get these slides in color from http://www.jcho.de/jc/Pubs/

ICNP 2002

Paris, France, Nov. 12, 2002

Tutorial C

SIEMENS

Information and Communication Networks

Internet Traffic

Characteristics, Performance and Models

Joachim Charzinski

j.charzinski@ieee.org • http://www.jcho.de/jc/

SIEMENS

Outline

SIEMENS

Why Bother?

Section 1 Introduction
Why Bother?
Dimensioning
Internet

- Support for QoS will require some knowledge about traffic
- non-bottleneck links
  - traffic not to be influenced by the link being dimensioned
  - use traffic patterns occuring on the link if capacity $\to \infty$
  - 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 parameter
- Evaluation of user perceived quality of service
  - SLA validation and advertising

SIEMENS

Dimensioning

Section 1 Introduction
Why Bother?
Dimensioning
Internet

- Dimensioning targets
  - optimum tuning of link capacities in a network
  - exploitation of economy of scale
  - Service Level Agreements
- Problem: growth
  - exponential growth (factor 1.5 to 10 p.a.)
  - all network nodes exchanged every 1 to 3 years
- Problem: traffic forecast
  - new applications introduced “over night”
  - very dynamic private market (entertainment!)
- Problem: heterogeneous network
  - new network properties cannot be introduced by central “prescription”
  - Who guarantees assured QoS?
  - Who pays for QoS assurance?

SIEMENS

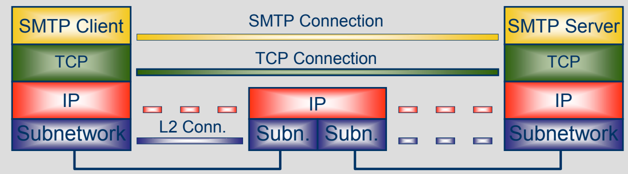
Traffic Engineering vs. Traffic Management

- The IETF 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
- Traffic Engineering (IETF) / Traffic Management (trad.)
  - managing dynamic traffic load
  - route adaptation
  - capacity management
  - ⇒ a network management task

different definitions!

SIEMENS

Internet Layers
Example: E-Mail



- SMTP connection realised using TCP/IP
- only connectionless packet switching used in WAN
- subnetwork links between IP routers can be connection oriented or connectionless

Traffic determined by applications, protocols, configuration and users

SIEMENS

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

Traffic modeling is Important in both cases!

SIEMENS

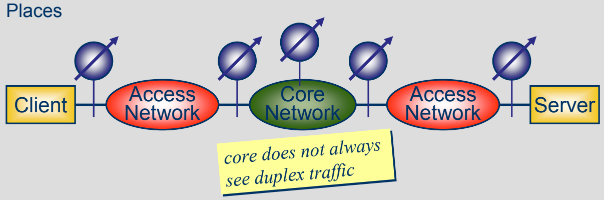
Outline

SIEMENS

Internet Measurement

Section 2 Measurement
- Measurement
- Distributions
- Power Tails

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

(Packet trace evaluated offline … Cyclic reading of counter values: passive; (ping) delay and bandwidth tests, application layer tests: active)

SIEMENS

Internet Measurement Data Collection

Section 2 Measurement
- Measurement
- Distributions
- Power Tails

- Packet trace
- Flow trace: one record per
  - TCP connection
  - other flow levels
- Pre-processed 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

SIEMENS

Internet Measurement Some Tools

Section 2 Measurement
- Measurement
- Distributions
- Power Tails

- 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
  - specialized measurement boxes

SIEMENS

Traces used here

Section 2 Measurement
- Measurement
- Distributions
- Power Tails

- Packet traces (acquired close to users)
  - Trace A: ADSL Uni Münster, May–Dec. 1998
  - Trace B: Modem/ISDN Fünfseenland, Mar. 1999
  - Trace C: Auckland IV, one week during Feb. 2001

	Trace A	Trace B	Trace C
Packets	60 M	43 M	219 M
SMTP connections	2.1 k	3.4 k	335 k
SMTP mails	2.1 k	4.3 k	324 k
POP3 connections	34 k	31 k	88 k
POP3 mails	5 k	12.8 k	5.2 k
IMAP connections	–	–	6.3 k
IMAP mails	–	–	7.5 k

Trace Evaluation

- timestamp, IP and TCP headers only
- no application level data

timestamp	pkt size	prot	source IP addr.	destination IP addr.	source port	dest port	TCP flags
17:05:20.848707	80	udp	154.232.114.71	128.176.0.12	1033	53	
17:05:20.852981	290	udp	128.176.0.12	154.232.114.71	53	1033	
17:05:20.876821	60	tcp	154.232.114.71	128.176.188.76	1034	25	.S...
17:05:20.880071	60	tcp	128.176.188.76	154.232.114.71	25	1034	AS...
17:05:20.894943	60	tcp	154.232.114.71	128.176.188.76	1034	25	A....
17:05:21.069365	60	tcp	128.176.188.76	154.232.114.71	1530	113	.S...
17:05:21.085330	60	tcp	154.232.114.71	128.176.188.76	113	1530	A..R.
17:05:21.090537	140	tcp	128.176.188.76	154.232.114.71	25	1034	A...P
17:05:21.106804	76	tcp	154.232.114.71	128.176.188.76	1034	25	A...P
17:05:21.109469	248	tcp	128.176.188.76	154.232.114.71	25	1034	A...P
17:05:21.128375	90	tcp	154.232.114.71	128.176.188.76	1034	25	A...P
17:05:21.273811	60	tcp	128.176.188.76	154.232.114.71	25	1034	A....
17:05:22.342421	97	tcp	128.176.188.76	154.232.114.71	25	1034	A...P

- trace replayed into pseudo protocol state machines
- latency distributions etc measured

SIEMENS

Probability Distributions

Section 2
Measurement
Measurement
Distributions
Power Tails

Random Variable X

- described by the probability to take certain values

- discrete random variables
  - $X = x$
  - examples:
    - number of downloads per session
    - number of active users

- continuous random variables
  - $X \in [x, x+dx]$
  - examples:
    - session duration
    - packet interarrival time

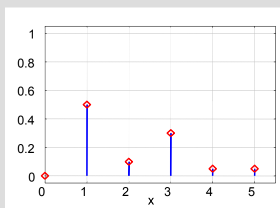
SIEMENS

Discrete Distributions

Section 2
Measurement
Measurement
Distributions
Power Tails

- Probability Distribution, Probability Mass Function

$p_X(x) = P\{X = x\}$

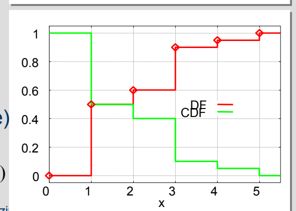


- (Cumulative) Distribution Function

$F_X(x) = P\{X \le x\}$

- Complementary (Cumulative) Distribution Function

$C_X(x) = P\{X > x\} = 1 - F_X(x)$



SIEMENS

Continuous Distributions

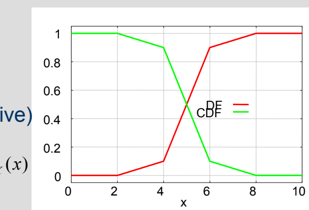
Section 2
Measurement
Measurement
Distributions
Power Tails

- (Cumulative) Distribution Function

$F_X(x) = P\{X \le x\}$

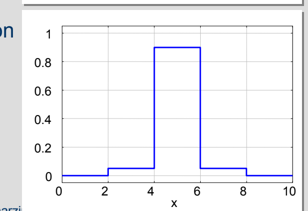
- Complementary (Cumulative) Distribution Function

$C_X(x) = P\{X > x\} = 1 - F_X(x)$



- Probability Density Function

$f_X(x) = \frac{d}{dx} P\{X \le x\}$



Most results will be given as Complementary Distribution Functions

SIEMENS

- Complementary (cumulative) distribution function

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

Logarithmic scaling!

