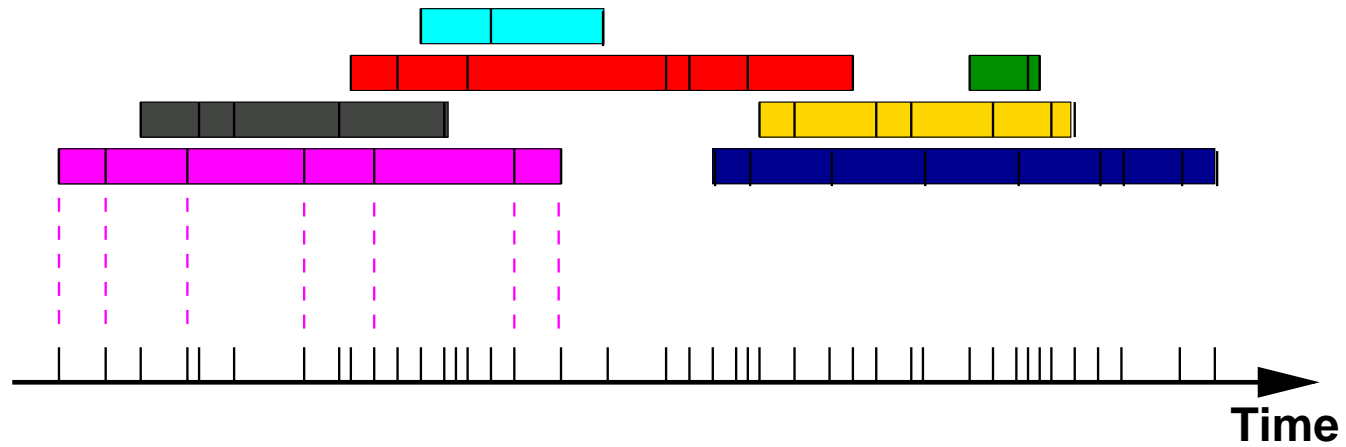
A Short History of Multifractal Traffic Modelling

- 1997: **Ethernet** (Taqqu, Teverovsky, Willinger) – not MF
time domain | discrete packet and byte counts | $\delta = 10\text{ms}$.
- 1997: TCP, LAN gateway (Riedi, Véhel) – MF at ‘high freq’
increments | packet sizes, iat’s, packet and byte counts | $\delta = 150\text{ms}$.
- 1998: **Ethernet** (Abry, Veitch) – not MF
wavelet distributions | continuous time byte counts.
- 1997-8: TCP, LAN gateway (Feldmann, Gilbert, Willinger, Kurtz) – MF small, Mono large.
wavelet domain; discrete packet counts | $\delta = 10\text{ms}$ | large & small regimes
- 1998: TCP, WAN (Feldmann, Gilbert, Willinger) – MF at small, Mono large
wavelet domain | discrete packet counts | $\delta = 10\text{ms}$.
- 1999: ISP and simulated (Feldmann, Gilbert, Huang, Willinger) – MF at small, but dirty
wavelet domain | discrete packet counts | $\delta = 10\text{ms}$.
- 1999-2000: TCP, WAN (Veitch, Abry, Flandrin, Chainais) – IDC holds over large and small.
wavelet distributions | TCP connection counts | $\delta = 10\text{ms}$ | CI’s used.
- 2001: TCP, WAN (Roux, Veitch, Abry, Huang, Flandrin, Micheel) – IDC, but \approx mono.
wavelet distributions | TCP connection counts, packet iat’s and counts, byte counts $\delta = 10\text{ms}$ | CI’s used
- 2003: TCP, WAN, high rate (Zhang, Ribeiro, Moon, Diot) – Mono everywhere
wavelet domain | discrete byte counts | $\delta = 10\text{ms}$. | CI’s used
- 2003: TCP, WAN, high rate (Hohn, Veitch, Abry) – Empirical scaling misleading?
wavelet domain | continuous packet counts | $\delta = 5\mu\text{s} \rightarrow 5\text{ms}$ | CI’s used | $q = 2$

