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Tutorial

Internet Traffic Measurement and Modelling

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Outline

- 1. Introduction
  2. User and Application Behavior
  3. Application Behavior Measurements
  4. Self-Similarity
  5. User Behavior Measurements
  6. Backbone Measurements
  7. Web Performance
  8. Models
  9. Implications for Simulation
  10. Implications for Quality of Service

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1. Introduction

- Dimensioning (what for)
- Measurement
- Tools
- CDF Graphs

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THE Internet?

The Internet versus other IP Networks

- The Internet
  - publicly accessible network
  - worldwide connectivity
  - looks different to different users
  - multiple worldwide ISPs
  - no single backbone
  - connectivity is changing
- Other IP networks
  - company networks, Intranets
  - local area networks
  - special purpose networks
    - VoIP, telephony signalling (future)
    - network management
    - measurement networks

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Dimensioning for IP Traffic

- non-bottleneck links
  - traffic not to be influenced by the link being dimensioned
  - use traffic patterns occuring on the link if capacity $\rightarrow \infty$
  - dimension to the rate needed to have given small impact on traffic
- bottleneck dimensioning
  - consider TCP behavior
  - dimension to offer a certain rate to every active connection or subscriber
- blocking considerations
  - if access control is performed, the blocking probability is also an important paramter
- Example
  - access network with access lines and common trunk line
  - dimension trunk line to fit access lines capacity
  - including the statistical multiplexing gain

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Dimensioning Applications

- Evaluation of user perceived quality of service
  - for SLAs
  - for advertising
- Matching of capacities within network element
  - processor vs. line capacity
  - line card vs. backplane bit rates
  - link bandwidth between modules
- buffer sizes
  - for a TCP connection
  - for a subscriber / port
  - for rate adaptation
- compute / predict system performance
  - number of subscribers to be served (depending on subscriber model)
  - fitness for future traffic demands

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Traffic Engineering vs. Traffic Management

There are different definitions around!

- The MPLS-related term “Traffic Engineering” (e.g. in MPLS) corresponds to traditional “Traffic Management”
- Traffic Engineering (trad.)
  - network planning
  - traffic forecast
  - link and node dimensioning
  - capacity planning
  - long term task
- Traffic Management (trad.) / Traffic Engineering (IETF)
  - managing dynamic traffic load
  - route adaptation
  - capacity management
  - shorter term task

  ⇒ a network management task

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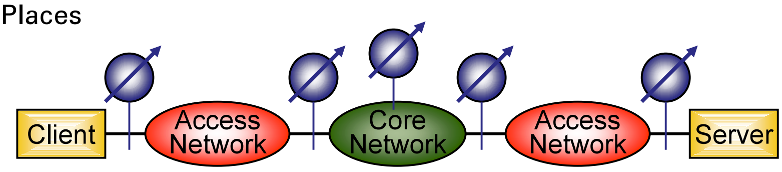
Internet Measurement

Places



Methods

- Packet trace evaluated offline
- Online pre-processed packet trace
- Access Logging (e.g. in proxies)
- Cyclic reading of counter values
- (ping) delay and bandwidth tests
- application layer tests

(first four: passive; last two: active)

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Internet Measurement Data Collection

- Packet trace
- Flow trace: one record per
  - TCP connection
  - other flow levels
- Preprocessed data
  - average values
  - Wavelet coefficient sets

Access Log

- one or two record(s) per dial-in session

Active Measurements

- Measure delay, loss, bandwidth, application performance between two points

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Internet Measurement
Some Tools

- Packet Trace Tools
  - tcpdump (Paxson)
  - Ethereal, argus, etc
- Flow detecting / higher layer tracing tools
  - OC3mon (Apisdorf/Claffy/Thompson) + CoralReef
  - NeTraMet (Brownlee)
  - BLT (Feldmann)
  - tcpanaly (Paxson)
- Active test tools
  - visit NIMI at http://www.ncne.nlanr.net/nimi/
- Network management tools
  - use SNMP to retrieve counter values from network elements
  - RMON probes

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Most results will be given as
Complementary Distribution Functions

- Complementary distribution function

$$F_X^C(x) = P\{X > x\} = 1 - P\{X \le x\}$$

Logarithmic scaling!

- Example: negative exponential distribution, $x_0 = E[X]$

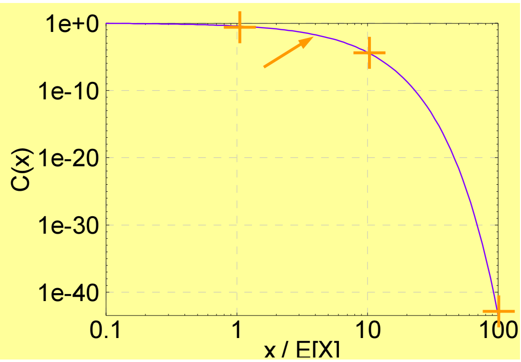
$$F_{\exp}^C(x) = e^{-x/x_0}$$

$P\{X > E[X]\} = 0.368$

$P\{X > 10E[X]\} = 4.5 \cdot 10^{-5}$

$P\{X > 100E[X]\} = 4 \cdot 10^{-44}$

$P\{X > 4.61E[X]\} \approx 0.01$



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Outline

Information and Communications

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2. User and Application Behaviour

- Activity Levels
- Separation of User and Applications Behaviour
- TCP Effects
- Flow Definitions

Information and Communications

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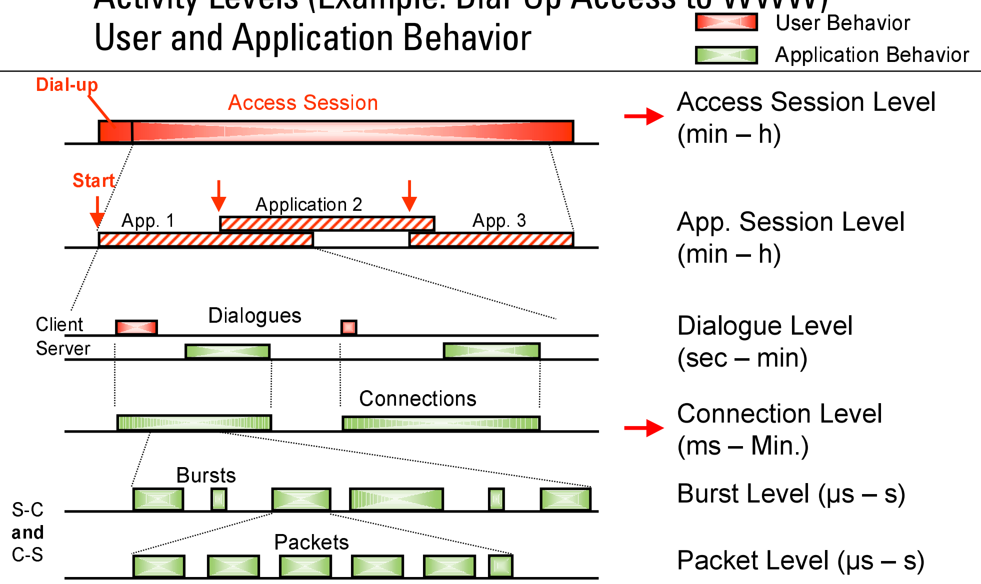
Activity Levels (Example: Dial-Up Access to WWW) User and Application Behavior



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Separation of User and Applications Behaviour

User Behaviour

- Access session start
- Choice and usage of Applications

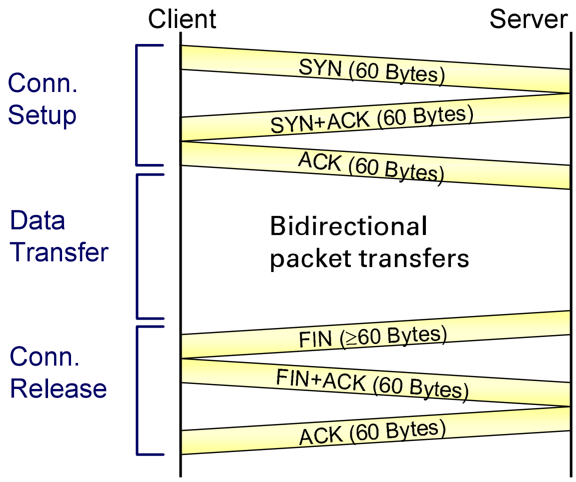
Applications Behaviour

- size distribtution of E-Mail, HTTP page, FTP download
- packet traffic due to
  - TCP connection management
  - TCP acknowledgements
  - higher layer protocols (authentication, GET/PUT, etc)
  - stream flow control
- also: (in parts): application usage duration

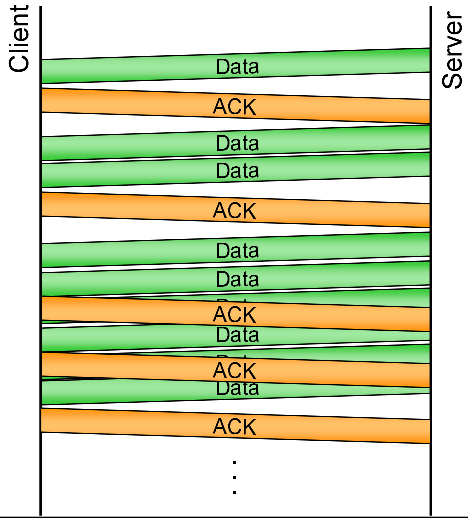
TCP
Effects

- TCP introduces traffic patterns / dependencies (see later)
- lightweight connection management
  - 3 packets to open a connection
  - 3 packets to close a connection
  - connections only seen by end points
  - applications can use short-lived TCP connections
  - application behavior differs from “typical ATM” applications
- Reliable Transport
  - Acknowledgements in reverse direction
- Flow Control
  - TCP adapts its rate to the “fair share” on a bottleneck link
  - influence of delay and loss
  - different implementations around

TCP
Connection Management



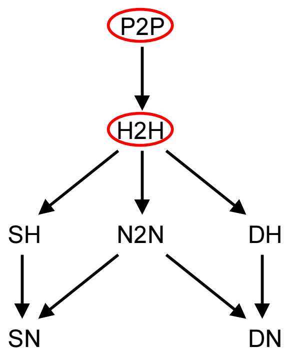
TCP
Bulk Data Transfer



- Acknowledgements in reverse direction
- “Delayed ACK” option: only acknowledge every 2nd packet (+timeout)
- Slow start
  - exponential growth of sender’s window

Flow Definitions
Traffic Aggregation Relations

- Port to Port (P2P)
  - single TCP connection or UDP relation
  - fixed IP addr., TOS, protocol and port numbers at both ends
- Host to Host (H2H)
  - same pair of IP addresses
- Network to Network (N2N)
  - same pair of network addresses
- Source Host (SH)
- Source Network (SN)
- Destination Host (DH)
- Destination Network (DN)
- others (e.g. application specific, bidirectional)
  - single HTTP item
  - HTTP download activity in reaction to user click
  - all Client traffic (CL)



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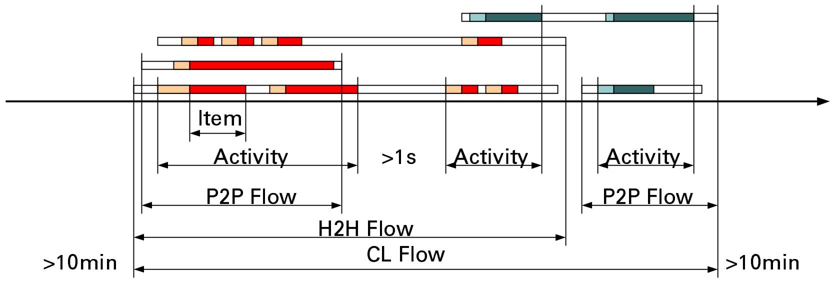
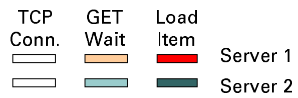
Measurement
Flow Definitions etc



- P2P Flow (TCP connection)
- H2H Flow (one server)
- CL Flow (one client session)
- Activity
- Element



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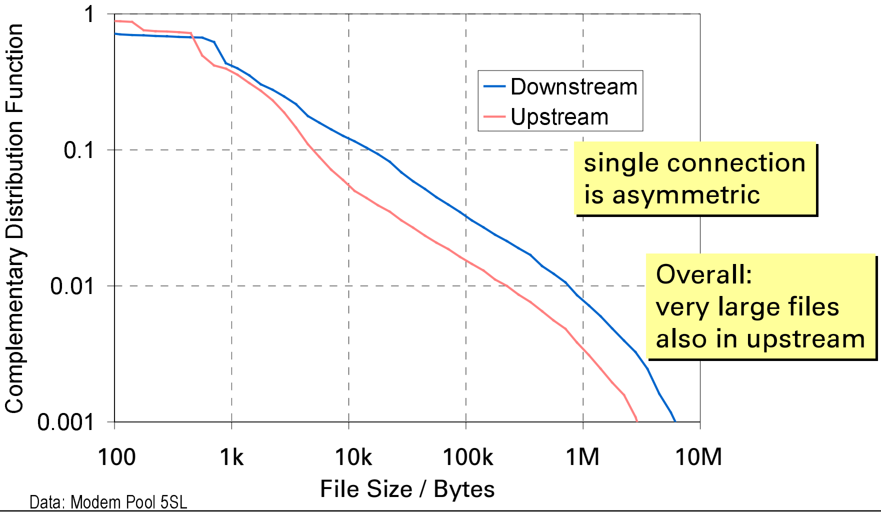
3. Application Behaviour Meas.