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

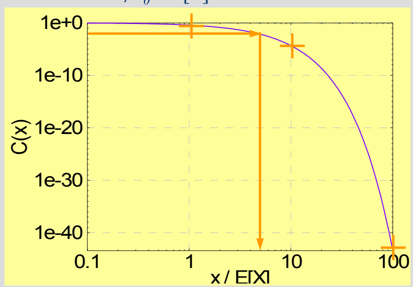
$$F_{\exp}^C(x) = e^{-x/x_0}$$

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

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

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

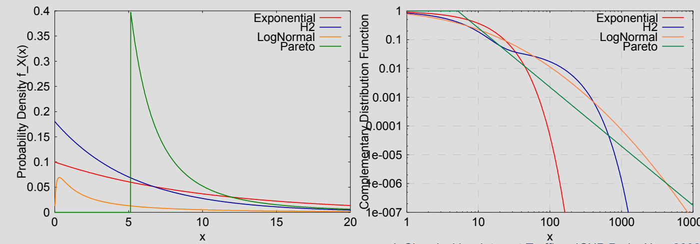
$P\{X>4.61E[X]\} \approx 0.01$



Probability Distributions Examples

SIEMENS

- 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



Distribution Fitting Methods

SIEMENS

- 1st step: select appropriate distribution
  - either optically
  - or from hypotheses / knowledge about underlying processes
- Moment Fitting
  - Estimate mean and variance
  - set distribution parameters
- Optical / Distribution Fitting
  - minimize difference (e.g. MSE) between measured and analytical distribution
- Maximum Likelihood Method
  - maximize Likelihood for getting the observed samples $X_1 \ldots X_n$

$$L(\lambda_1, \lambda_2, \ldots \lambda_k) = \prod_{i=1}^{n} f_{\lambda_1,\lambda_2,\ldots\lambda_k}(X_i)$$

Distribution Fitting Tests

SIEMENS

- χ^2 Test
  - divide observed and expected distribution into k classes
  - ≥ 10 observations per class
  - determine $\chi^2 = \sum_{i=1}^{k} \frac{(f_{oi} - f_{ei})^2}{f_{ei}}$
  - check probability of rejection using χ^2 table
  - Test ignores tails
  - Test tries to evaluate "Do values come exactly from this distribution?"
- Optical Tests: e.g. Q-Q plot
  - For $p \in [0,1]$, x_o is plotted versus x_e in a double log plot,
    x_o: $P\{X_o > x_o\} = p$ (observed)
    x_e: $P\{X_e > x_e\} = p$ (expected)
  - distributions can be compared over a wide range of values

SIEMENS

Power Tails

Section 2 Measurement
Measurement
Distributions
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 $\rightarrow \infty$

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

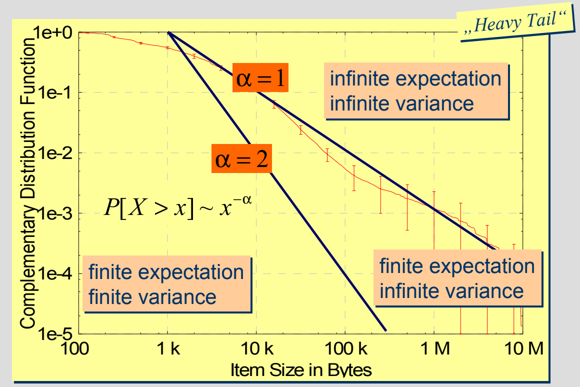
- very large values of X occur with a much higher probability than expected from “usual“ distributions

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

SIEMENS

Power Tails (2)

Section 2 Measurement
Measurement
Distributions
Power Tails



J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

SIEMENS

Power Tails
Example

Section 2 Measurement
Measurement
Distributions
Power Tails

- Negative exponential distribution

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

- Pareto distribution

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

- 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

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

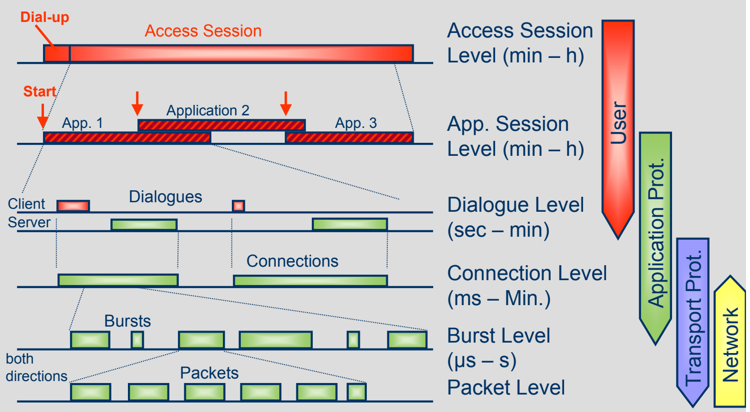
SIEMENS

Outline

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

Activity Levels in User and Application Behavior

SIEMENS



Separation of User and Applications Behavior

SIEMENS

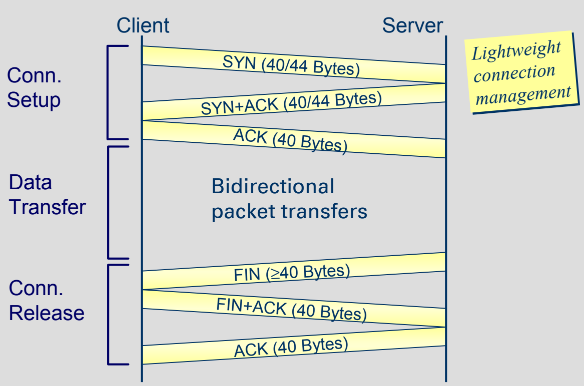
Section 3
Users and Apps.
Separation
TCP
Flows

- User Behavior
  - Access session start
  - Choice and usage of Applications
- Applications Behavior
  - size distribution of E-Mail, HTTP page, FTP download
  - application layer protocols
    - authentication, request/response, app. layer acknowledgments
  - also: (in parts): application usage duration
- Transport Protocol and Network Behavior
  - packet traffic due to
    - TCP connection management
    - TCP acknowledgements
    - stream flow control (influenced by network performance)

TCP Connection Management

SIEMENS

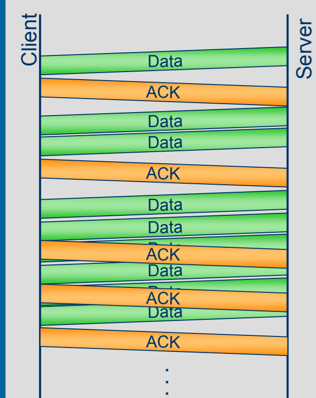
Section 3
Users and Apps.
Separation
TCP
Flows



TCP Bulk Data Transfer

SIEMENS

Section 3
Users and Apps.
Separation
TCP
Flows

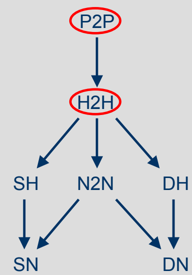


- Acknowledgements in reverse direction
- "Delayed ACK" option: only acknowledge every 2nd packet (+timeout)
- Rate influenced by network congestion (delay, loss)
- Slow start
  - exponential growth of sender's window

Flow Definitions
Traffic Aggregation Relations

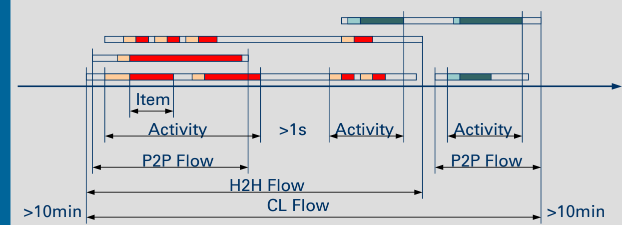
SIEMENS

- 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)

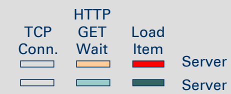


Measurement
Flow Definitions etc

SIEMENS



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



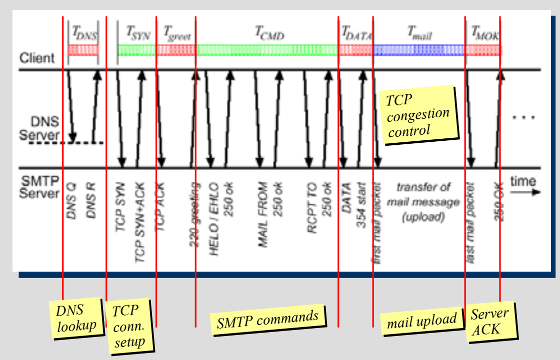
Outline

SIEMENS

1. Introduction
2. Measurement and Distributions
3. User and Application Behavior
4. Application Behavior Characteristics
5. Self-Similarity
6. User Behavior Characteristics
7. Backbone Measurements
8. Performance
9. Models
10. Implications for Simulation