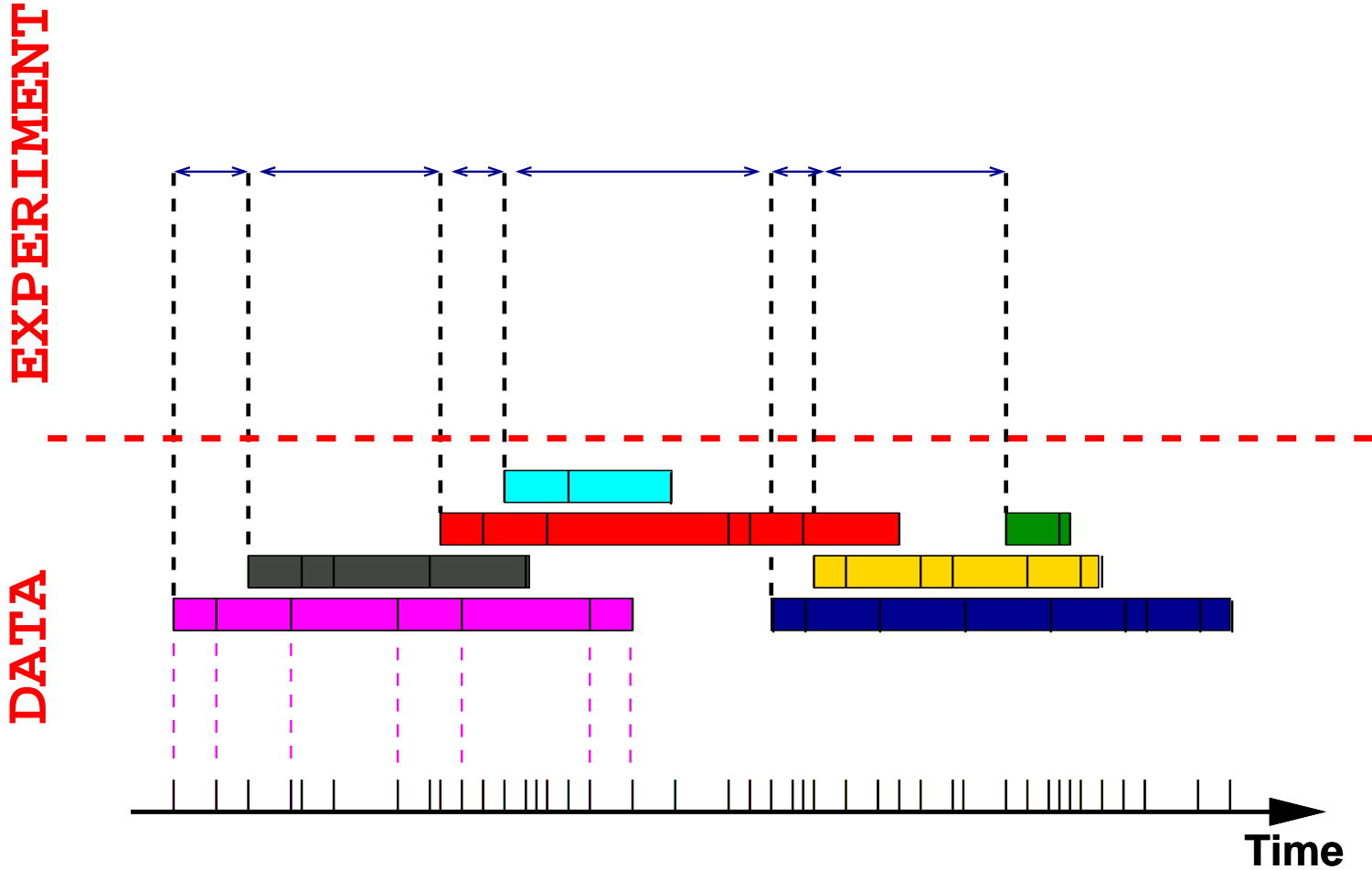
Similar Data, A Less Flattering View



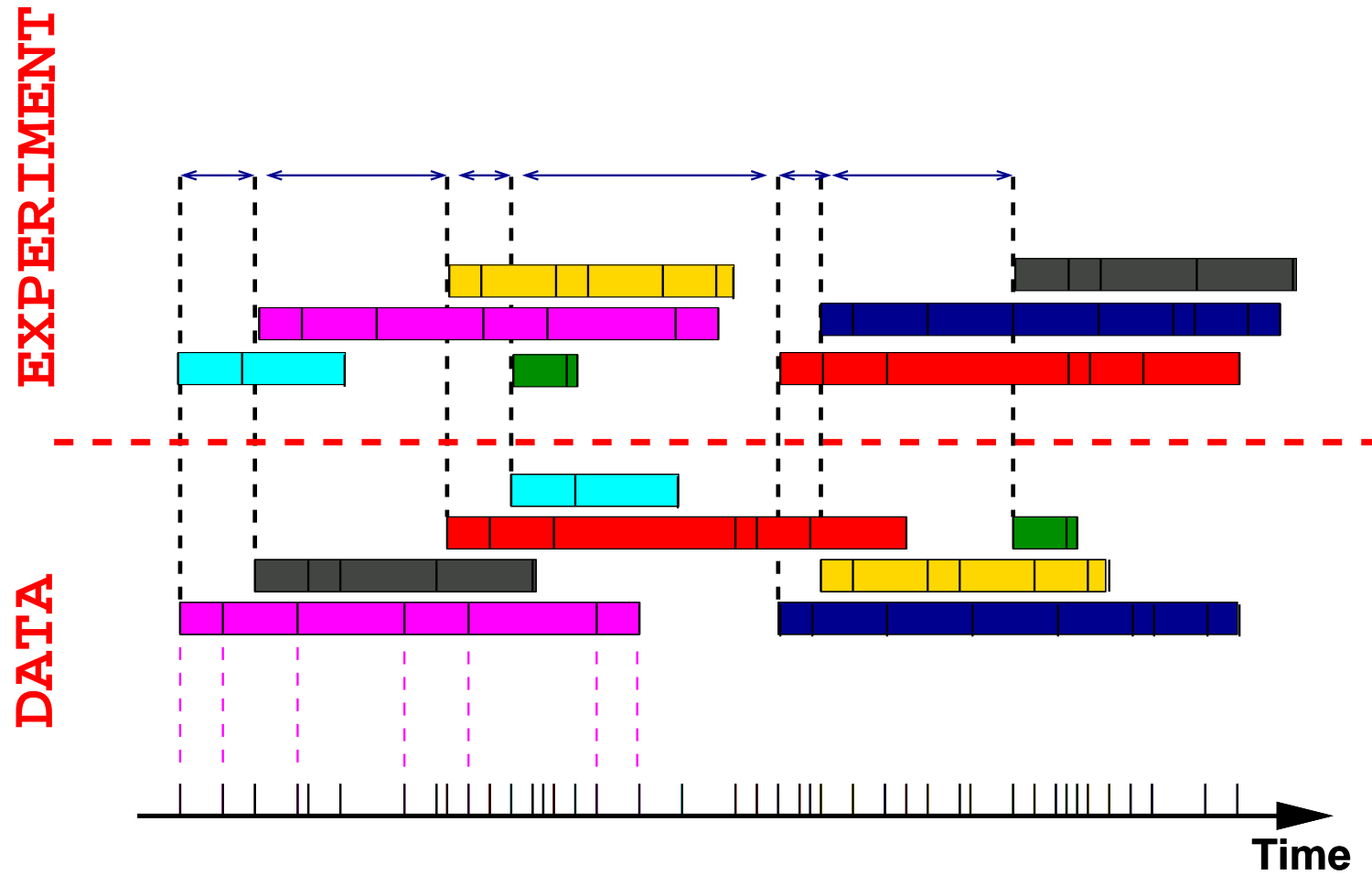