- E-Mail
- File Transfer Protocol
- WWW Access
- Multimedia Applications
- Online Games
- Others

E-Mail
File Size Distributions



Data: Modem Pool 5SL

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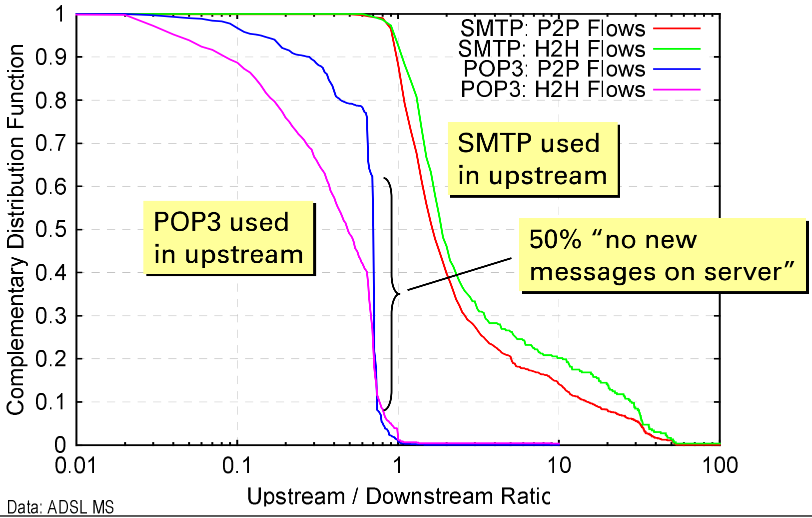
E-Mail
Rate Ratio Distributions



Data: ADSL MS

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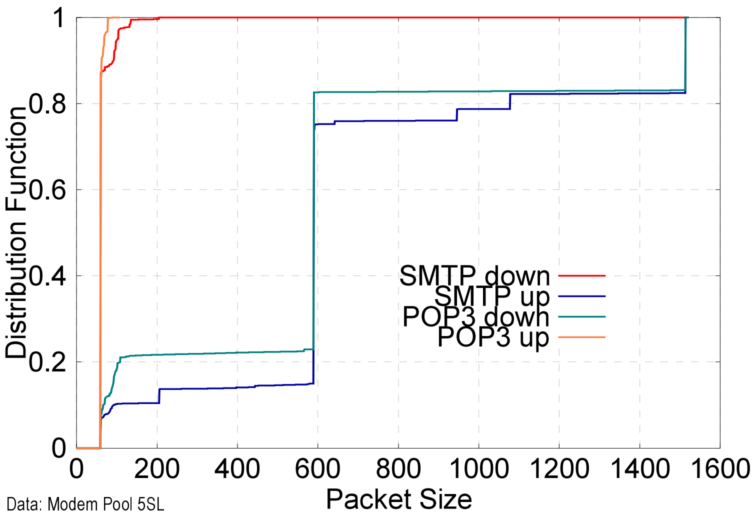
E-Mail
Packet Size Distributions



Data: Modem Pool 5SL

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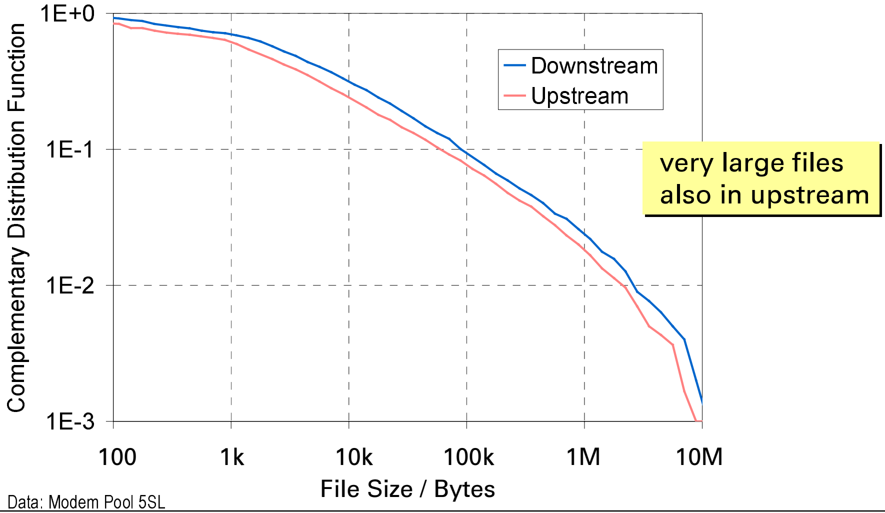
FTP
File Size Distributions



Data: Modem Pool 5SL

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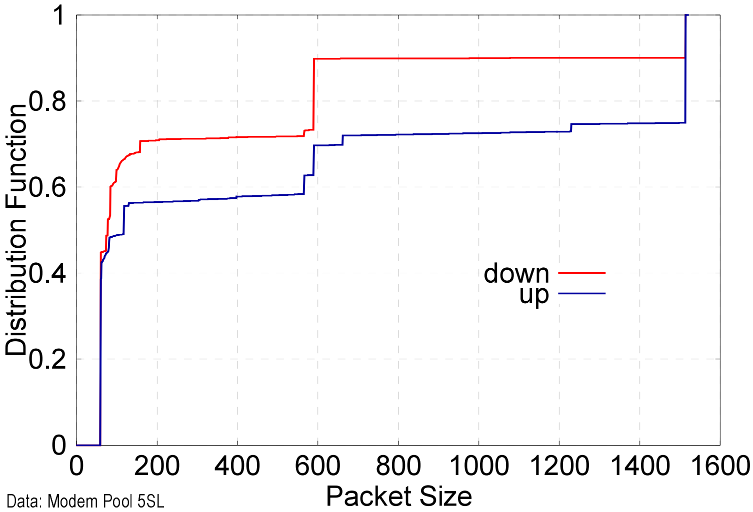
FTP
Packet Size Distributions



Data: Modem Pool 5SL

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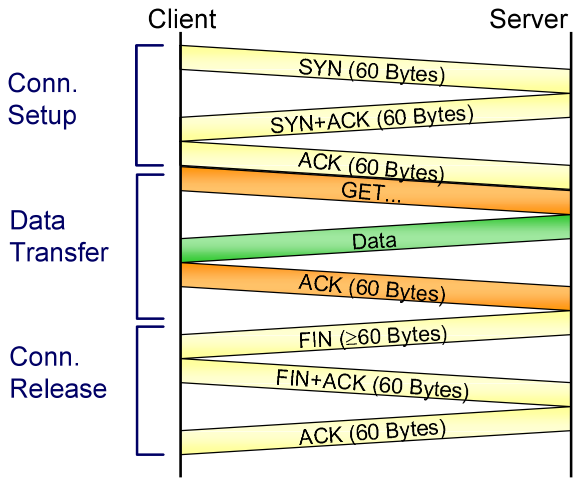
WWW Access



Message	% Pkts	Pkt./ Conn.	% Bytes
SYN (60 Bytes)	4	1	0.5–0.7
SYN+ACK (60 Bytes)	4	1	0.5–0.7
ACK (60 Bytes)	4	1	0.5–0.7
GET...	6	1.5	5–6
Data	40	10	83–88
ACK (60 Bytes)	30	7.5	3–5
FIN (≥60 Bytes)	3	0.75	<1
FIN+ACK (60 Bytes)	3	0.75	0.4
ACK (60 Bytes)	2	0.5	0.4

Up/down ratios:
1:1.05 1:7.9

Measurements: ADSL MS and Modem Pool 5SL: >2 mio. connections

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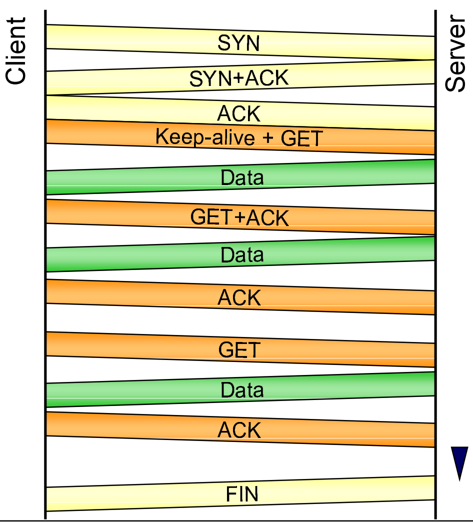
WWW Access
Keep-Alive / Persistent Connections



HTTP Version 1.0:
- Keep-alive
- to be negotiated

HTTP Version 1.1
- persistent connections
- default

Timeout (e.g. 15sec)

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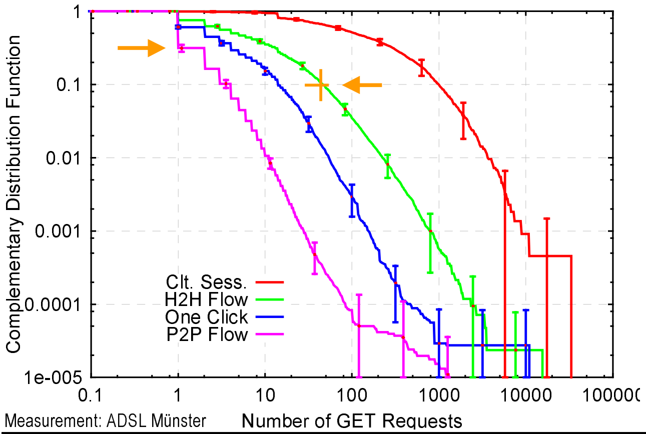
WWW Access
Number of GET Requests per HTTP/TCP Connection



P2P = Port to Port
H2H = Host to Host
CL = Client

Timeout = 10min

30% of all connections serve more than one request

90% of all flows get less than 40 elements from the same server

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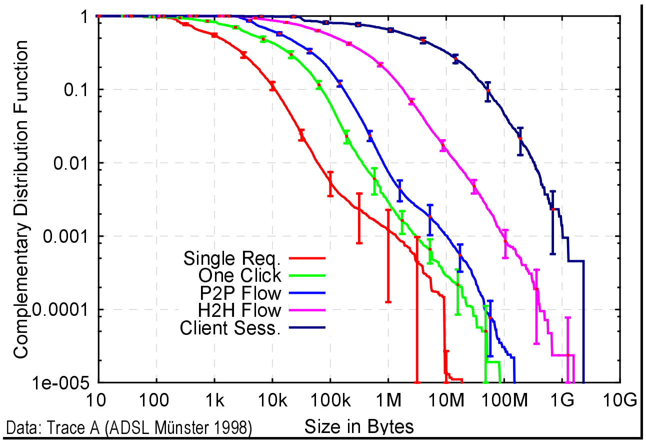
WWW Access
Flow Volumes



P2P = Port to Port
H2H = Host to Host
CL = Client

Timeout = 10min

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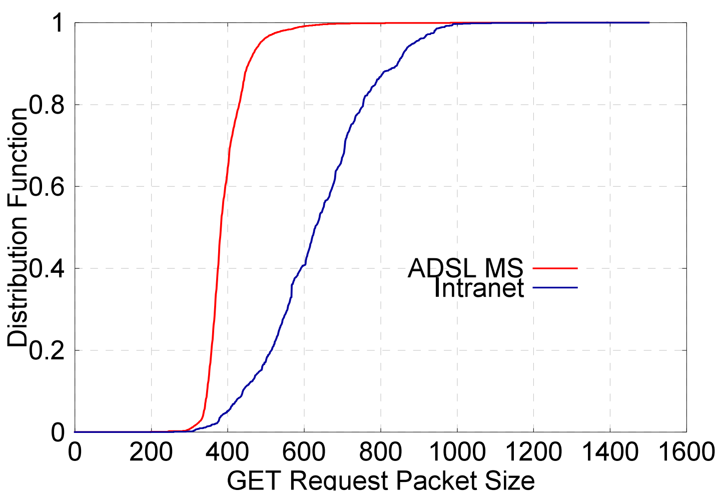
WWW Access
Distribution of GET request packet sizes