E-Mail
The SMTP Protocol

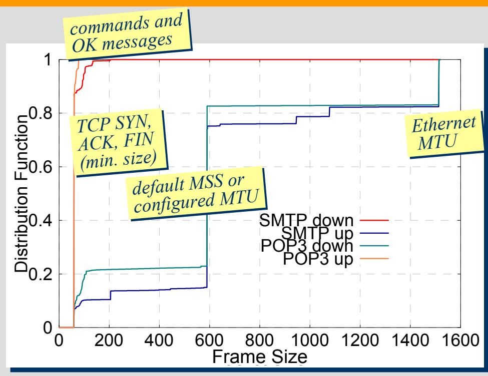
SIEMENS



- high degree of serialized command exchanges

E-Mail
Packet / Frame Sizes

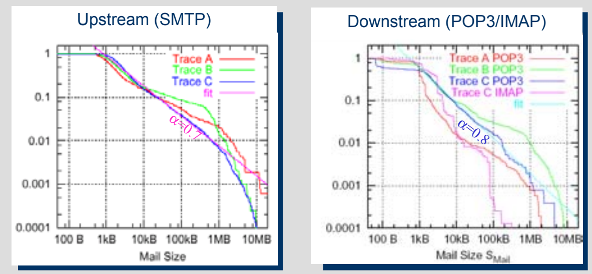
SIEMENS

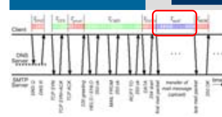


Data: Modem Pool 5SL

Size Distributions of Single E-Mails

SIEMENS

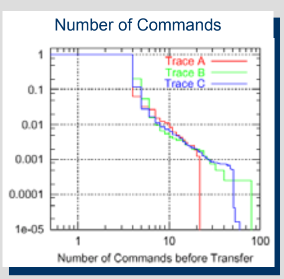




very large mails are observed in upstream and downstream

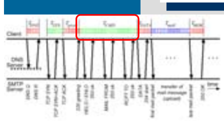
Command Exchange

SIEMENS



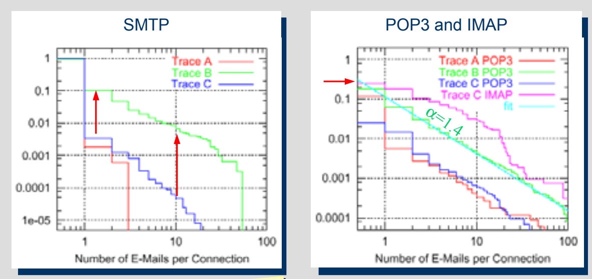
... number of recipients

Single command models cover only a part of reality



Number of E-Mails per Connection

SIEMENS



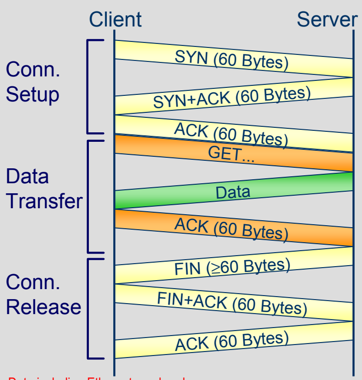
more mails per connection in low-speed dial-up

many "check only" connections

WWW Access
HTTP and TCP minimum connection

SIEMENS

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer



% Pkts	Pkt./ Conn.	% Bytes
4	1	0.5–0.7
4	1	0.5–0.7
4	1	0.5–0.7
6	1.5	5–6
40	10	83–88
30	7.5	3–5
3	0.75	<1
3	0.75	0.4
2	0.5	0.4

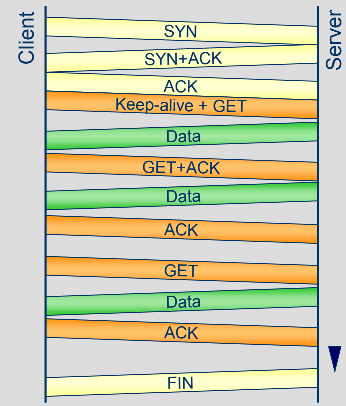
Up/down ratios:
1:1.05 1:7.9

Data including Ethernet overhead
Measurements: ADSL MS and Modem Pool 5SL: >2 mio. connections

WWW Access
Keep-Alive / Persistent Connections

SIEMENS

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer



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

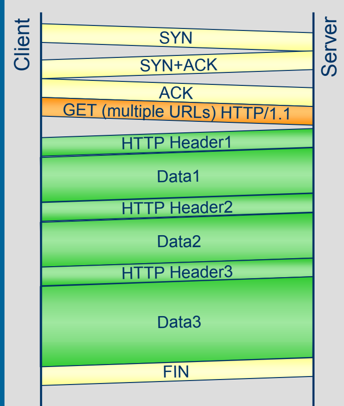
HTTP Version 1.1
- persistent connections
- default
- plus pipelining (optional in HTTP/1.1)

Timeout (e.g. 15sec)

WWW Access
Pipelining

SIEMENS

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer

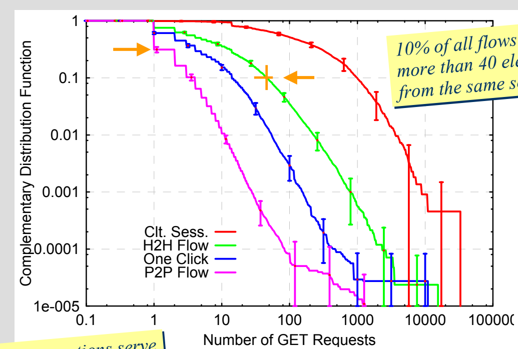


- feature of HTTP Version 1.1
- saves on latency
- content-length field in HTTP header used for in-band data delineation
- problem with dynamic elements:
  - size unknown in advance
  - server closes connection to mark end of data
  - browser needs to keep track of delivered elements

WWW Access
Number of GET Requests per Flow

SIEMENS

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer



10% of all flows get more than 40 elements from the same server

30% of all connections serve more than one request

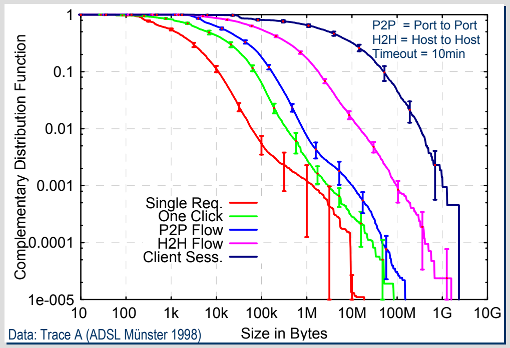
P2P	Port to Port
H2H	Host to Host
Clt.	Client
Timeout	10min