Semi-Experiments on Packet Arrivals



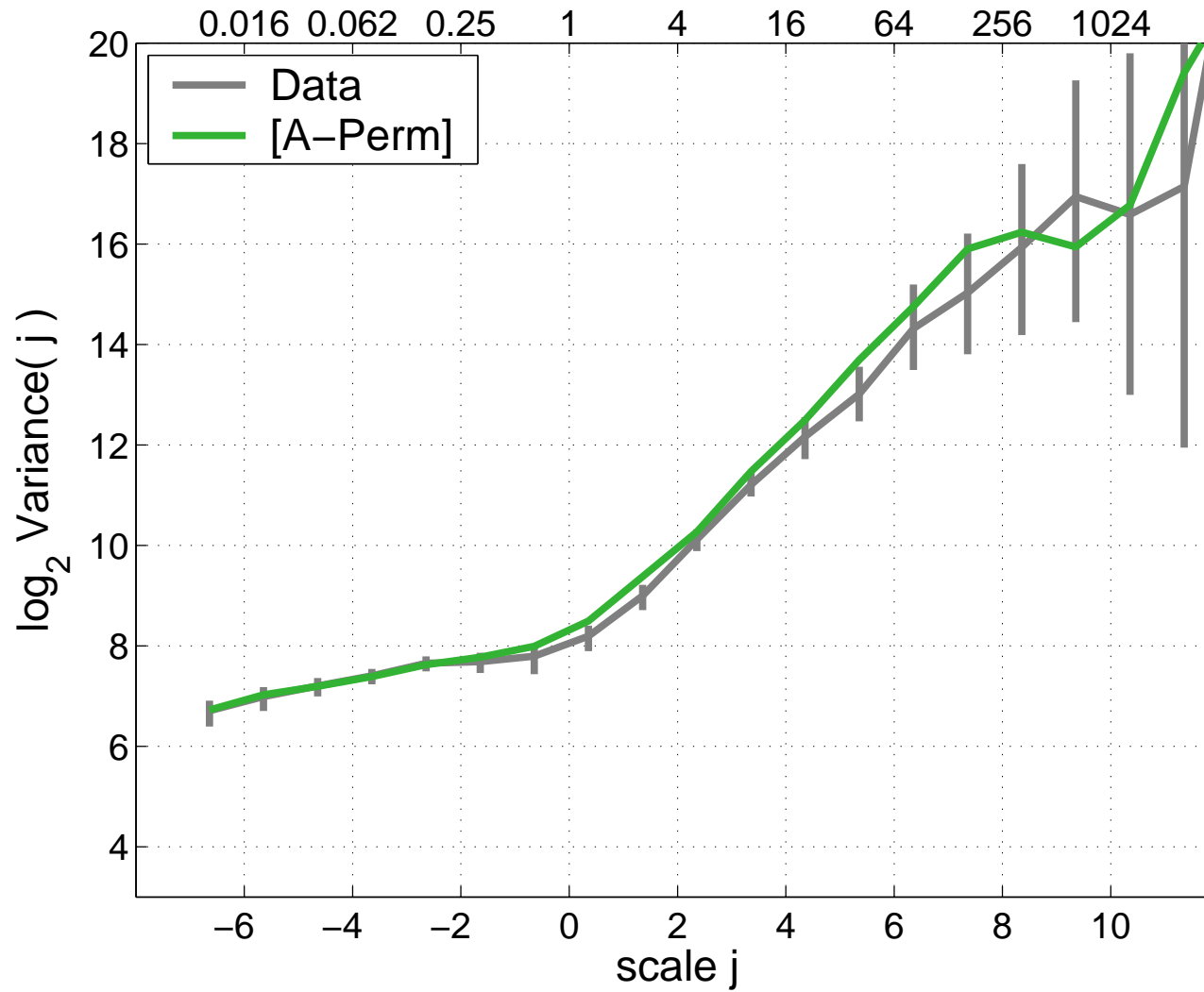
Original TCP Data



Permutation of Flows [A-Perm]