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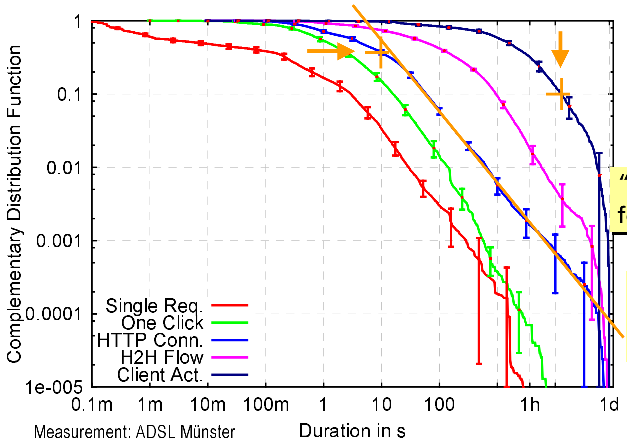
WWW Access
Connection, Flow and Usage Duration



P2P = Port to Port Flow
H2H = Host to Host Flow
CL = Client Usage
Timeout = 10min

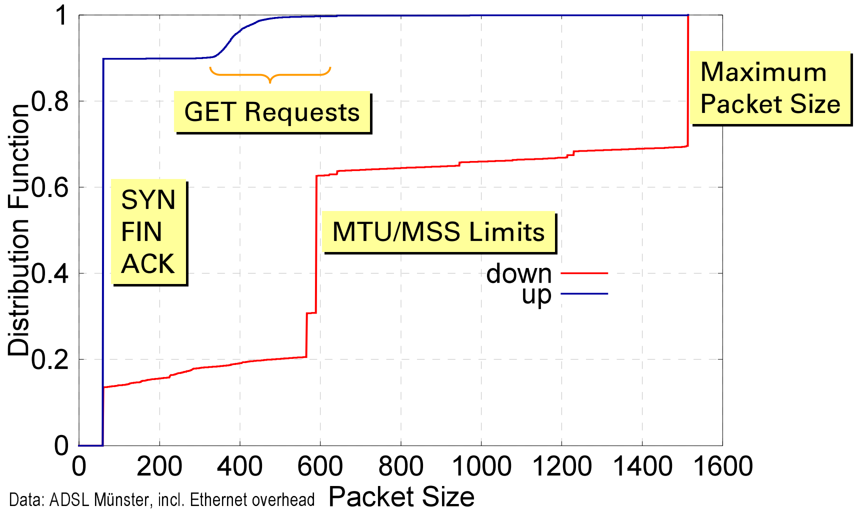
"Power Laws" for nearly four orders of magnitude

$\alpha<1$
→ infinite expectation if continued until ∞

60% of all connections are shorter than 10 sec

10% of all Web sessions are longer than 3 hrs

WWW Access
Packet Size Distribution



Data: ADSL Münster, incl. Ethernet overhead

WWW Access
Locality

- Majority of connections with external servers
- Large percentage of unresolvable network addresses
- Example: ADSL measurement
  - local = within DFN WiN (German Research Network)
  - non-local = outside DFN WiN
  - undefined = no reverse resolution of IP address possible

Locality	% P2P Flows	% H2H Flows
Local	12	7
Non-local	63	63
Undefined	25	30

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WWW Access
Distributions Summary

- GET request packet size
  - URL length + HTTP protocol information
  - Normal Distribution around 400 –700, s.d. 50–200 bytes
  - Larger in database-enabled environments
- Number of GET requests
  - Power tail (?), α=2–2.5
- Downstream connection volume
  - Power tail, α=1.1–1.5
  - infinite variance
- Connection duration
  - Power tail, α=0.6–1.2
  - infinite variance and expectation
- Packet sizes depend on configuration
  - minimum TCP+IP=40Byte for SYN, FIN, ACK
  - maximum given by MTU (client and server configuration dependent)

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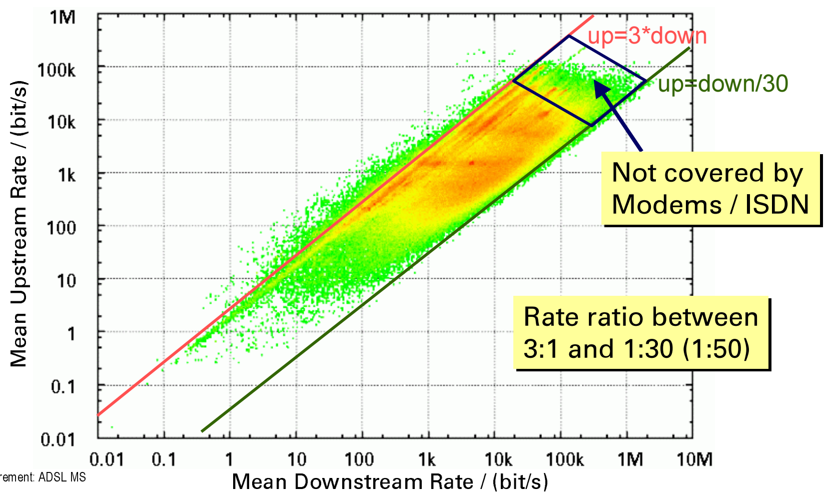
WWW Access
Bit Rate Symmetry



Measurement: ADSL MS

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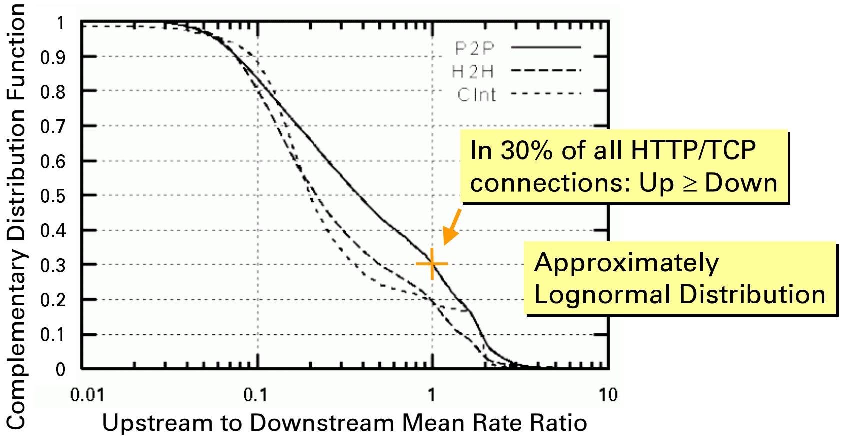
WWW Access
Bit Rate Symmetry Distributions



Data: ADSL Münster

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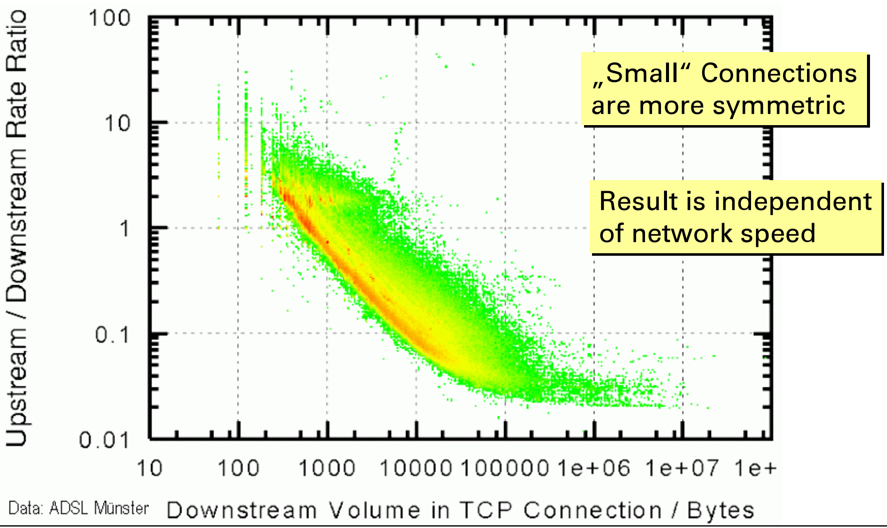
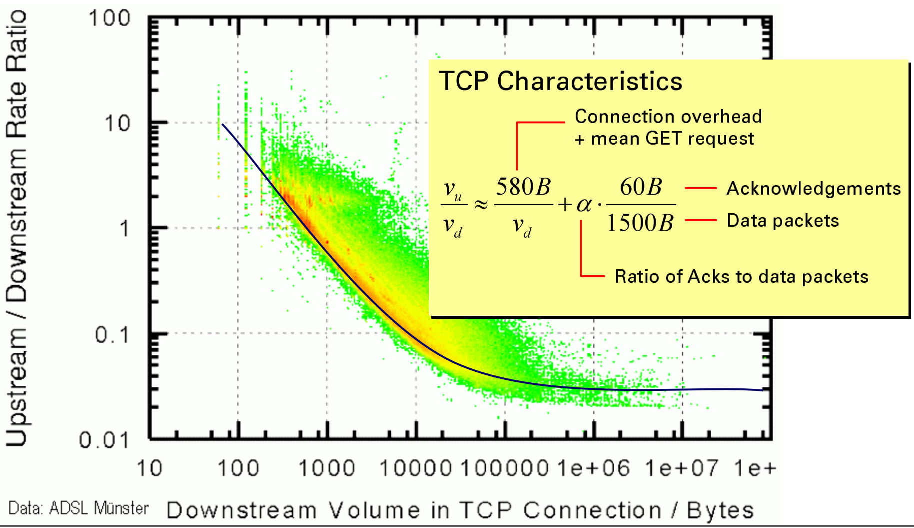
WWW Access
Bit Rate Symmetry

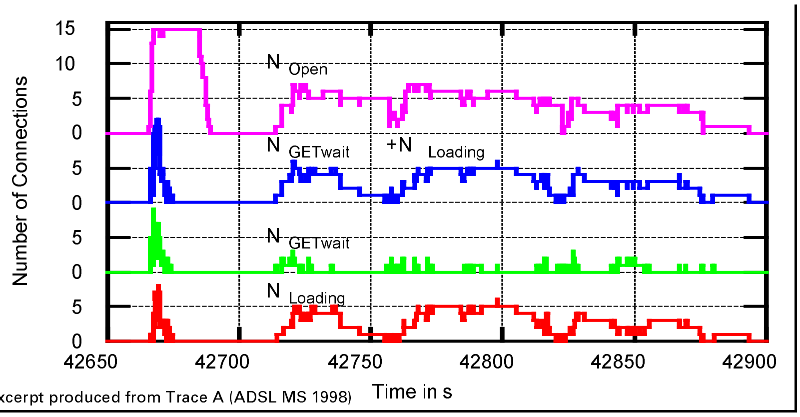


Data: ADSL Münster

WWW Access
Bit Rate Symmetry

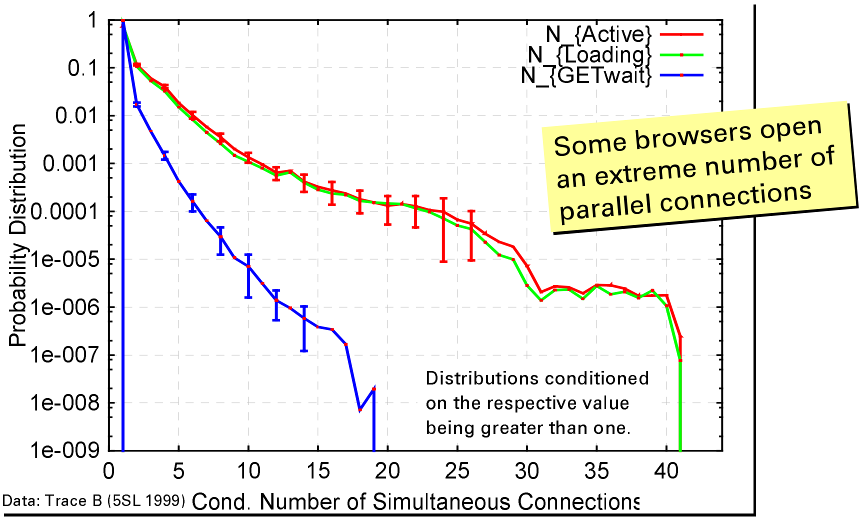


WWW Access
Parallel Connections



- Parallel connections are either idle or loading
- only a few wait for data

WWW Access
Number of Parallel Connections



Data: Trace B (5SL 1999)