Data: ADSL Münster

WWW Access
Flow Volumes

SIEMENS

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer

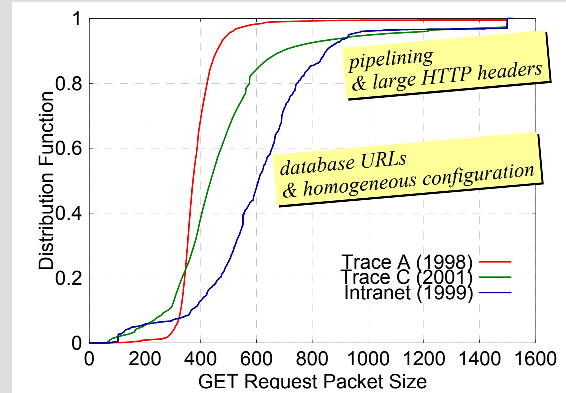


J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

WWW Access
Distribution of GET Request packet sizes

SIEMENS

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer

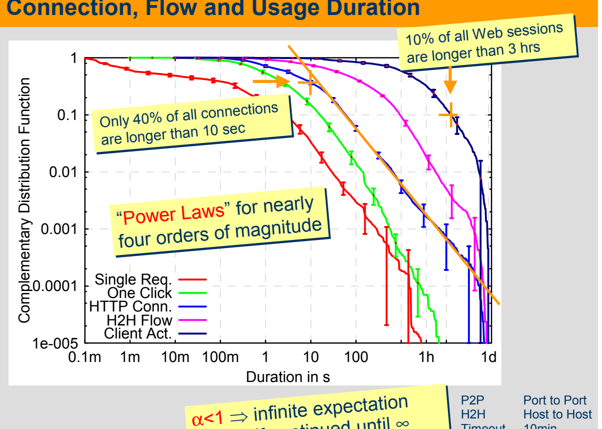


J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

WWW Access
Connection, Flow and Usage Duration

SIEMENS

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer



P2P Port to Port
H2H Host to Host
Timeout 10min

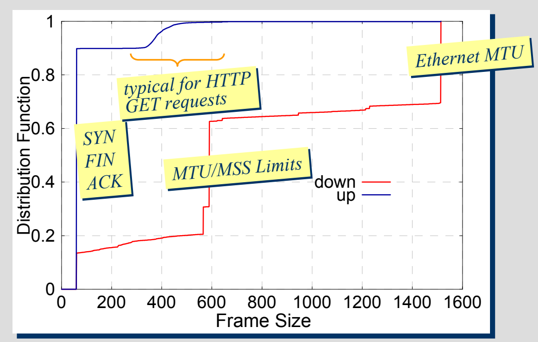
Measurement: ADSL Münster

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

WWW Access
Packet/Frame Size Distribution

SIEMENS

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer

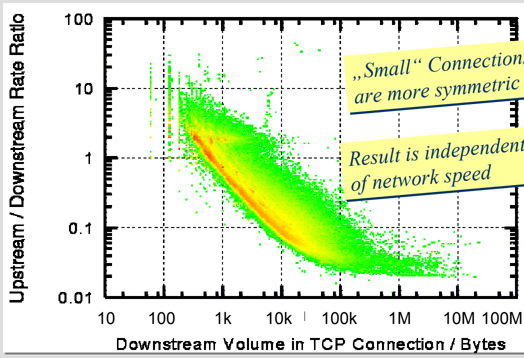


Data: ADSL Münster, incl. Ethernet overhead

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

WWW Access
Bit Rate Symmetry

SIEMENS

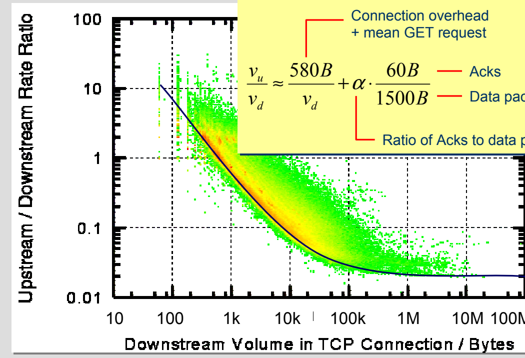


„Small“ Connections are more symmetric

Result is independent of network speed

WWW Access
Bit Rate Symmetry

SIEMENS



TCP Characteristics

$$\frac{v_u}{v_d} \approx \frac{580B}{v_d} + \alpha \cdot \frac{60B}{1500B}$$

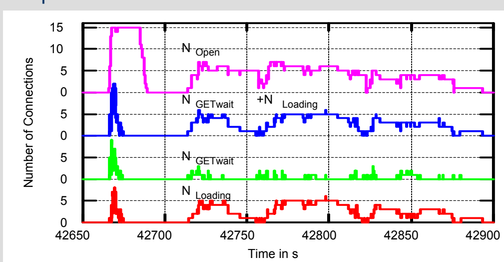
- 580B: Connection overhead + mean GET request
- 60B: Acks
- 1500B: Data packets
- α: Ratio of Acks to data packets

Data: ADSL Münster

WWW Access
Parallel Connections

SIEMENS

- Excerpt from a trace for one client



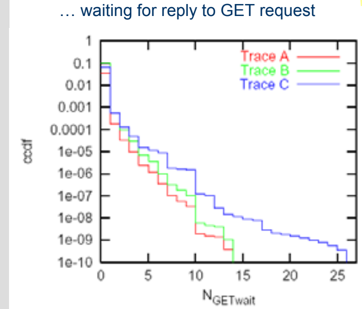
... most models assume one connection per user ...

WWW Access
Number of Parallel Connections

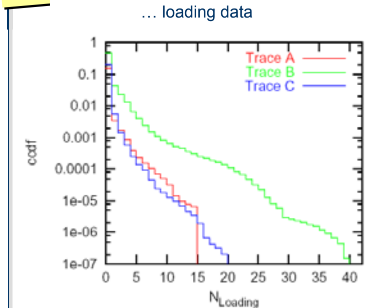
SIEMENS

>40 loading connections per client observed!

… waiting for reply to GET request



… loading data



results depend on implementations: - browser, server, proxy, and TCP

SIEMENS

Online Games

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer

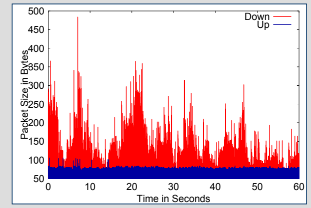
- different concepts
  - complete download of executable game (e.g. Java applet)
  - user plays against server
  - direct interaction between multiple users
- different games and players
  - periodic state updates vs. transmission of state changes
  - action vs. thinking games
  - activity patterns of 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

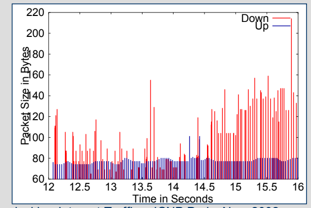
SIEMENS

Online Games Example

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer

- 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





SIEMENS

Peer to Peer Applications

Section 4 Applications
- E-Mail
- Web Access
- Games
- Peer to Peer

- examples: napster, gnutella
- distributed architecture for exchanging (large) files
  - directory queries and content exchanged between different hosts
- topology is highly dynamic
  - low IP and application layer uptimes
    - only 20% of hosts are online more than 93% of the time
- new traffic characteristics
  - LOTS of control traffic
  - long lasting sessions (20% longer than 3 hours)
  - large files (typical MP3 file is around 4MB, video even larger)
- usage depends heavily on network restrictions
  - more than 50% of total traffic in unrestricted environments
  - often blocked by firewalls and/or local administration policies

[Saroiu, Gummadi, Gribble (MMCN2002)]

SIEMENS

Outline

Power Tails

SIEMENS

Section 5 Self-Similarity
- Power Tails
- Self-Similarity

Observations from application behavior:

- high variance distributions
  - number of bytes per element
  - number of elements per transfer (Web page, HTTP connection, E-Mail connection)
- duration distributions are “more power tailed” than size distributions
- most tail coefficients in the “infinite variance” range
  - measurement results are all finite but often unreliable

Long-Range Dependence and Self-Similarity

SIEMENS

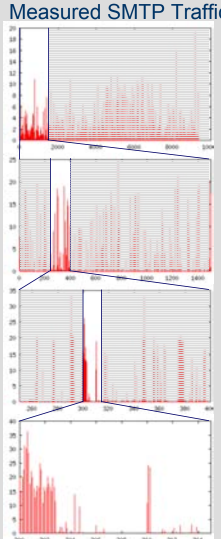
Section 5 Self-Similarity
- Power Tails
- Self-Similarity

- Relative variance does not decrease as fast as expected
  - on time scale aggregation
  - still usual reduction 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

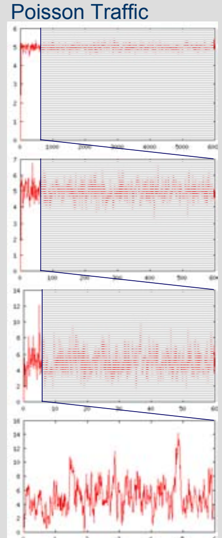
High File Size Variance → Long-Range Dependence → Self-Similarity

- Limits
  - packet level time resolution
  - instationarity
  - -> check time dependence of traffic parameters

Measured SMTP Traffic



Poisson Traffic



10s Aggregates over 10000s

1s Aggregates over 1500s

0.1s Aggregates over 150s

10ms Aggregates over 15s

Self-Similarity Different Views

SIEMENS

Section 5 Self-Similarity
- Power Tails
- Self-Similarity

- 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

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

Section 5
Self-Similarity
Power Tails
Self-Similarity

SIEMENS

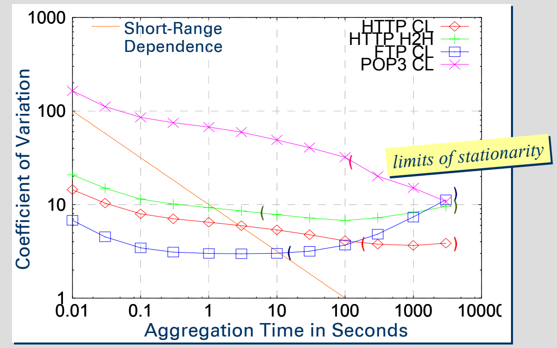
Self-Similarity
Estimating the Hurst Parameter

- 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

Section 5
Self-Similarity
Power Tails
Self-Similarity

SIEMENS

Variance-Time Plot
Example



- Mean Bit Rate in Aggregation Time Intervals *m*
- proportional to $m^{-(1-H)}$

Section 5
Self-Similarity
Power Tails
Self-Similarity

SIEMENS

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

Section 5
Self-Similarity
Power Tails
Self-Similarity

SIEMENS

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

Wavelet Analysis

SIEMENS

Section 5
Self-Similarity
Power Tails
Self-Similarity

- works roughly like a fourier analysis, but
  - on frequency and time scale
  - on logarithmic scales
- captures different scaling behavior on different time scales
- captures instationarity
- main applications
  - study and identify instationarity
  - study scaling properties
  - determine Hurst Parameter
- applicable to pattern recognition problems
  - Classify e.g. link load patterns as „good“ or „bad“ state
  [Huang, Feldmann, Willinger IMW2001]