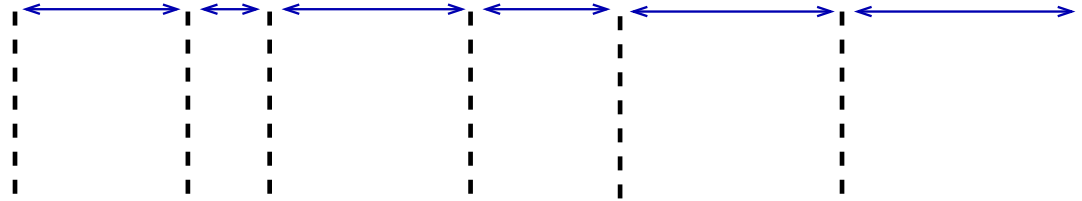
Permutation of Flows [A-Perm]



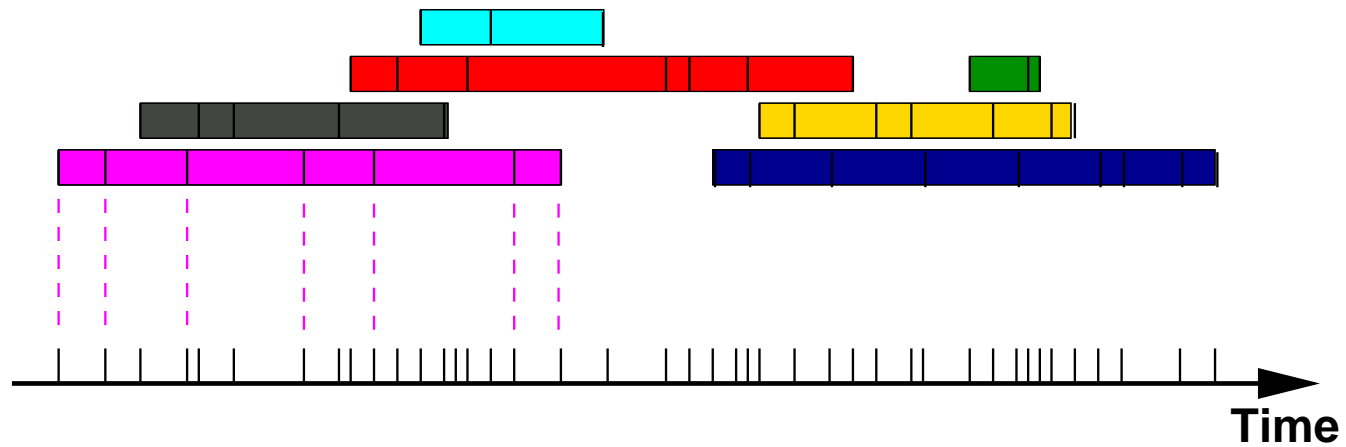
Original Order Poisson Arrivals [A-Pord]

EXPERIMENT

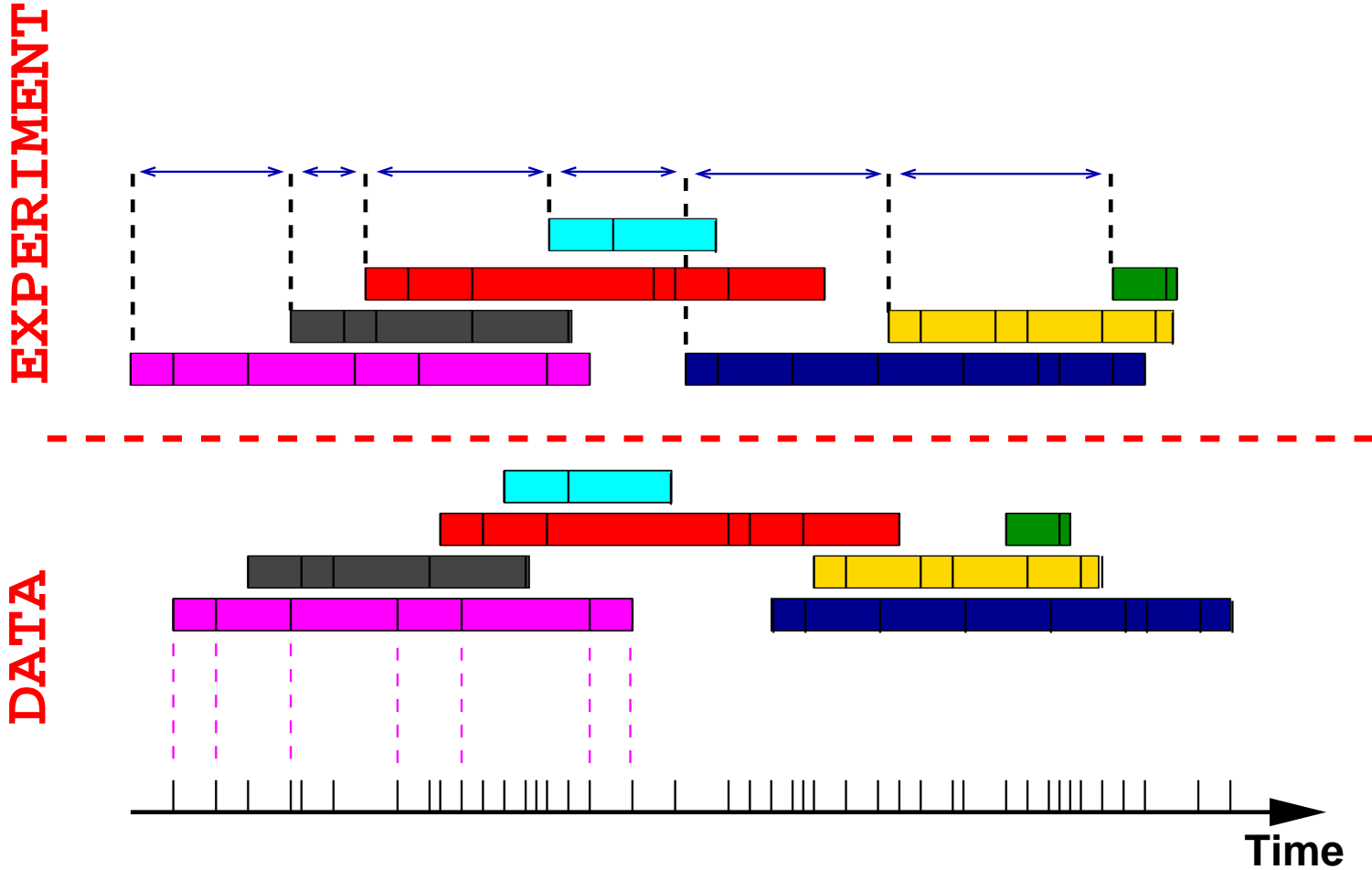
(a smooth form of *internal shuffling*)