Multimedia Applications

- Real-time streams
  - Internet Telephony
  - Video Conferencing
- Non-real-time streams
  - audio/video streaming
  - e.g. real audio/video (see next slides)
- Stream traffic + additional control traffic
- examples here:
  - traffic characteristics VoIP
  - real audio measured traffic

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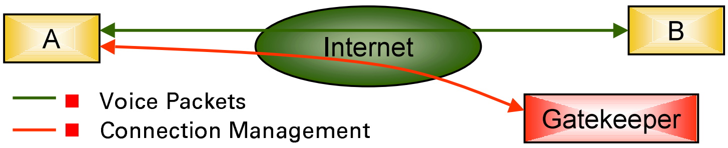
Internet Telephony

- packetized voice, e.g.
  - ITU G.723 (10–20kbit/s, with silence suppression -> nearly ON-OFF)
  - G711 (64kbit/s uncompressed)
  - GSM standard
- transmission via RTP/UDP
- connection management using ITU H.323 or SIP
- Gatekeeper for
  - address translation
  - connection admission control (if applicable)



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Real Audio

- Transfer of audio clips in the Internet
  - CD clips
  - live concerts
  - speech (newscasts)
- Ports
  - control
  - data
- rate can be adapted to local connection
  - choice e.g. between 14/28/56/112k modems / T1 / LAN
  - large buffers used to compensate for delay variation and packet loss

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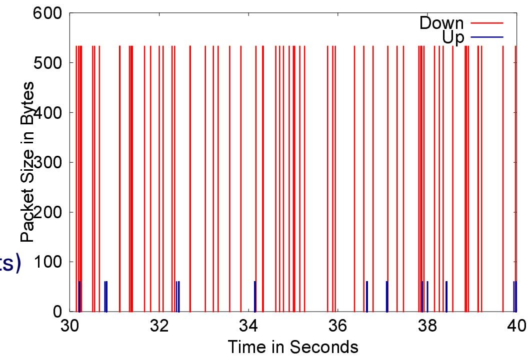
Real Audio
Traffic Characterization

- Data stream
  - UDP
  - relatively constant packet size of 280–550 Bytes
- Data Control stream
  - UDP
  - intra-stream control (during UDP stream)
- Media Selection
  - TCP
  - selection (before UDP stream starts)



Data: Modem Pool 5SL

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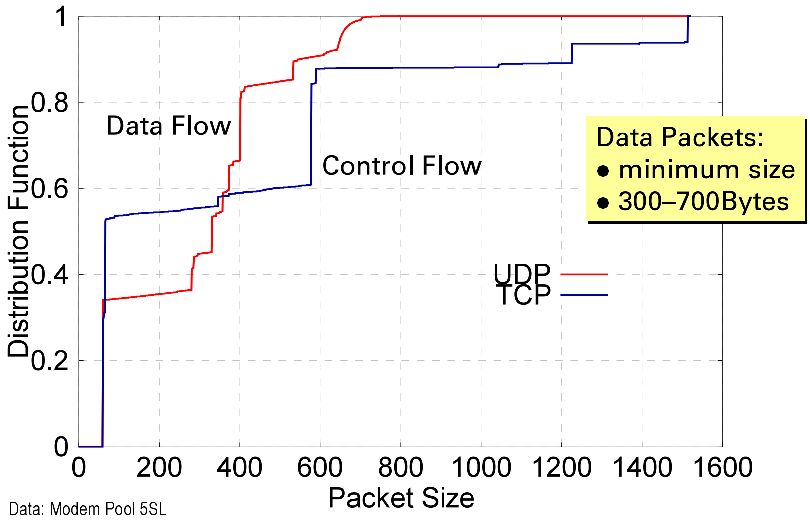
Real Audio
Packet Size Distribution



Data: Modem Pool 5SL

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Online Games

- different concepts
  - complete download of executable game (e.g. Java applet)
  - user plays against server
  - direct interaction between multiple users
- different games and players
  - periodic state updates vs. transmission of state changes
  - action vs. thinking games
  - activity patterns of individual users (“hunt” vs. “wait”)
- interactive games: UDP traffic
  - extreme delay requirements (few ms)
  - high background load (small packets at high rate)
  - additional traffic peaks
  - often very long usage (many hours)
  - mixed distributions of packet interarrival time and packet length

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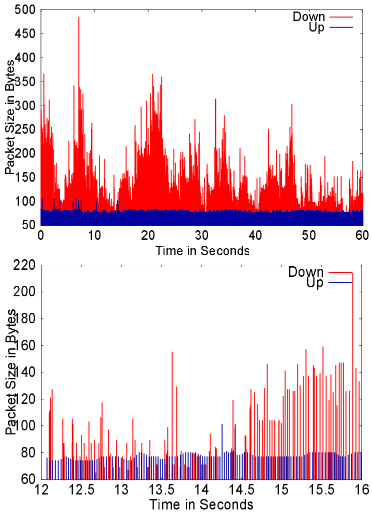
Online Games
Example

- Data measured in ADSL field trial on 29.Aug. 1998
- 00:00 until 01:45
- upstream
  - 20kbit/s rather constant rate
  - 30–35 packets per second
- downstream
  - 30–40kbit/s variable
  - 30–35 packets per second
  - packet size and bit rate peaks



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Other Applications

Wide Area Networks
- Domain Name System (DNS)
- Network News (nntp)
- Routing Protocols

Corporate Networks
- File Services
  - e.g. Network File System (NFS)
- Printer services
- Database access
- Specific Corporate Applications

- Network Management
- Backup Services

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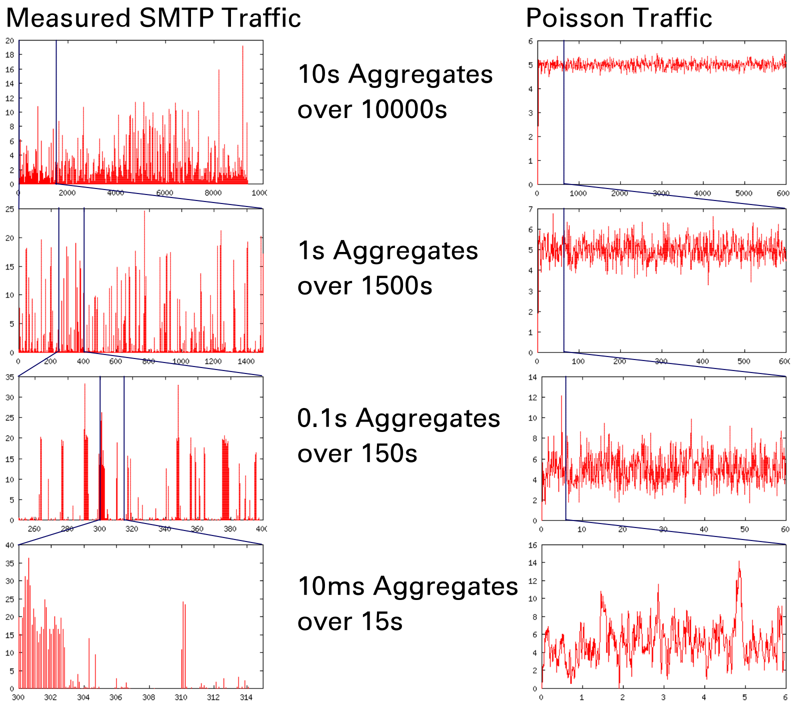
Information and Communications

4. Self-Similarity

- Scaling Example
- Heavy-tailed distributions, power tails
- Hurst Parameter
- Construction
- Influences
- Consequences
- Multifractals



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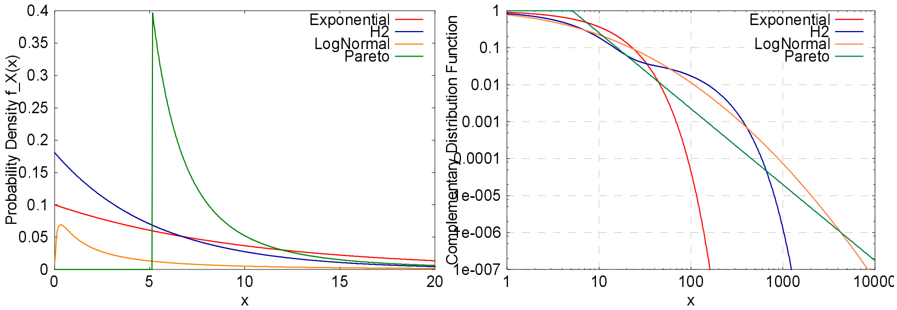
Probability Distributions
Examples

- Same mean = 10
- Coefficient of variation c_V=3 (except for exponential distribution)
  - Exponential: λ=0.1
  - Hyperexponential: p_1=0.947; λ_1=0.189; p_2=0.053; λ_2=0.0106
  - Lognormal: σ^2=2.3; μ=1.15
  - Pareto: x_0=5.132; α=2.054



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Power Tails

- The complementary distribution function C(x)=P{X>x} decays like

  $$C(x) \sim x^{-\alpha} \cdot L(x)$$

  for a slowly varying L(x) as x $\to \infty$

Alpha	Distribution	Mean	Variance
≤ 0	Invalid	–	–
$\in (0,1]$	Valid	∞	∞
$\in (1,2]$	Valid	Finite	∞
>2	Valid	Finite	Finite

- very large values of X occur with a much higher probability than expected from "usual" distributions

Power Tails
Example

- Negative exponential distribution

  $C_X(x) = P\{X > x\} = e^{-\lambda x}, \quad x \geq 0$

- Pareto distribution

  $C_X(x) = P\{X > x\} = (x_0/x)^{\alpha}, \quad x \geq x_0$

- Common mean value = 10

Distribution Type	Neg. Exp.	Pareto	Pareto
Parameters	λ=0.1	α=4; x_0=7.5	α=1.5,x_0=3.3
P{X>10}	0.37	0.32	0.07
P{X>100}	5e-5	3e-5	6e-3
P{X>1000}	4e-44	3e-9	2e-4

Self-Similarity

- Variance does not decrease as fast as expected
  - on time scale aggregation
  - on ensemble aggregation (multiple sources)
- "fractal" or "self-similar" characteristics
  - mean bit rates over time
  - mean packet rates over time
- due to heavy-tailed distributions of ON phases
  - causing long-range dependence

Large File Size Variance → Long-Range Dependence → Self-Similarity

- Limits
  - packet level time resolution
  - instationarity

  -> check time dependence of traffic parameters

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Self-Similarity
Different Views

- Dependence of variance on aggregation time
  - Hurst Parameter H

$$Y_t^m = \frac{1}{m} \sum_{s=m(t-1)+1}^{mt} X_s \longrightarrow VAR(Y_t^{(m)}) \sim m^{-2(1-H)}$$

- Long-Range Dependence
  - autocorrelation function decays with $k^{2(H-1)}$
  - Hyperbolic instead of exponential decay of autocorrelation

$$\rho(k) = Cov(X_t, X_{t+k}) \sim k^{2(H-1)} \qquad k \to \infty$$

- Spectral Density
  - pole at zero

$$f(\lambda) = \frac{\sigma^2}{2\pi} \sum_{k=-\infty}^{\infty} \rho(k) e^{ik\lambda} \sim \lambda^{1-2H} \qquad \lambda \to 0 \;;\; \lambda \in [-\pi, \pi]$$

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Self-Similarity
Estimating the Hurst Parameter

- Variance-Time Analysis
  - plot variance of aggregate versus aggregation time
  - simple, easy to understand
  - also gives second (variance) parameter
  - slightly unreliable
- R/S Analysis
  - classical approach for unknown mean and variance
  - plot rescaled adjusted range versus interval length
- Periodogram Analysis
  - shows increase of spectral density at zero
- Abry-Veitch Estimator
  - using wavelet theory
  - independent of stationarity
  - determines H and variance parameter from regression of Wavelet coefficients

Self-Similarity
Construction

- ON/OFF sources
- Poisson arrivals
- Pareto distribution of ON duration B

$$P\{B \le x\} = 1 - \left(\frac{x_0}{x}\right)^{\alpha}$$

- B has infinite variance and finite mean if $\alpha \in (1,2]$
- Resulting traffic is self-similar with

$$H = \frac{3-\alpha}{2}$$

Influences on Self-Similarity

- File size distribution
  - main cause
  - Heavy tail creates self-similarity
- Idle time distribution
  - also relevant, further increases H in certain cases
- Mixing traffic flows with different H
  - resulting H is somewhat interpolated
- Network Topology
  - no significant influence
- Protocol Stack
  - TCP (congestion and error control) modulates H
- Network performance decreases smoothly with increasing H
  - queue lengths are more sensitive

from Park/Kim/Crovella in Park/Willinger 2000

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Self-Similarity
Consequences of Long-Range Dependence

- Huge buffers needed for unelastic traffic
  - Burst level queueing is inefficient
  - Only link capacity can help (lower utilization)
- Elastic traffic not modelled correctly by stiff self-similar traffic
  - TCP adapts to available bit rates and prevents excessive packet loss
- Successive measurements not independent
  - Huge confidence intervals for measurements and simulation
  - To reduce confidence interval by a factor of 10, measurement must be $10^{1/(1-H)}$ longer
  - Consider this in traffic measurement and simulation!