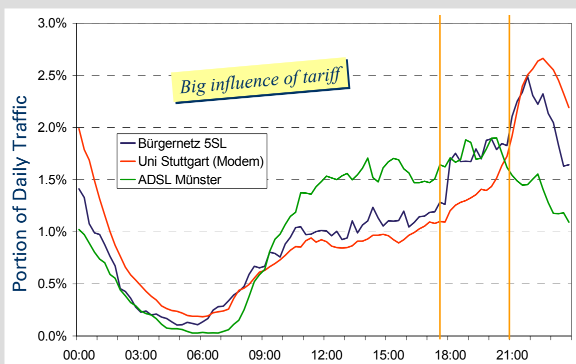
Outline

SIEMENS

Dialup Behaviour
Daily Traffic Curves

SIEMENS

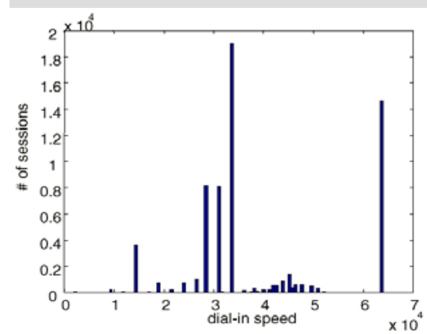
Section 6
Users

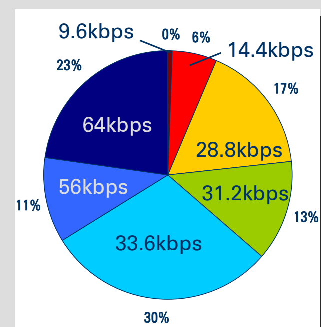


Data: 5SL, Uni Stuttgart, ADSL Münster: 15min values

Achieved Dialup Access Speeds

SIEMENS

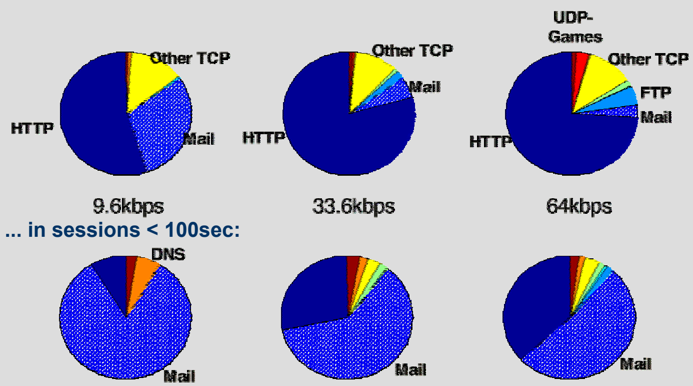




Source: University of Würzburg, 1999

Application Mixes

SIEMENS

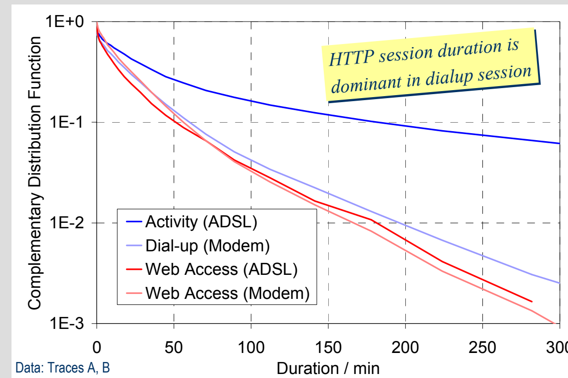


Source: University of Würzburg

Dialup Behaviour Session Duration (1)

SIEMENS

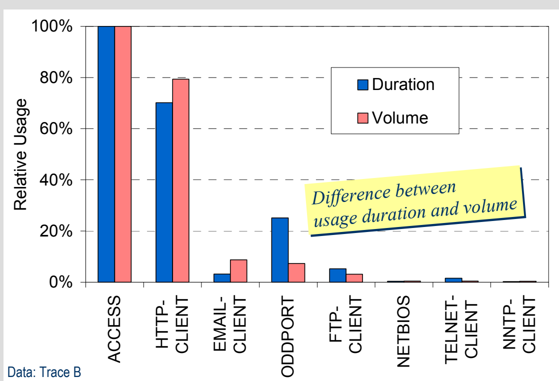
Section 6 Users



Applications Usage Volume vs. Duration

SIEMENS

Section 6 Users



Web Viewing Time

SIEMENS

Section 6 Users

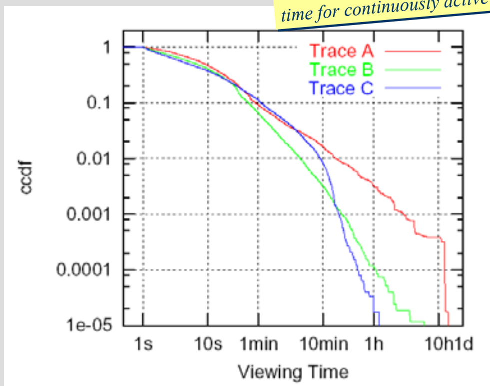
Excerpt from the HTTP state process analyzed for one client

Web Page Viewing Time

SIEMENS

Section 6
Users

indistinguishable from inter-session time for continuously active clients



J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

Outline

SIEMENS

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

Traffic Mixes

SIEMENS

Section 7
Backbone

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 ...

peer-to-peer has drastically increased

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

Periodic Changes and Symmetry

SIEMENS

Section 7
Backbone

- 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.

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

Network Characteristics

SIEMENS

Section 7
Backbone

Paxson's Measurements show

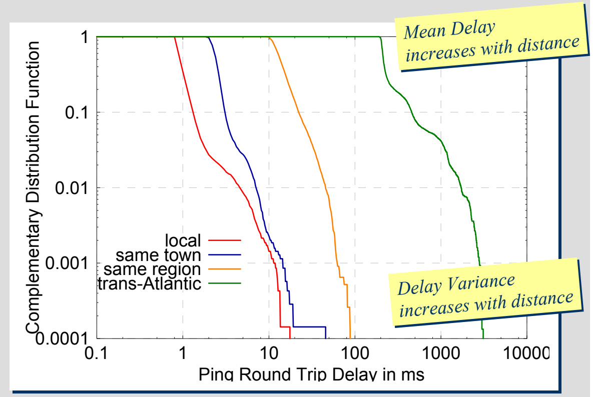
- Internet connections are mostly
  - "busy" (relatively high packet loss rate of 4–20%) or
  - "quiescent" (no packet loss)
- Consecutive packets mostly take the same path
  - reverse path may be different

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

Network Characteristics Delay Distributions

SIEMENS

Section 7
Backbone



J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

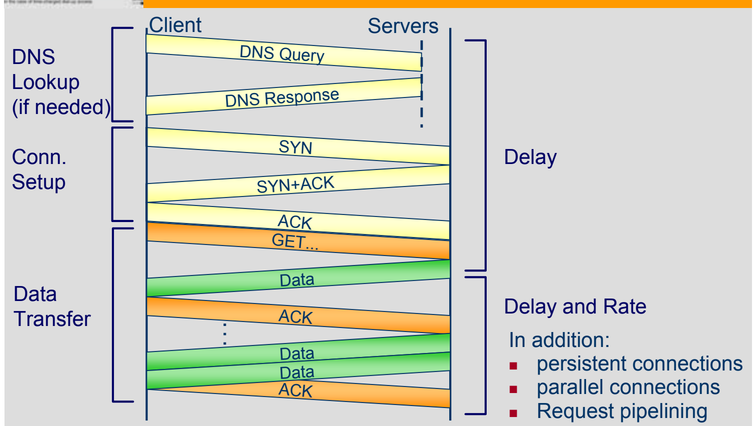
Outline

SIEMENS

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

Reminder DNS-HTTP-TCP

SIEMENS



In addition:

- persistent connections
- parallel connections
- Request pipelining

J. Charzinski • Internet Traffic • ICNP Paris, Nov. 2002

SIEMENS

Web Delay Components

- DNS latency
  - server reaction time
  - retries due to packet loss
  - retries due to false domain name extensions
- Network delay
  - propagation delay
  - processing delay (routing)
  - queuing delay (limited link bandwidth)
- Server reaction times
  - Connection establishment (socket creation, answer to SYN packet)
  - answer to GET request
  - database lookup and page construction time for dynamic pages

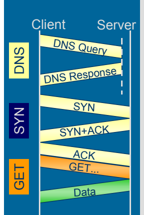
SIEMENS

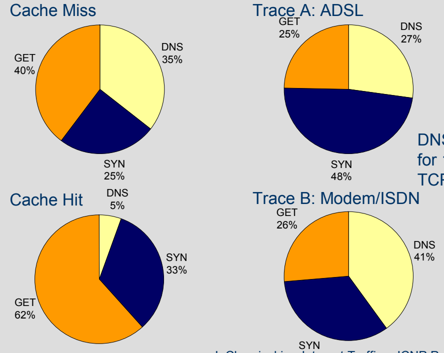
Web Delay Components (2)

- 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)