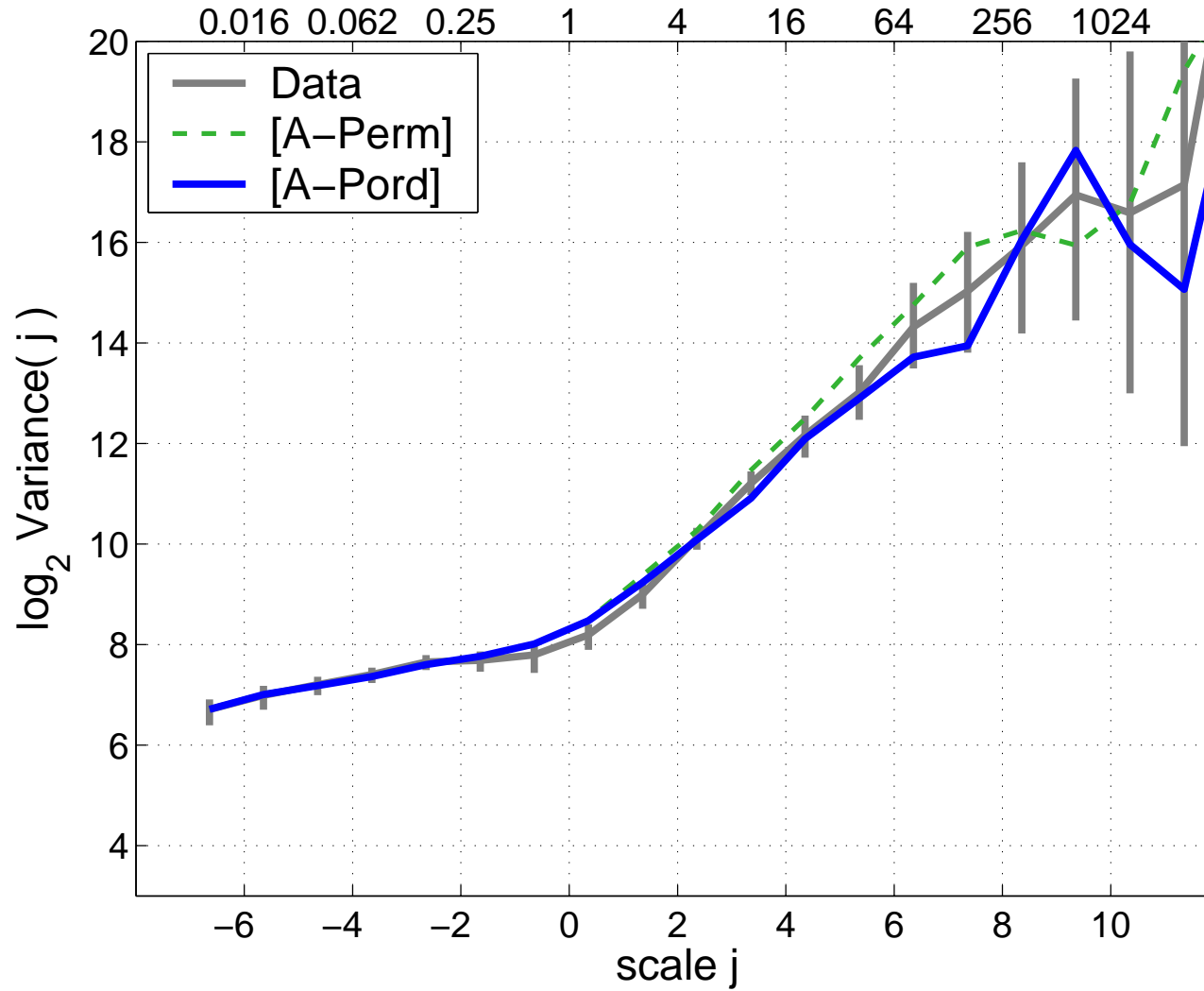
DATA



Original Order Poisson Arrivals [A-Pord]