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Multifractal Scaling

- Different scaling behavior observed on different time scales
- Scaling is not described exactly by monofractal law and one (Hurst) parameter
- Different causes on different time scales
  - Application Layer (file size distribution, connection arrivals)
  - TCP layer (flow&error control, timers, round trip time)
  - Media access

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Information and Communications

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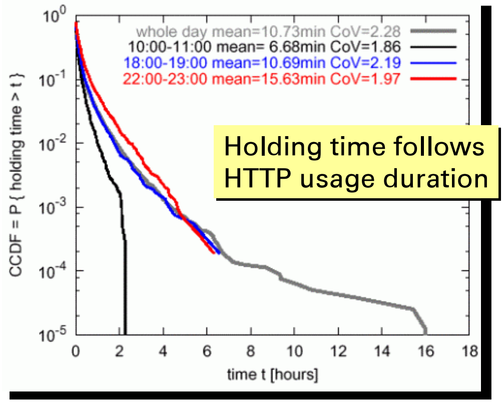
5. User Behaviour Measurements

- Dial-up traffic
- Influence of tariffing
- Applications usage
- Volume versus usage time
- Asymmetry

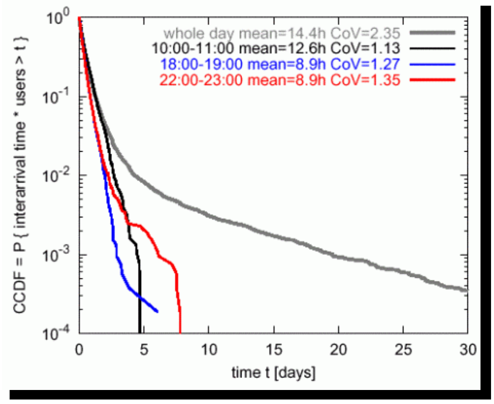
Information and Communications

Access Session Characteristics Distributions

Holding Time

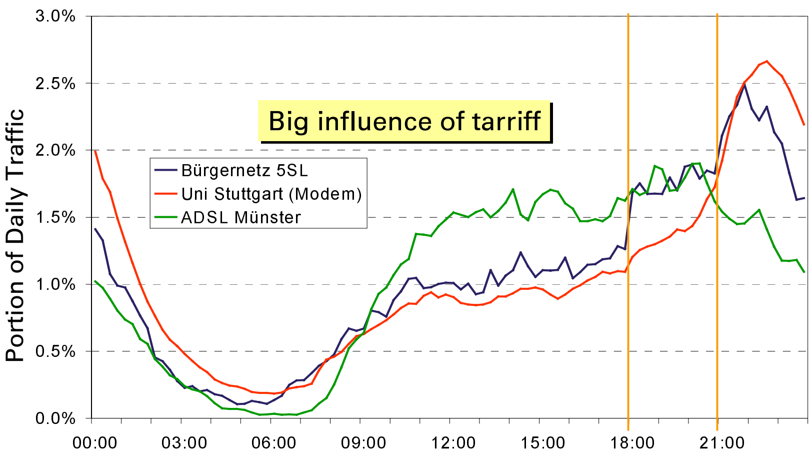


Cumulative Interarrival Time per User



Source: University of Stuttgart

Dialup Behaviour Daily Traffic Curves



Data: 5SL, Uni Stuttgart, ADSL Münster: 15min values

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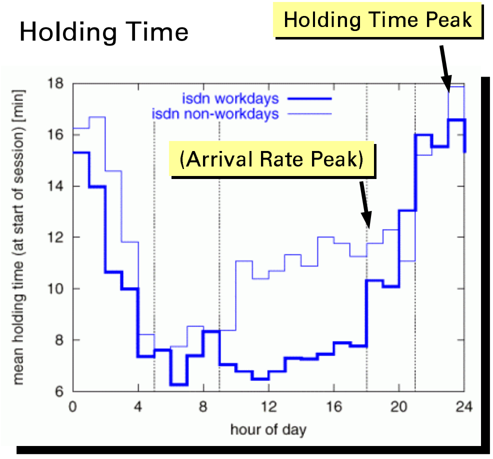
Access Session Characteristics
Daily Variation (2)

Holding Time



Few Long
Late Night Sessions

Source: University of Stuttgart

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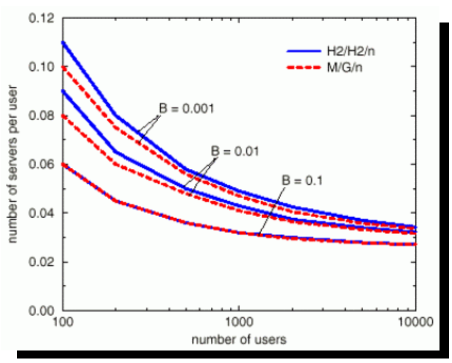
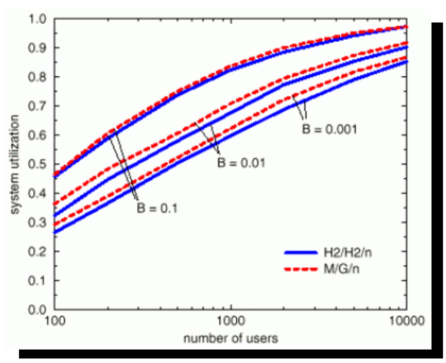
Access Session Characteristics
Dimensioning Examples

Economy of Scale



System Load



H2/H2/n-0 more realistic than M/G/n

Source: University of Stuttgart

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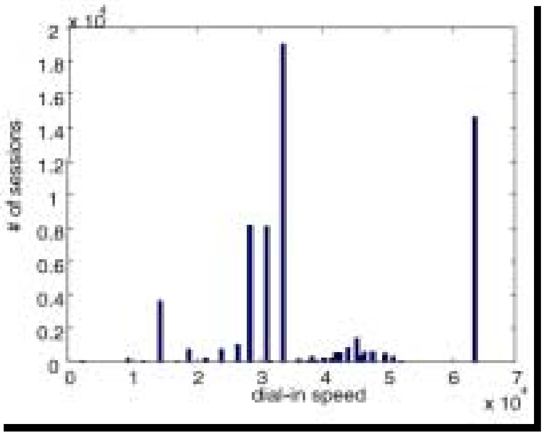
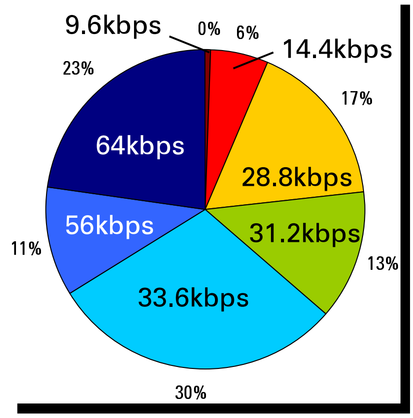
Achieved Dialup Access Speeds





Source: University of Würzburg

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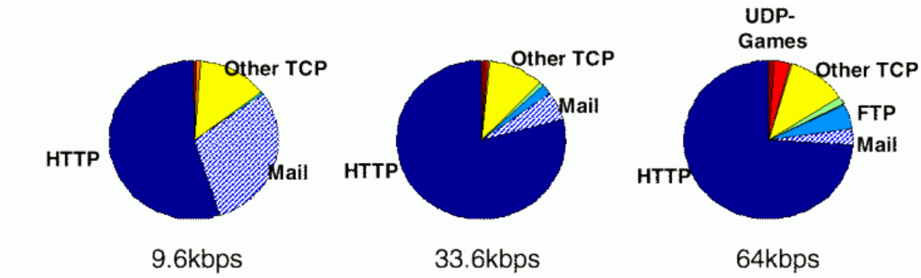
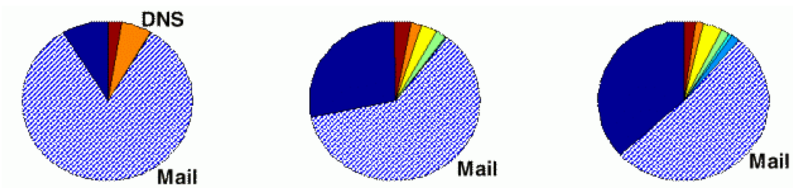
Application Mixes



... in sessions < 100sec:



Source: University of Würzburg

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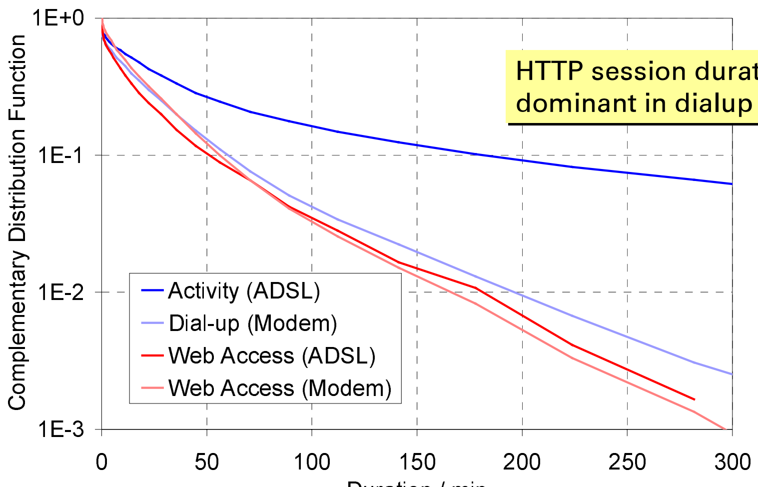
Dialup Behaviour
Session Duration (1)



HTTP session duration is dominant in dialup session

Data: 5SL, ADSL Münster

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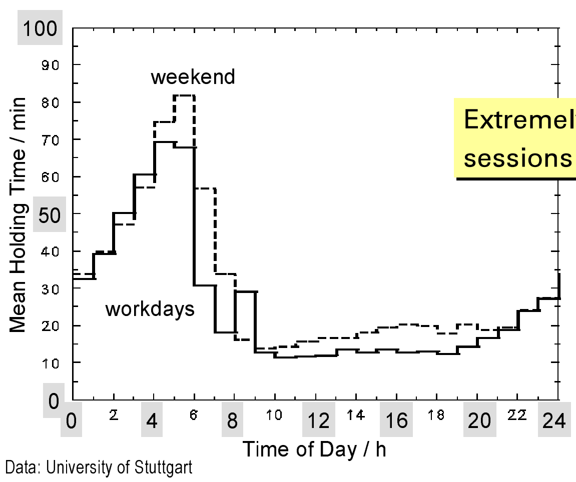
Dialup behaviour
Session Duration (2)



Extremely long dialup sessions during the night

Data: University of Stuttgart

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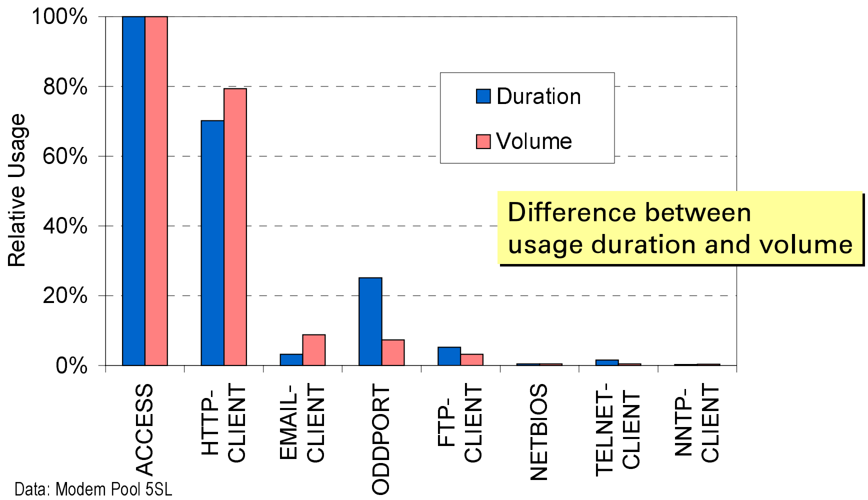
Applications Usage Volume vs. Duration