SIEMENS

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

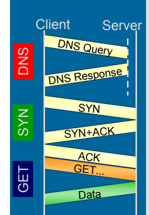


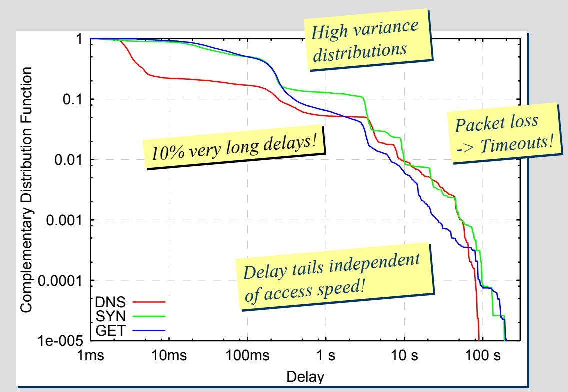


DNS Lookup only for 11% of all TCP connections

SIEMENS

Web Delay Components
Delay distributions for DNS / SYN / GET (one item)

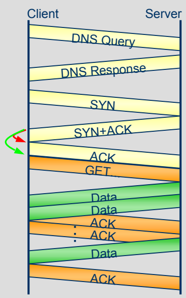


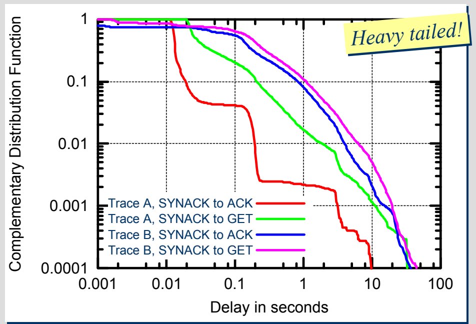


Data: ADSL Münster 1998 (Trace A)

Client Response Times

SIEMENS



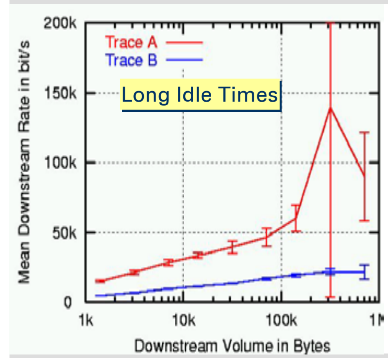


- 10% of clients needed longer than 200ms (1s) to send GET request
  - main reason: parallel connection handling

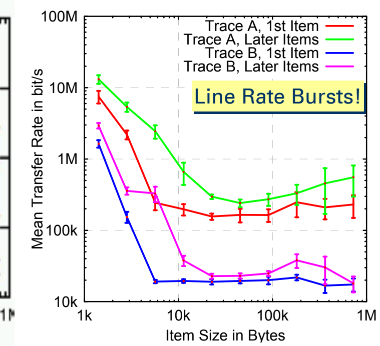
TCP and HTTP Keep-alive Connections Mean rates versus volume class

SIEMENS

Per HTTP/TCP Connection (P2P Flow)



Per Item (Response to one GET Request)



Web Performance General Observations

SIEMENS

Section 8 Performance
Web Access
E-Mail

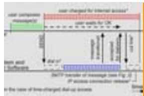
- DNS lookups can take significant time
- Connection establishment
  - routes and servers show “cold” and “warm” states
- small files:
  - most delay between GET request and start of transfer
  - server load is critical
- large files:
  - most delay during transmission
  - network load is critical (timeouts,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

Protocol and Architecture Options

SIEMENS

Section 8 Performance
Web Access
E-Mail

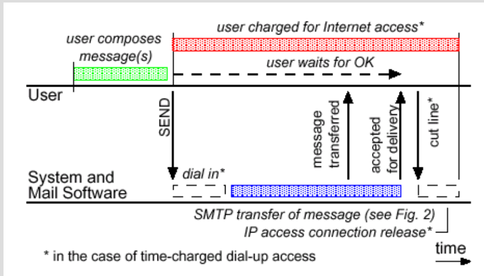
- Caching
  - validation time can be significant [Krishnamurthy/Wills]
  - does not help with dynamic content
- Persistent connections (HTTP/1.0 or HTTP/1.1)
  - can reduce network load
  - bad if server memory is a bottleneck [Barford/Crovella]
- Request pipelining
  - reduces influence of round-trip 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)



E-Mail Performance

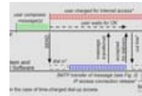
SIEMENS

Section 8 Performance
Web Access
E-Mail



- users limit their online time
- mail client blocks computer
- users wait for “mail sent successfully”

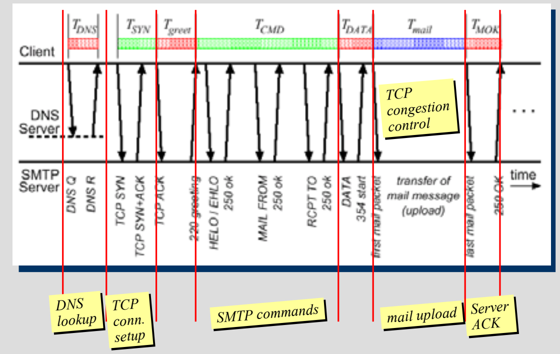
E-Mail transfer is an interactive service at the user side!



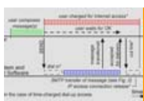
The SMTP Protocol

SIEMENS

Section 8 Performance
Web Access
E-Mail



- high degree of serialized command exchanges

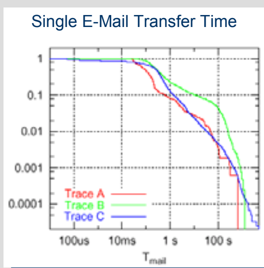


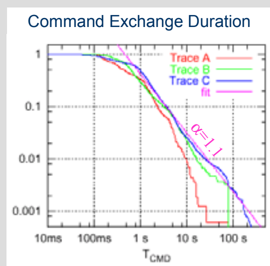
SMTP Single E-Mails

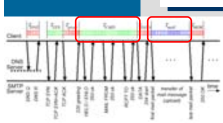
SIEMENS

Section 8 Performance
Web Access
E-Mail

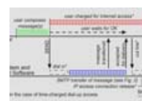
complementary cumulative distribution functions of ...







very long command exchanges and transfer times are observed

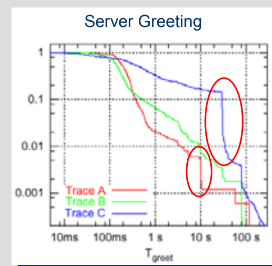


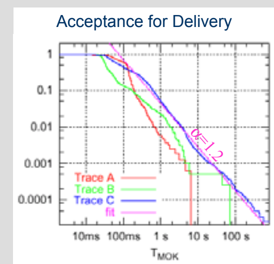
SMTP Server Latencies

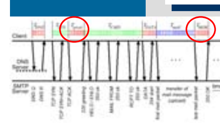
SIEMENS

Section 8 Performance
Web Access
E-Mail

complementary cumulative distribution functions of latencies...







IDENT bug causes unnecessary delay

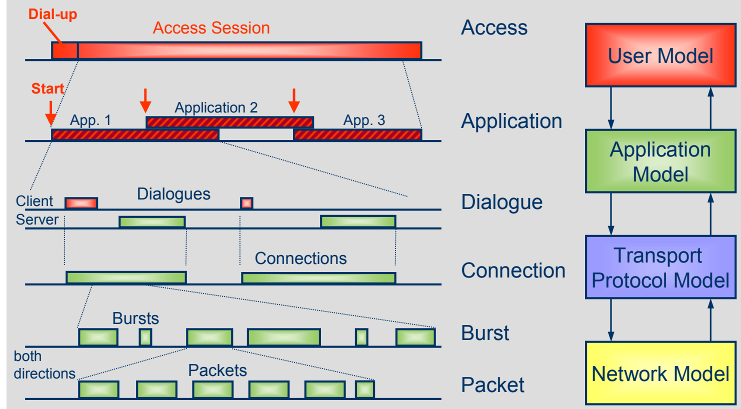
risk of protocol timeouts

Outline

SIEMENS

Model Types

SIEMENS



Model Types (2)

SIEMENS

- 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

Input Traffic on Different Activity Levels Access Session Traffic

SIEMENS

- 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

Input Traffic on Different Activity Levels
Application Session Traffic

SIEMENS

Within an Access Session:

- 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, ...