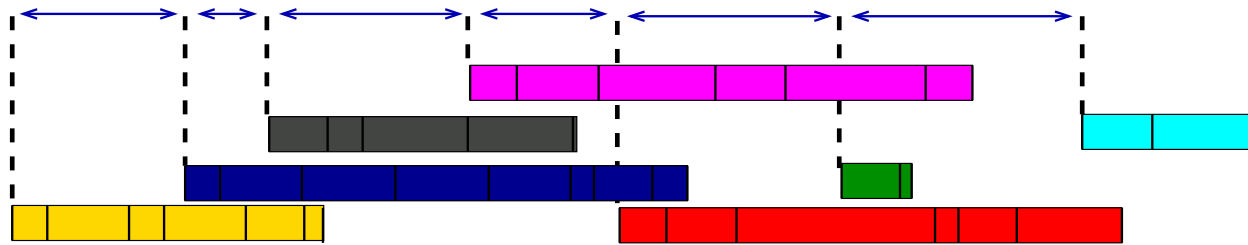


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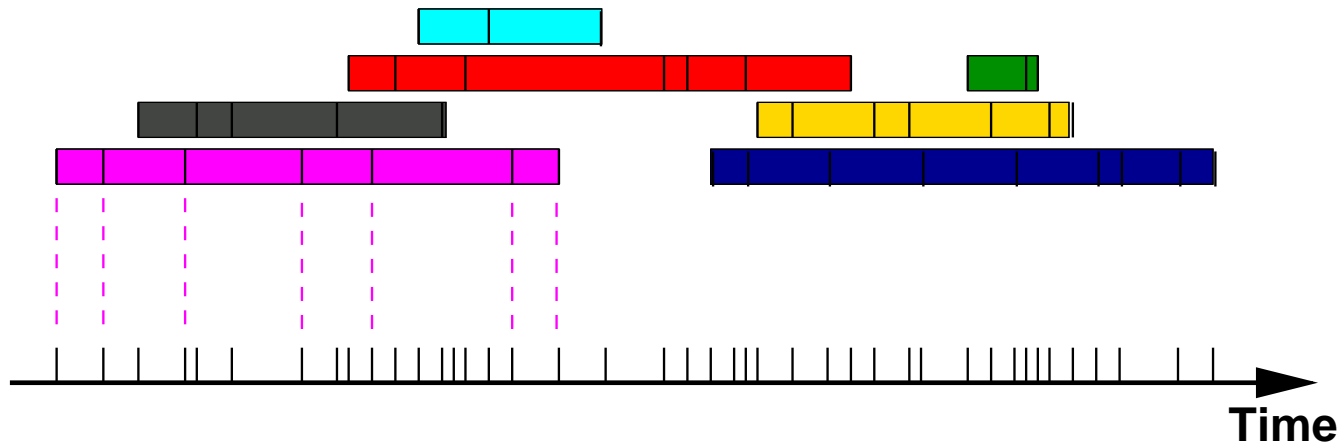


Permuted Poisson Arrivals [A-Pois]