Data: Modem Pool 5SL

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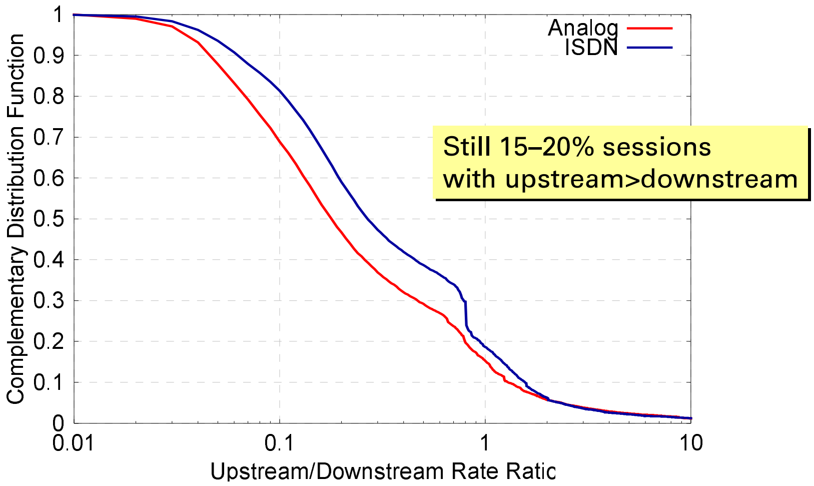
Overall Access Traffic Asymmetry



Data: 5SL

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6. Backbone Measurements

- Traffic mixes (Protocols, Applications)
- Periodic Changes
- Symmetry Relations
- Internet Network Characteristics
- Flow aggregation characteristics

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Traffic Mixes

In addition to local traffic:

- Domain Name System (DNS)
- Network News (nntp)
- Routing Protocols
- Network Management

- CAIDA (www.caida.org) March 2000 (5 min @22:07)
  - 30% HTTP
  - 25% FTP data
  - 13% other TCP
  - 6% Napster
  - 6% Squid Web Cache
  - 5% SMTP
  - 5% Liquid Audio
  - and many more ...

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Periodic Changes and Symmetry

- Daily patterns
  - less activity during early morning (2:00–7:00)
  - prime time during the day (10:00–18:00) or evening (depends on ISP)

- Weekly patterns
  - less activity on Saturday / Sunday

- Asymmetry on international links varies during the day
  - determined by client/server relations
  - mostly export of documents from U.S.

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Network Characteristics

Paxson's Measurements show

- Internet connections are mostly
  - "busy" (relatively high packet loss rate of 4–20%) or
  - "quiescent" (no packet loss)
- Consecutive packets mostly take the same path
  - reverse path may be different

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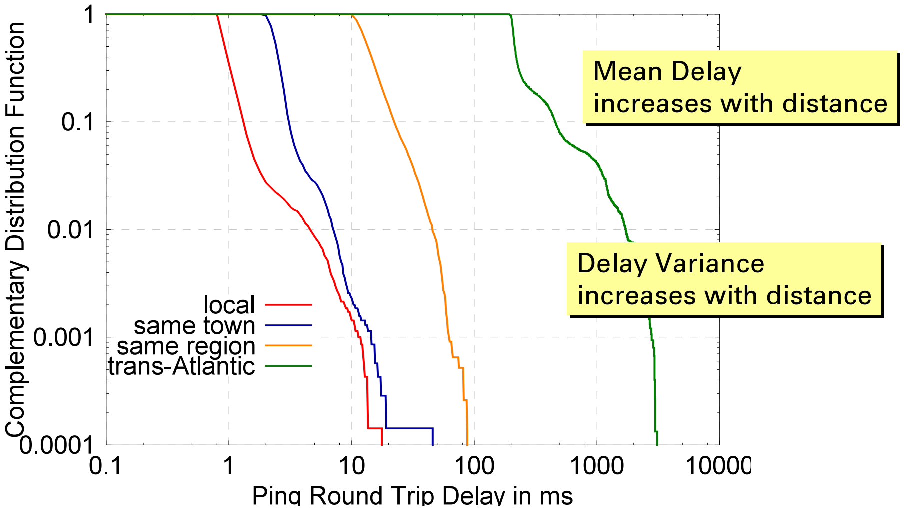
Network Characteristics
Delay Distributions



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Flow Characteristics

- Caution!
  - Flow volume and duration have heavy-tailed distributions
  - expected duration may be infinite
  - volume variance may be infinite
  - mean values are very hard to measure correctly

Normalized characteristics allow comparison:

- Setup rate
  - (new flows per second) / (total traffic bit rate) = 1/(mean flow volume)
- Up-number
  - number of active flows per transported traffic bit rate
- bit fraction
  - fraction of traffic that could be transported in a shortcut

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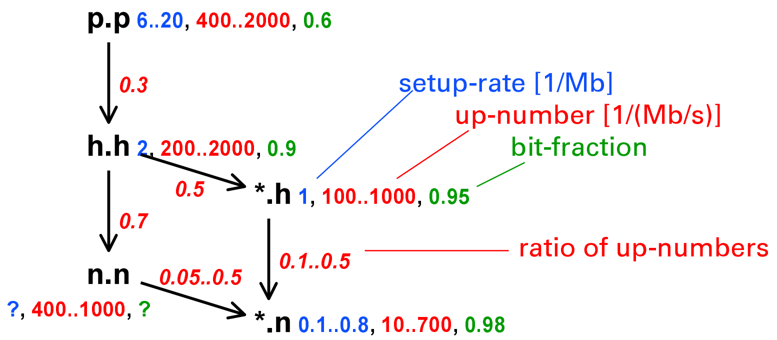
Flows
Aggregation Properties



- bit-fraction improves significantly with aggregation
- up-number typically a few hundred shortcuts per Mb/s with strong variation; small aggregation gain
- smaller up-numbers only for *.n shortcuts beginning close to destination network

data deduced by Paul Schlüter from Copeland et al. (1999), Feldmann et al. (1998), Nagami et al. (1999)

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Outline

Information and Communications

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7. Web Performance

- Delay and Rate influence Performance
- Delay Components
- Delay Distributions
- Protocol and Architecture Options

Information and Communications

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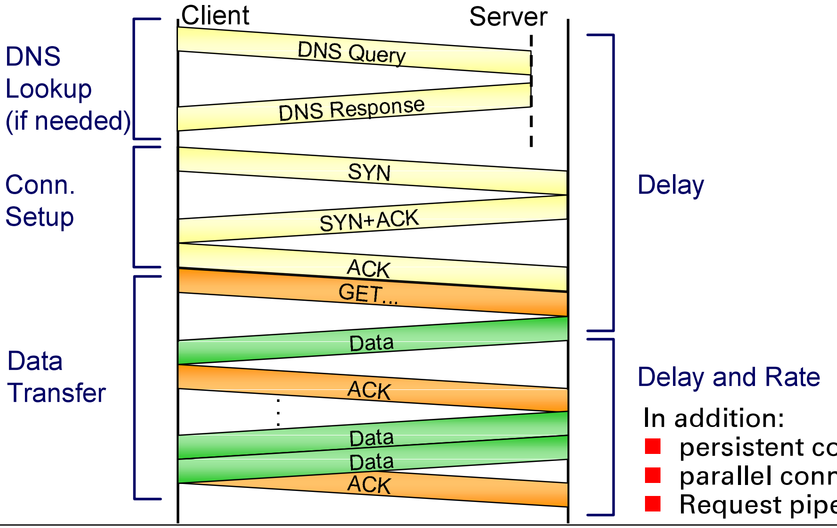
Reminder
DNS-HTTP-TCP



In addition:

- persistent connections
- parallel connections
- Request pipelining

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Web Delay Components

- DNS latency
  - server reaction time
  - retries due to multiple (false) domain name extensions
- Network delay
  - propagation delay
  - processing delay (routing)
  - queueing delay (limited link bandwidth)
- Server reaction times
  - Connection establishment (socket creation, answer to SYN packet)
  - answer to GET request
  - database lookup, page construction time for dynamic pages
- Client reaction times
  - reaction to DNS answer
  - reaction to connection set-up (SYN+ACK)
- Content transmission time (determined by bottleneck bandwidth)
- Others
  - HTTP redirections
  - protocol mismatches (GET causing RST)

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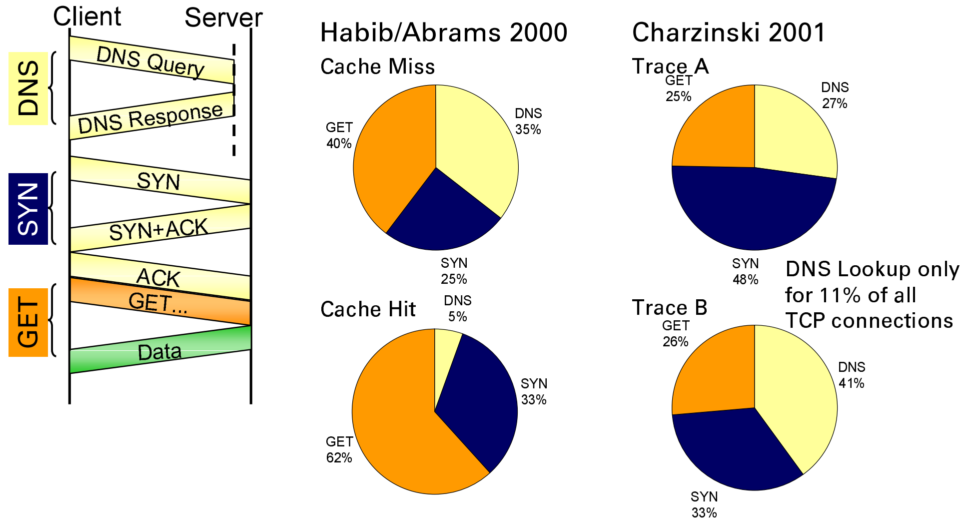
Web Delay Components
Mean shares during DNS-SYN-GET (for first item)



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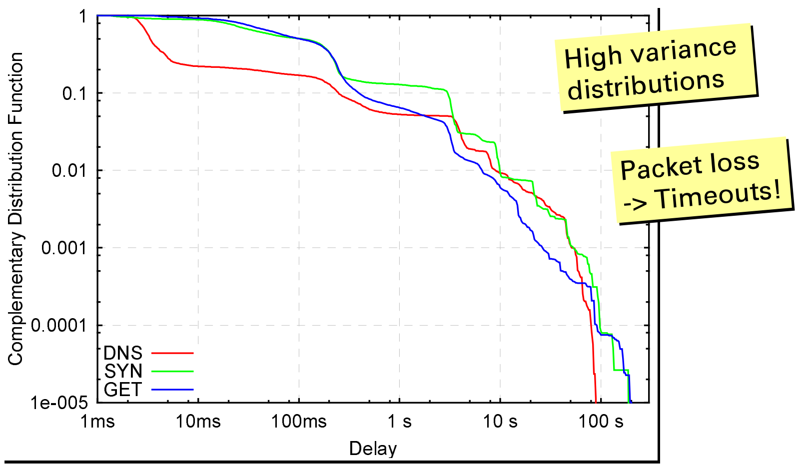
Measured Delay Distributions



Data: ADSL Münster 1998 (Trace A)

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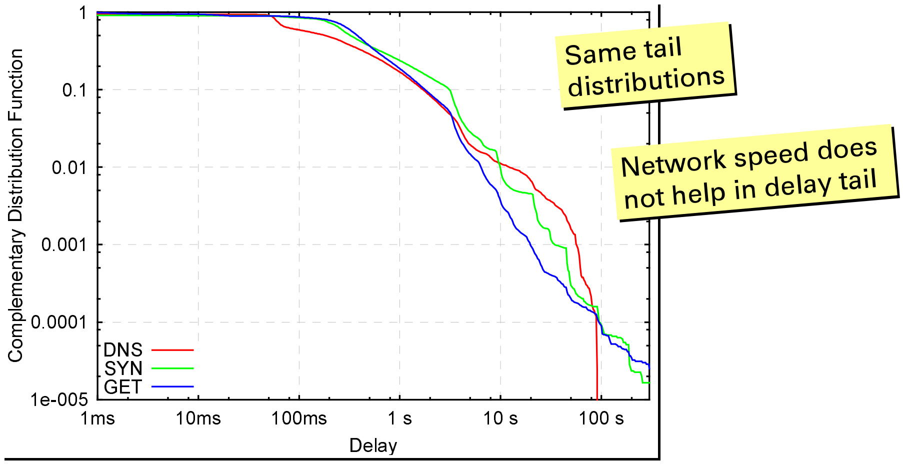
Measured Delay Distributions