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

SIEMENS

Section 9
Models
Model Types
Single-Level Models
Multi-Level Models
Validation
Dimensioning
TCP Models

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

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

SIEMENS

Section 9
Models
Model Types
Single-Level Models
Multi-Level Models
Validation
Dimensioning
TCP Models

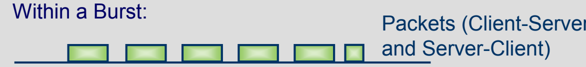
- Connection interarrival times
  - Weibull distribution
  - timer driven
- TCP's flow control adapts to available bit rate
  - Limit measured from packet loss (or excessive RTD)
  - When is a link "correctly dimensioned"?
  - Packet traffic traces cannot be re-used in another scenario
  - Packet loss 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

SIEMENS

Section 9
Models
Model Types
Single-Level Models
Multi-Level Models
Validation
Dimensioning
TCP Models

Within a Burst:

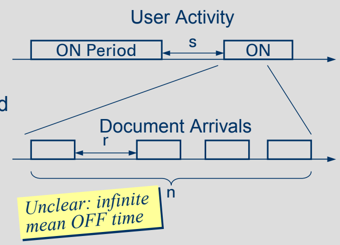


- Packet Size Distribution
- Packet Interarrival Time
- Correlations
- Upstream/Downstream Correlations due to TCP
  - Media Access Control issues
  - Time Division Duplex issues

Multilevel Models
Shuang Deng, ICC'96

SIEMENS

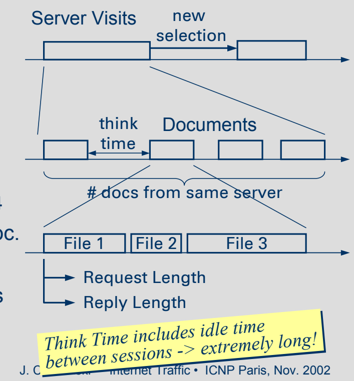
- ON-OFF model
- Single HTTP user
- Upstream or downstream traffic
- Burst Level
- Duration n of ON period
  - Weibull
- Duration s of OFF period
  - Pareto (infinite mean)
- Interarrival time r
  - approx. Weibull



Multilevel Models
Bruce Mah, Infocom'97

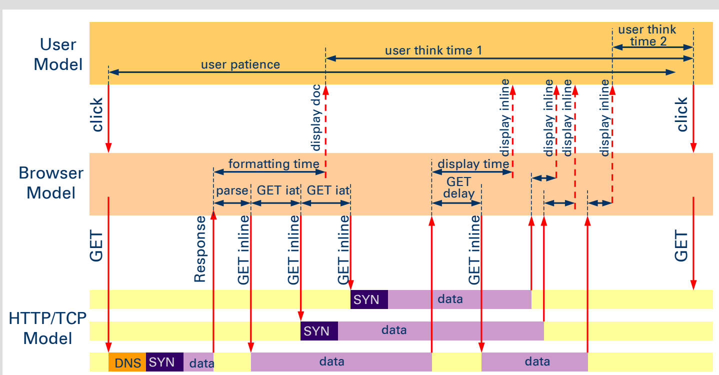
SIEMENS

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



Multilevel Models
Färber 2002

SIEMENS



Multilevel Models
Parameters

SIEMENS

- 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

SIEMENS

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

SIEMENS

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

SIEMENS

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}

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

SIEMENS

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

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

M/G/r-PS Processor Sharing Model

SIEMENS

Section 9 Models
- Model Types
- Single-Level Models
- Multi-Level Models
- Validation
- Dimensioning
- TCP Models

- 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

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

Multiplexing Gain

SIEMENS

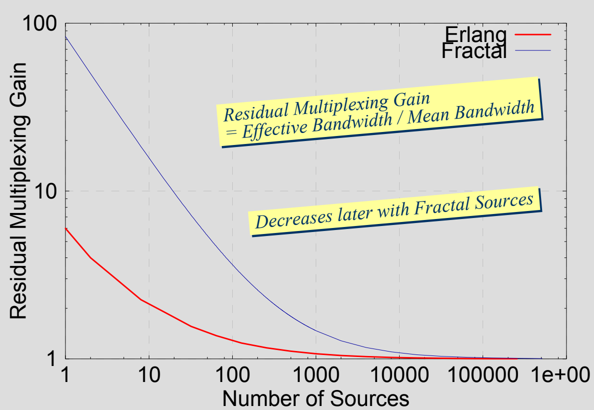
Section 9 Models
- Model Types
- Single-Level Models
- Multi-Level Models
- Validation
- Dimensioning
- TCP Models

- 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
- ensemble vs. time scale aggregation
  - time scale aggregation described by Hurst parameter
  - (quite) normal behavior for ensemble aggregation [Cleveland et al, Sigmetrics 2001]

Multiplexing Gain Example

SIEMENS

Section 9 Models
- Model Types
- Single-Level Models
- Multi-Level Models
- Validation
- Dimensioning
- TCP Models



TCP Models

SIEMENS

Section 9 Models
- Model Types
- Single-Level Models
- Multi-Level Models
- Validation
- Dimensioning
- 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
  - Extensions into network models to be solved iteratively
- 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
Main Result

SIEMENS

Section 9
Models
- Model Types
- Single-Level Models
- Multi-Level Models
- Validation
- Dimensioning
- TCP Models

- 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 acknowledged packets per ACK received

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

Outline

SIEMENS

Steady State and Confidence

SIEMENS

Section 10
Simulation

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

SIEMENS

Section 10
Simulation

Don‘t try to simulate infinity!

- ... 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 chang… limit?)
  - introduce corresponding mechanisms into networks (e.g. limit on e-mail sizes)

infinite variance ⇒ infinite confidence intervals

Input Parameters

SIEMENS

Section 10
Simulation

- Don not use the Normal (Gaussian) 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

Deterministic Scenarios

SIEMENS

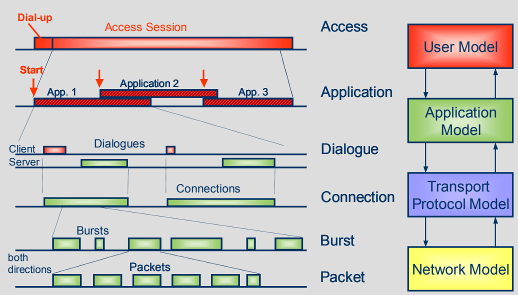
Section 10
Simulation

- 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

Time Scales

SIEMENS

Section 10
Simulation



- Simulation over too many time scales is dangerous
  - Slow convergence on highest time scale and lots of unnecessary operations on low time scales

References

General Literature

D. Comer, ”Internetworking with TCP/IP”, 4th. Ed., Prentice Hall, Englewood Cliffs, NJ, USA, 2000

S. Floyd, V. Paxson, ”An Overview of Internet Engineering, Measurement, and Modeling”, Tutorial International Teletraffic Congress ITC-15, Washington D.C., USA, June 1997

J.W. Roberts, “Traffic Theory and the Internet.” IEEE Communications Magazine 39’(1) 2001, pp. 94–99

Internet growth and traffic figures

As statistics for Internet growth and Internet traffic have a very short life, we mostly give URLs here. URLs themselves often also have a relatively short life, but they still live somewhat longer than the data they point to.

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

http://nis.nsf.net/statistics/nsfnet/

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

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

V. Paxson, "Growth Trends in Wide-Area TCP Connections", IEEE Network 8(4)1994, pp.8-17

K.C. Claffy, H.-W. Braun, G.C. Polyzos, "Tracking Long-Term Growth of the NSFNET." Communications of the ACM 37(8) Aug. 1994, pp. 34-45

Routing

C. Huitema, ”Routing in the Internet”, Prentice-Hall, 1995

V. Paxson, ”End-to-End Routing Behavior in the Internet.” Proc. ACM SIGCOMM’96, Stanford, CA, USA, Aug. 1996, pp. 25–38. Available at ftp://ftp.ee.lbl.gov/papers/routing.SIGCOMM.ps.Z

C. Labovitz, G.R. Malan, F. Jahanian, ”Internet Routing Instability.” Proc. ACM SIGCOMM´97, Cannes, France, Sep. 1997, pp. 115–126

Backbone Traffic

J. Apisdorf, K. Claffy, K. Thompson, R. Wilder, "OC3MON: Flexible, Affordable, High-Performance Statistics Collection." Online Proceedings of Inet97, Kuala Lumpur, Malaysia, June 1997. Available at http://www.isoc.org/isoc/whatis/conferences/inet/97/proceedings/F1/F1_2.HTM

C.J. Bovy, H.T. Mertodimedjo, G. Hooghiemstra, H. Uijterwaal, P. van Mieghem, “Analysis of End-to-end Delay Measurements in Internet”, Proc. PAM 2002

R.L. Carter, M.E. Crovella, "Measuring Bottleneck Link Speed in Packet-Switched Networks." Boston University, CS Dept, Boston, MA 02215 Technical Report BU-CS-96-006, Mar. 1996. Available at ftp://cs-ftp.bu.edu/techreports/96-006-measuring-bottleneck-link.ps.Z