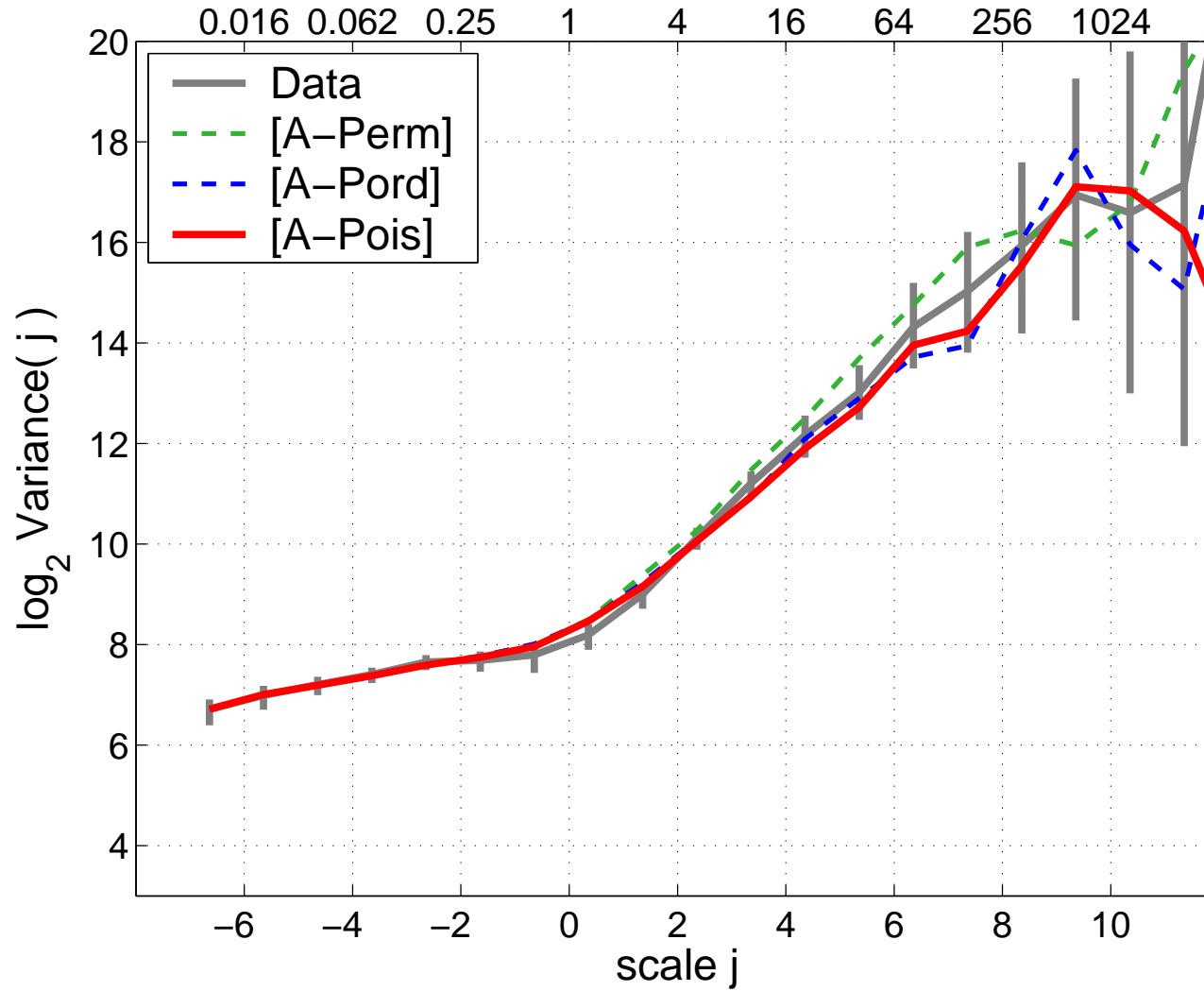
EXPERIMENT



DATA



Permuted Poisson Arrivals [A-Pois]



From simple (Semi-)Experiments, we learn a lot

From these flow arrival *manipulations*:

- Correlations between flows can be **neglected**
 - **No need** for session level hierarchical models
 - TCP dynamics between flows can be **neglected**
- **For IP modelling**, flow arrivals can be modelled as **Poisson**
 - Justifies an assumption commonly used in traffic modelling.

Note: true flow arrival process is **LRD**.

Semi-Experiment Outcomes

Flow Arrival Manipulation

- Correlation between flows can be **neglected**,
- **For IP modelling**, flow arrivals can be modelled as **Poisson**,
- **[A-Clus]:** knee of Y affects knee of X !

Packets within Flow Manipulation

- LRD not caused by arrival process of packets within flows,
- Small scale behaviour governed by **structure within flows**,
- **Finite Poisson process** a reasonable 0-th order model,
- **[P-Pois]:** indistinguishable from **[P-Uni]**,
- **[P-ConstR]; [P-ScaledR]:** rate acts like a **scale parameter**,

Flow Selection

- Observed **LRD** caused by heavy-tailed flow volumes,
- **[S-Thin]:** random thinning consistent with **independent flows**,
- **[S-Dur]:** also kills LRD (flow duration slaved to volume),
- **[S-Pkt]:** LRD still present even without heavy tail!

Flow Truncation Manipulation

- **[T-Pkt]:** also kills LRD, makes X tend to Y ,

Poisson (Barlett-Lewis) Cluster Processes

Definition

- A Poisson process of seeds (flows), initiating independent groups of points (packets):

$$X(t) = \sum_i \mathcal{G}_i(t - t_F(i))$$

- Group: a finite renewal process with P points and inter-arrival distribution A :

$$\mathcal{G}_i(t) = \sum_{j=1}^{P(i)} \delta\left(t - \sum_{l=1}^{j-1} A_i(l)\right)$$

Parameters

- Flow arrivals: constant intensity λ_F
- Flow structure:
 - Packet arrivals: A , $\frac{1}{\mathbf{E}A} = \lambda_A < \infty$,
 - Flow volume: P , $\mathbf{E}P = \mu_P < \infty$,

cf: $\Phi_A(\omega)$, $\omega > 0$

pgf: $G_P(z) = \sum_{j=0}^{\infty} p_j z^j$, $|z| \leq 1$.