Data: 5SL Modem/ISDN 1999 (Trace B)

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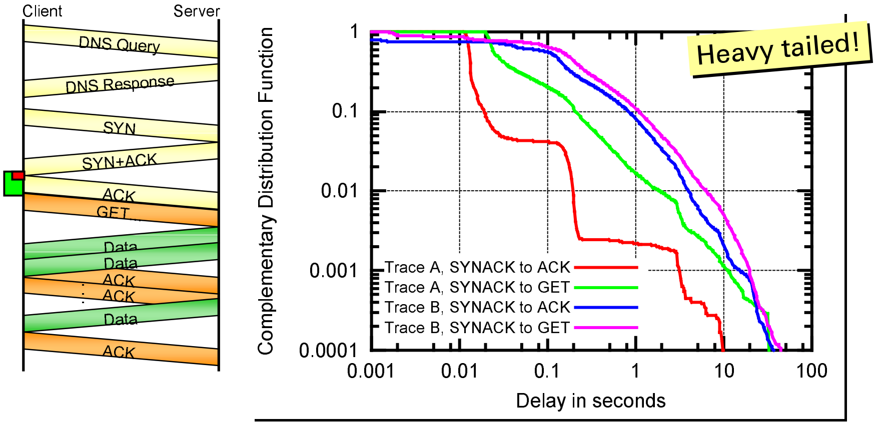
Client Response Times



- 10% of clients needed longer than 200ms (1s) to send GET request
  - main reason: parallel connection handling

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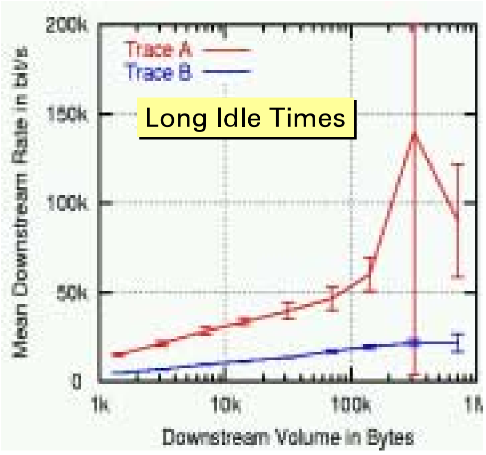
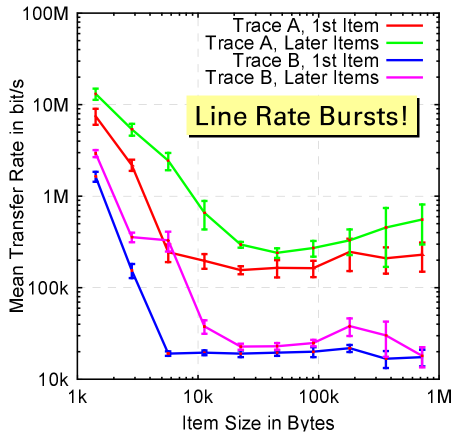
TCP and HTTP Keep-alive Connections
Mean rates versus volume class

Per HTTP/TCP Connection (P2P Flow)



Per Item (Response to one GET Request)



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Web Performance
General Observations

- DNS lookups can take significant time
- Connection establishment
  - routes and servers show “cold” and “warm” states
- small files:
  - most delay between GET request and start of transfer
  - server load is critical
- large files:
  - most delay during transmission
  - network load is critical (timeouts, fast retransmits)
- All delays show heavy-tailed distributions (!)
- High throughput needs good OS scheduling and I/O performance
  - on both sides

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Protocol and Architecture Options

- Caching
  - validation time can be significant [Krishnamurthy/Wills]
  - does not help with dynamic content
- Persistent connections (HTTP/1.0 or HTTP/1.1)
  - can reduce network load
  - bad if server memory is a bottleneck [Barford/Crovella]
- Request pipelining
  - reduces influence of round-trip times to GET more items
  - problem with servers closing connections
    (unclear client/server interaction) [Krishnamurthy/Wills]
- Browser/Proxy options [Cohen/Kaplan]
  - pre-resolving
  - pre-connecting
  - pre-warming (dummy HTTP HEAD)

Information and Communications

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Information and Communications

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8. Models

- Models on Different Activity Levels
- Multilevel Models
- Traffic Model Validation
- Link Dimensioning Models
- Multiplexing Gain
- TCP Models

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Model Types

- Different models for different levels
  - Layer 3 traffic models to drive lower layer simulations
  - user/application models to drive TCP simulations
  - session level models to drive loss simulations
- User and application models
- Single user / backbone traffic models
- Network models
  - e.g. for TCP behaviour
- Multilevel models
  - e.g. for HTTP users or HTTP traffic

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Input Traffic on Different Activity Levels
Access Session Traffic

Access Session

- Holding time
- Arrival rate (single / multiple subscribers)
- Daily traffic variations
- Tradeoff between holding time and arrival rate
  - important e.g. in ISDN or AO/DI access with extremely short conection set-up times
- Influence of tariffs

Models

- M/G/n-0 -> Erlang-B formula
- GI/G/n-0

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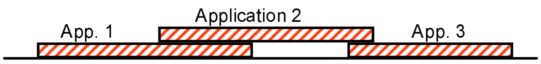
Input Traffic on Different Activity Levels
Application Session Traffic

Within an Access Session:



Application Sessions

- Holding time
- Application usage share
  - correlated with access session holding time!
- HTTP: holding time corresponds to dial-up session h.t.
- Application preferences change over the years
  - e-mail -> Web access -> audio streaming
  - video, games, 3D chat, ...
- Applications evolve over the years
  - lynx, Mosaic, Netscape, Internet Explorer
  - animated GIFs, Frames, Java, Javascript, ...

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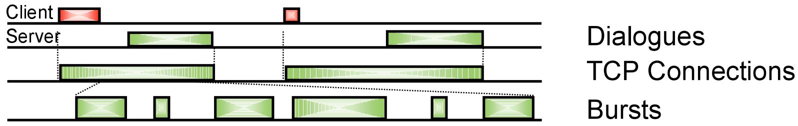
Input Traffic on Different Activity Levels
Dialogues, TCP Connections, Bursts

Within an HTTP Application Session:



- User actions
- Element size distributions
- number of elements per user request
- connection duration distribution
- parallel connections
- Feedback from Network
- TCP: Interaction with other users’ connections
- Bursts within one connection also due to
  - download of multiple elements
  - database look-up in server
  - TCP flow control

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Input Traffic on Different Activity Levels
Dialogues, TCP Connections, Bursts (2)

- Connection interarrival times
  - Weibull distribution
  - timer driven
- TCP’s flow control adapts to available bit rate
  - Limit measured from packet loss (or excessive RTD)
  - When is a link “correctly dimensioned”?
  - Packet traffic traces cannot be re-used in another scenario
  - Packet loss is an unsuitable QoS criterion
  - “fun factor” dimensioning
- Models
  - M/G/R-PS, ON/OFF Fluid Flow
  - Markov models for TCP behaviour
  - FBM Fluid Flow

Input Traffic on Different Activity Levels
Packet Traffic

Within a Burst:

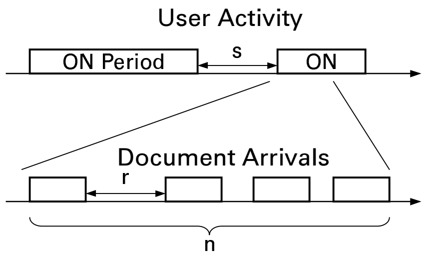
Packets (Client-Server and Server-Client)

- Packet Size Distribution
- Packet Interarrival Time
- Correlations
- Upstream/Downstream Correlations due to TCP
  - Media Access Control issues
  - Time Division Duplex issues

Multilevel Models
Shuang Deng, ICC'96

- ON-OFF model
- Single HTTP user
- Upstream or downstream traffic
- Burst Level

- Duration n of ON period
  - Weibull
- Duration s of OFF period
  - Pareto (infinite mean)
- Interarrival time r
  - approx. Weibull



- Unclear: infinite mean OFF time

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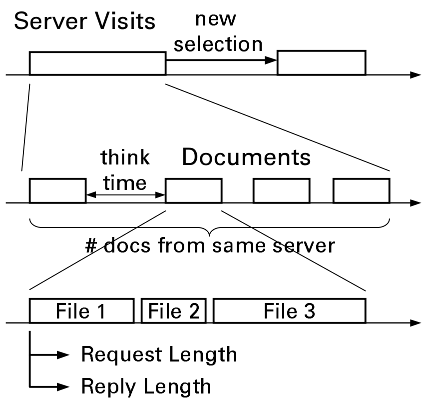
Multilevel Models
Bruce Mah, Infocom'97

- Session and Burst Level
- Single HTTP user
- Upstream and downstream traffic
- Request Length
  - bimodal
- Reply Length
  - Pareto, $\alpha \approx 1.04 – 1.14$
- Number of files per doc.
- Think Time
- Number of docs per server
- Server Selection
  - Zipf's Law



- Think Time includes idle time between sessions -> extremely long!

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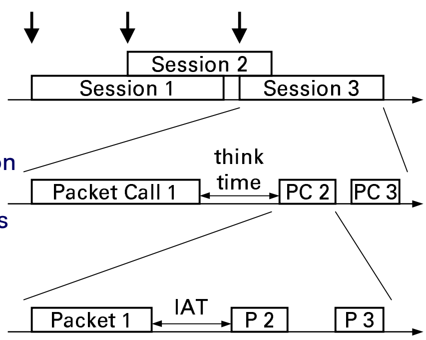
Multilevel Models
"ETSI/3GPP UMTS" Traffic Model

- Session arrivals (Poisson Point Process)
- "Packet Calls"
  - number of packet calls per session (geometric)
  - reading time between packet calls (geometric)
- Packets
  - number per packet call (open)
  - packet IAT (geometric/open)
  - packet size (cut-off Pareto)



- Packet Call length instead of packet size should be Pareto

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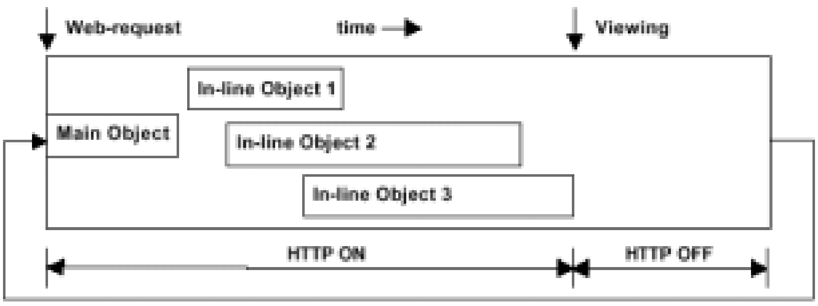
Multilevel Models
Choi and Limb, ICNP'99

Choi/Limb 1999



- parallel connections
- detailed structure of HTTP downloads

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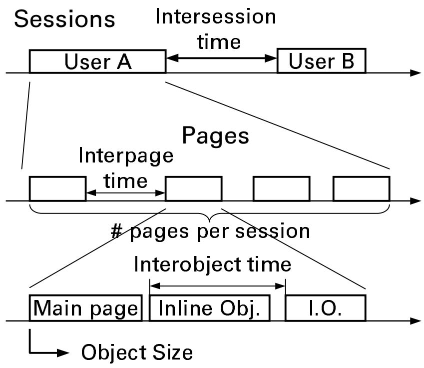
Multilevel Models
Feldmann et al, Sigcomm 1999

- Session and Burst Level
- used to drive TCP simulations
- Weibull or timer-driven connection interarrival times