Fourier Spectrum

$$\Gamma_X(\nu) = \lambda_F \left(\frac{\mu_P}{\lambda_A} \Gamma_g(\nu) + (S_g(\omega) + S_g(-\omega)) \right),$$

$\Gamma_g(\nu)$: spectrum of *stationary* renewal process with inter-arrivals A , and

$$\mathcal{R}(S_g(\omega)) = \frac{\Phi_A(\omega)}{(1 - \Phi_A(\omega))^2} \left(G_P(\Phi_A(\omega)) - 1 \right).$$

Verify LRD:

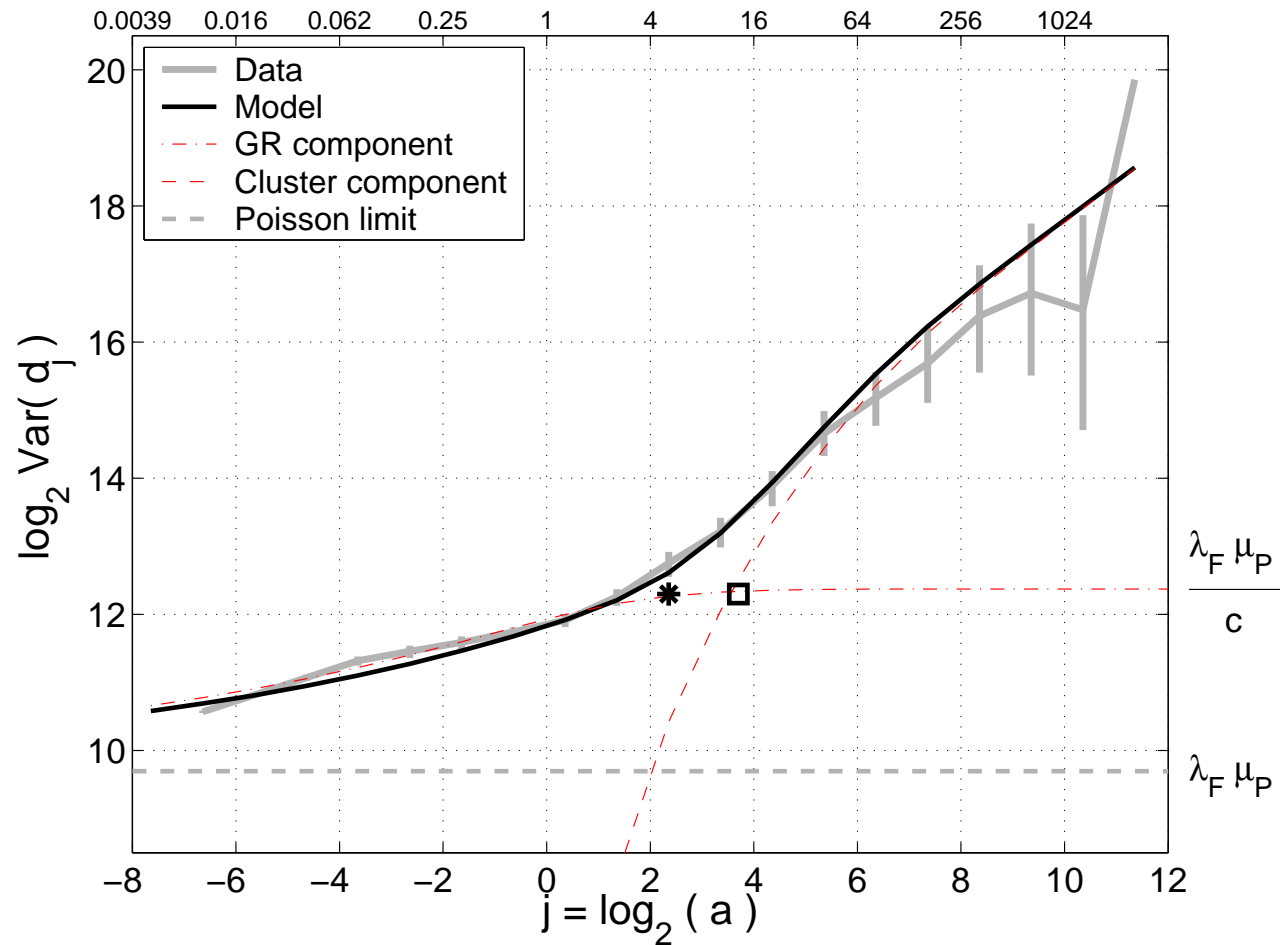
$$\begin{aligned} \mathcal{R}(S_g(\omega)) &\stackrel{\omega \rightarrow 0}{\sim} LB(\beta)(2\pi\lambda_A)^{2-\beta} \omega^{-(2-\beta)} \rightarrow \infty \\ &\stackrel{\omega \rightarrow \infty}{\sim} \frac{\cos(c\pi/2)}{(b\omega)^c} \rightarrow 0 \end{aligned}$$

where $B(\beta) = \psi(1 - \beta) \cos(\pi\beta/2) / (2\pi)^{(2-\beta)} > 0$

Properties

- λ_F just a variance multiplier: ‘more of same’
- has scale parameter $1/\lambda_A$ if A has: $\Gamma_X(\omega; \lambda_F, \lambda_A, c, F_P) = \Gamma_X(\omega/\lambda_A; \lambda_F, 1, c, F_P)$
- Two terms dominating small-large scales
 - **First term (small scales)**: scaled renewal process, no detailed P dependence
 - **Second term (large scales)**: LRD, no A dependence beyond λ_A

Modelling a Typical Auckland IV Trace



* : $j_{GR}^* = -\log_2 \lambda_A + \log_2(\pi^2(c+1)/(3\epsilon c^2))$

□ : $j_{PGR}^{**} = -\log_2 \lambda_A + \frac{1}{2-\beta} (\log_2 \mu_P - \log_2(2LB(\beta)) - \log_2 c)$

Comparison between data and fitted Cluster Model