- Good description of parameters

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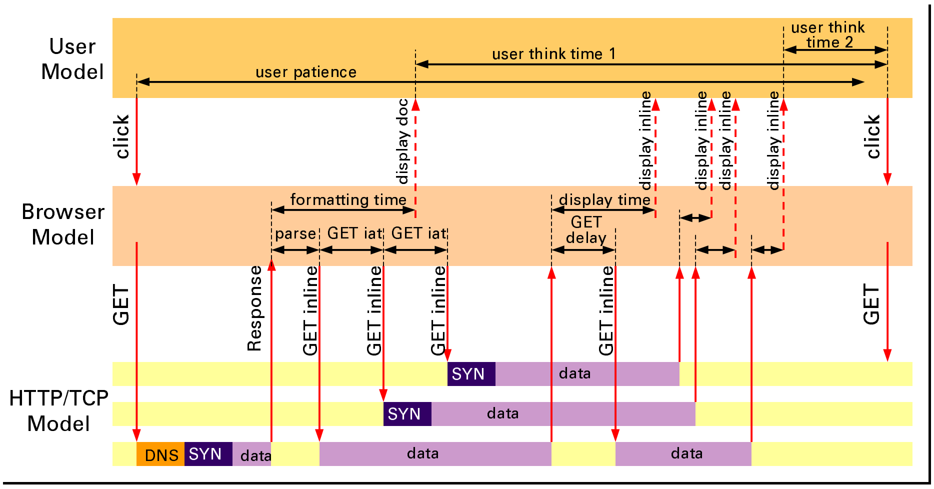
Multilevel Models
Färber 2001 (unpublished)



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Multilevel Models
Parameters

- Many parameters but easy to understand
- How to determine parameters?
  - Often difficult to extract even from packet trace measurements
- Parameters depend on other constraints
  - network speed
  - computer (client / server) speed
  - delays
  - tariffs
- Contrast: Multi-fractal models
  - canonical set of parameters (per time scale octave)
  - measurement based
  - with little physical meaning

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Traffic Model Validation

- Equivalence of generated traffic:
  Check statistics
  - size / interarrival time distributions
  - correlation structure
- Validation within system/network model of interest:
  Check model against measured trace in simulation
  - same queue length / delay statistics or
  - same loss probability
- don't just
  - generate optically equivalent traffic
  - postulate user behaviour

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Link Dimensioning

- Bufferless models
  - burst scale approximation
  - assumption: enough buffer for packet scale multiplexing
  - no burst buffering capability
- Buffer models
  - take burst scale buffering into account
  - inefficient with long-range dependent traffic
- unelastic models
  - take traffic as inevitable
  - compute loss probability (and packet delay)
- elastic models
  - include TCP's flow control
  - compute total delay e.g. for transfer of a given file

Worst-Case (low loss) models
Rate Envelope Multiplexing (REM)

- Make sure that the considered link is not a bottleneck
  - make the loss rate on this link low enough
  - -> TCP will not be influenced by this link
  - use bufferless burst scale model to make sure small packet scale buffers will suffice
- Example: ON-OFF Rate Envelope Multiplexing
  - n ON/OFF sources with ON probability β and rate r_{ON}

$$p_{loss} = \sum_{i=\lceil c_L / r_{ON} \rceil}^{n} \binom{n}{i} \beta^i (1-\beta)^{n-i} \frac{i\, r_{ON} - C_L}{\rho C_L}$$

Norros' Fractional Brownian Motion Model

- Input traffic is FBM with drift
  $A_t = mt + \sqrt{ma} Z_t$
  - mean rate m, Hurst parameter H, variance coefficient a
- Captures long-range dependence
  - buffer can be dimensioned including LRD effects
  - several approximations reduce accuracy of results
  - rate dimensioning results do not differ significantly from approaches that take the variance into account but ignore LRD

$$C = m + (H^H (1-H)^{1-H} \sqrt{-2\ln\varepsilon})^{\frac{1}{H}} a^{\frac{1}{2H}} x^{\frac{H-1}{H}} m^{\frac{1}{2H}}$$

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M/G/r-PS
Processor Sharing Model

- Input traffic
  - Poisson arrivals of fluid ON/OFF traffic streams
  - arrival rate λ, maximum ON rate r_{ON}
  - generally distributed (e.g. heavy-tailed) ON volume
- TCP flow control modeled by Processor Sharing discipline
  - simple approximation for TCP behaviour on a single link
  - result: (time) mean of delay factor f_R

$$f_R = 1 + \frac{1}{r(1-\rho)} \frac{\frac{(r\rho)^{r_g}}{r_g!}}{(1-\rho)\sum_{i=0}^{r_g-1}\frac{(r\rho)^i}{i!} + \frac{(r\rho)^{r_g}}{r_g!}}$$

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Multiplexing Gain

- In order to achieve the same level of QoS, less resources are needed when traffic is aggregated.
  - Packet (cell) level: "Multiplexing Gain"
  - Connection (call) level: "Economy of Scale"
- gain can be achieved as long as there is variance in the traffic
  - Self-similar traffic also shows multiplexing gain
  - Self-similar traffic still shows multiplexing gain at high aggregation levels

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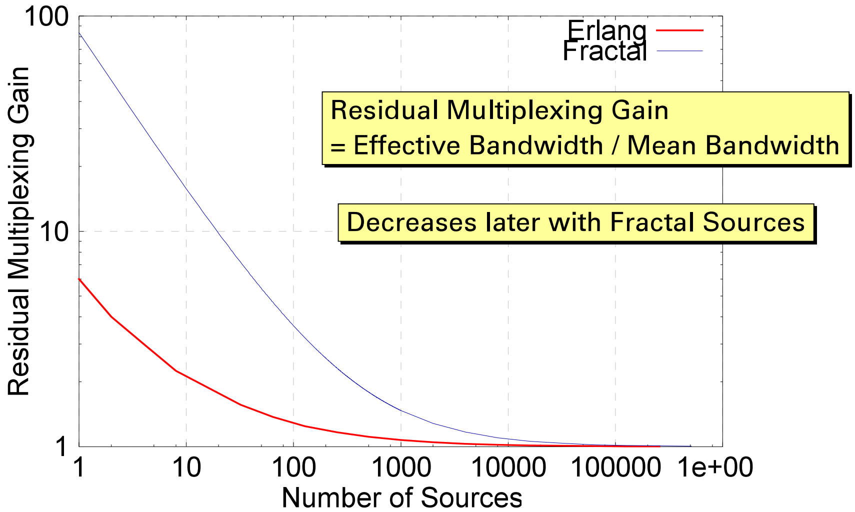
Multiplexing Gain
Example



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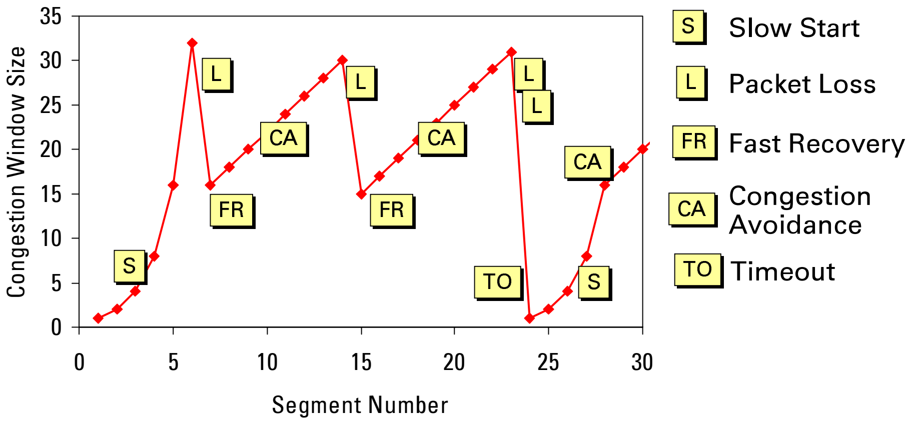
TCP Models

- Analytical models include relevant system states
  - basic idea: get stochastic distribution of system state occupancy and derive other measures (e.g. throughput) from that
- CWND
  - congestion window
  - sender can send CWND segments until acknowledgement is needed
- Threshold
  - CWND value at which exponential increase ("slow start") is replaced by linear increase ("congestion avoidance")
- Often additional assumptions
  - greedy source
  - fresh connection
  - independent packet losses
- There are different TCP versions around!

TCP Models
General Behaviour

- TCP Reno trace



TCP Models
Main Result

- Steady state bandwidth [Padhye, Firoiu, Towsley, Kurose 1998]

$$B \sim \frac{1}{RTT} \cdot \sqrt{\frac{3}{2 \cdot b \cdot p}}$$

B achievable throughput
RTT round trip time
p packet loss probability (low)
b number of acknowledget packets per ACK received

- fast decrease for higher packet loss rates
- lower throughput for long round trip times

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Outline

1. Introduction
2. User and Application Behavior
3. Application Behavior Measurements
4. Self-Similarity
5. User Behavior Measurements
6. Backbone Measurements
7. Web Performance
8. Models
9. Implications for Simulation
10. Implications for Quality of Service

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9. Implications for Simulation

- Steady State and Confidence
- Infinite Expectations
- Input Parameters
- Deterministic Scenarios

Steady State and Confidence

Effects of long-range dependent traffic

- steady state reached slowly
  - stochastic generators (input processes!)
  - observed system state (e.g. queue length)
- High variability at steady state
  - high probability of "swamping" observation
- Standard deviation of batch means decreases slowly
  - To reduce batch means standard deviation by a factor of 10: simulate factor of $10^{1/(1-H)}$ longer
  - H=0.5: factor 100 longer
  - H=0.9: factor 10 000 000 000 longer!

Infinite Expectations

- ... can never be simulated ☺
- M/G/1 has infinite expected waiting time if the "G" has infinite variance
  - Mean Waiting Time $E[W] = E[S]\frac{\rho(1+c_S^2)}{2(1-\rho)}$
  - Residual Lifetime $E[R] = \frac{c_x^2+1}{2}E[X]$
- model carefully
  - consider packets instead of bursts or
  - for TCP, use M/G/r-PS or M/D/1-PS instead of M/G/1
- limit distributions
  - check validity of assumption (e.g. do simulation results change with limit?)
  - introduce corresponding mechanisms into networks (e.g. limit on e-mail sizes)

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Input Parameters

- Don not use the Normal distribution
  - Finite probability for X<0
- Use input parameters that have a meaning
  - and make sure the corresponding random variables have finite mean
- TCP traces are generally invalid
  - if simulation includes TCP model -> use file sizes
  - if simulation does not include TCP -> only binary result possible
    - YES: the simulated network does not disturb TCP
    - NO: the simulated network disturbs TCP and results will be fundamentally different
- The “mean packet size” is generally uninteresting
  - Packet sizes have multimodal distributions

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Deterministic Scenarios

- Be careful not to simulate trivial scenarios ad infinitum
- Ensemble statistics vs. single source statistics
- Applications:
  - Voice over IP on packet level
  - other constant rate sources
- Solutions
  - in simple models: identify period and change phase cyclically
  - use phase changing generators
  - use frequency shifted generators

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Outline

Information and Communications

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10. Some Remarks on QoS

- Traffic Types
- QoS for Elastic Traffic?
- Problems of Admission Control for Web Traffic

Information and Communications

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Traffic Types

- Elastic Traffic
  - transported over TCP
  - given amount of data are to be transmitted "as fast as possible"
  - error control with automatic repetition (ARQ)
  - utilization of maximum available bandwidth (without excessive loss)
  - Classical (stream oriented) traffic descriptors (Leaky Bucket) are invalid

→ Network bandwidth determines "fun factor"

- Stream Traffic
  - given bit rate
  - using e.g. RTP/UDP as transport protocol
  - delay, loss and delay variation to be limited
  - blocking to be limited

→ Network bandwidth determines usability

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QoS for Elastic Traffic?

- Web access is an important service in IP networks
- reason for investing in IP access (besides e-mail)
- fundament for other modern services
  - e-commerce, e-business, etc

- Our performance picture of the Internet is determined by the Web!

→ Web performance is an important issue

- QoS should not only be considered for streaming applications

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QoS for Elastic Traffic

- Problem: compliance with bandwidth sharing model
- Use e.g. congestion marking/pricing

- Guaranteeing QoS to elastic traffic needs admission control
- ... and effective pricing!

- Flat rate and no admission control leads to highway situation
  - congestion
  - priority helps you get faster to the next point of congestion [P.Key]

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Problems of Admission Control with Web Browsing

Admission Control on a per-TCP connection basis:

- wrong unit of transfer
  - multiple requests per connection with pause in between
- penalizes many short connections instead of one long one
  - long conn. can restart transmission at arbitrary byte number in HTTP/1.1
  - average size is more variable than arrival rate
- application view
  - bad QoS even for admitted “flows” if one out of n connections for loading a page is blocked
  - basis for admission control should be multi-connection transaction rather than single TCP connections
  - problems with predictability and describability of traffic

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www.nw.com or http://www.isc.org/dsview.cgi?domainsurvey/index.html

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http://www.ripe.net/statistics/index.html

http://www.dfn.de/win/allinfo/statistik/

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