K.C. Claffy, H.-W. Braun, G.C. Polyzos, "A Parametrizable Methodology for Internet Traffic Flow Profiling." IEEE JSAC 13(8) Oct 1995, pp. 1481-1494

K. Claffy, G. Miller, K. Thompson, "The nature of the beast: recent traffic measurements from an Internet backbone." Proceedings of the INET'98 Conference, April 1998. Available at http://www.caida.org/Papers/Inet98/index.html

J.A. Copeland, R. Abler, K.L. Bernhardt, "IP Flow Identification for IP Traffic Carried over Switched Networks." Computer Networks and ISDN Systems 31(5), 1999, pp. 493-504

J. Cao, W.S. Cleveland, D. Lin, D.X. Sun, “On the Nonstationarity of Internet Traffic.” Proc. ACM Sigmetrics / Performance 2001, Cambridge, MA, USA, June 2001, pp. 102–112

Feldmann A, Rexford J, Cáceres R. 1998. Efficient Policies for Carrying Web Traffic Over Flow-Switched Networks. IEEE/ACM Trans. Netw. 6, 673-685

S. Lin, N. McKeown, “A Simulation Study of IP Switching.” Comp. Comm. Rev. 27(4) 1997, pp. 15-24

S. McCreary, kc claffy, “Trends in Wide Area IP Traffic Patterns: A View from Ames Internet eXchange.“ Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

K. Mochalski, J. Micheel, S. Donnelly, “Packet Delay and Loss at the Auckland Internet Access Path“, Proc. PAM 2002

K. Nagami, H. Esaki, Y. Katsube, O. Nakamura. Flow Aggregated, Traffic Driven Label Mapping in Label-Switching Networks. IEEE J. Select. Areas Comm. 17, 1999, pp. 1170-1177

V. Paxson, "End-to-End Internet Packet Dynamics." ACM Computer Communication Review 27(4) Oct. 1997, pp. 139-152. Available at ftp://ftp.ee.lbl.gov/papers/vp-pkt-dyn-sigcomm97.ps.Z

B. Ryu, D. Cheney, H.-W. Braun, “Internet Flow Characterization: Adaptive Timeout Strategy and Statistical Modeling”, Proc. PAM 2001

K. Thompson, G.J. Miller, R. Wilder, "Wide-Area Internet Traffic Patterns and Characteristics." IEEE Network 11(6) Nov./Dec. 1997, pp. 10-23. Available at http://www.vbns.net/presentations/papers/MCItraffic.ps

Y. Zhang, N. Duffield, V. Paxson, S. Shenker, “On the Constancy of Internet Path Properties”, Proc. ACM Internet Measurement Workshop 2001

Application and user traffic and models (mostly HTTP)

M.F. Arlitt, C. L. Williamson, "A Synthetic Workload Model for Internet Mosaic Traffic." Proc. SCSC'95, Ottawa, Canada, July 1995, pp. 852-857

M.F. Arlitt, C.L. Williamson, "Web Server Workload Characterization: The Search for Invariants." ACM Performance Evaluation Review 24 (1) May 1996, pp. 126-137. Available at ftp://ftp.cs.usask.ca/pub/discus/paper.96-3.ps.Z

D. Bauer, J. Charzinski, V. Held, "Virtuelle Universität durch ADSL-Technologie: Studenten im Geschwindigkeitsrausch durch breitbandigen Internet-Zugang." ITG-Fachtagung "Internet-Frischer Wind in der Telekommunikation", Stuttgart, Okt. 1999 (in German)

M.S. Borella, "Source Models of Network Game Traffic", Proc. Networld+Interop'99, Las Vegas, USA, May 1999. Available at http://www.xnet.com/~cathmike/MSB/Pubs/game-traffic.ps.Z

L.D. Catledge, J.E. Pitkow, "Characterizing browsing strategies in the World-Wide Web." Computer Networks and ISDN Systems 27(6) April 1995, pp. 1067-1073

J. Charzinski, “Internet Client Traffic Measurement and Characterisation Results“, Proc. ISSLS, Stockholm, Sweden, June 2000.

J. Charzinski, J. Färber, M. Frank, J. Tölle, "The AMUSE Residential Multimedia Trials: Phase 1 Monitoring Results Summary." Proc. NOC'98, Manchester, UK, June 1998, pp. 86-93

H.-K. Choi, " A Behavior Model of a Web Traffic", 7th International Conference on Network Protocols 99' (ICNP 99'), Toronto, Canada, Nov. 1999

A.E. Conway, S.B. Moon, P. Skelly, "Synchronized Two-Way Voice Simulation Tool for Internet Phone Performance Analysis and Evaluation." Proc. 9th Conf. Computer Performance Evaluation, Modelling, Techniques and Tools, St. Malo, France, June 1997. Available at ftp://gaia.cs.umass.edu/pub/Moon96:Synch.ps.gz

C.R. Cunha, A. Bestavros, M.E. Crovella, "Characteristics of WWW Client-based Traces." Boston University, CS Dept, Boston, MA 02215 Technical Report TR-95-010, April 1995. Available at ftp://cs-ftp.bu.edu/techreports/95-010-www-client-traces.ps.Z

S. Deng, "Empirical Model of WWW Document Arrivals at Access Link." Proc. ICC´96, Dallas, TX, USA, June 1996, pp. 1797-1802

A.B. Downey, “Evidence for Long-Tailed Distributions in the Internet”, Proc. ACM Internet Measurement Workshop 2001

D.J. Ewing, R.S. Hall, M.F. Schwartz, "A Measurement Study of Internet File Transfer Traffic." Tech. Rep. CU-CS-571-92 Univ. of Colorado, Boulder, USA, Jan. 1992. Available at ftp://ftp.cs.colorado.edu/pub/cs/techreports/schwartz/FTP.Meas.ps.Z

J. Färber, M. Frank, J. Charzinski, "The WWW-Service in the AMUSE Field Trials: Usage Evaluation and Traffic Modelling." Proceedings of the Expert ATM Traffic Symposium, Mykonos, Greece, Sep. 1997. Available at http://www.ind.uni-stuttgart.de/IND/MA/Fa/papers/wwwusage.ps.gz

A. Feldmann, A.C. Gilbert, P. Huang, W. Willinger, "Dynamics of IP traffic: A study of the role of variability and the impact of control", Proc. ACM Sigcomm, Cambridge, MA, USA, August 1999. Available at http://www.cs.uni-sb.de/~anja/feldmann/papers/sigcomm99_trace_sim.ps.gz

J. Judge, H.W.P. Beadle, J. Chicharo, "Modeling World-Wide Web Request Traffic." Proceedings of the SPIE Conference 3020, San Jose, CA, USA, Feb. 1997, pp. 92-103

D.P. Heyman, T.V. Lakshman, A.L. Neidhardt, A.L., "A New Method for Analysing Feedback-Based Protocols with Applications to Engineering Web Traffic over the Internet." ACM Performance Evaluation Review 25(1) June 1997, pp. 24-38

P. Karlsson, Å. Arvidsson, "The Characteristics of WWW Traffic and the Relevance to ATM." Tech. Rep., Dept. Telecomm. and Math., Univ. of Karlskrona/Ronneby, Sweden; COST 257TD(97)21, May 1997. Available at ftp://www-info3.informatik.uni-wuerzburg.de/pub/cost/cost257/may97/257td97021.ps

B. Krishnamurthy, J. Rexford, "Web Protocols and Practice", Addison Wesley 2001

B. Mah, "An Empirical Model of HTTP Network Traffic." Proc. IEEE Infocom'97, Kobe, Japan, Apr. 1997. Available at http://www.ca.sandia.gov/~bmah/Papers/Http-Infocom.ps

I. Marsh, "IP Telephony Tracing and Simulation." www.sics.se/~ianm/Telephony/iptel.html

H.F. Nielsen, J. Gettys, A. Baird-Smith, E. Prud´hommeaux, H.W. Lie, C. Lilley, " Network Performance Effects of HTTP/1.1, CSS1, and PNG." Proceedings of ACM SIGCOMM´97, Cannes, France, Sep. 1997, pp. 155-166. Available at http://www.w3.org/Protocols/HTTP/Performance/Pipeline.html

V.N. Padmanabhan, J.C. Mogul, "Improving HTTP Latency." Computer Networks and ISDN Systems 28, Dec. 1995, pp. 24-35

J. Rosenberg, H. Schulzrinne, "The IETF Internet Telephony Architecture and Protocols." IEEE Network 13, May/June 1999, pp. 18-23

S. Saroiu, P.K. Gummadi, S.D. Gribble, "A Measurement Study of Peer-to-Peer File Sharing Systems", http://www.cs.washington.edu/homes/gribble/papers/mmcn.pdf

H. Schulzrinne, J. Rosenberg, "A Comparison of SIP and H.323 for Internet Telephony." Proc. NOSSDAV, Cambridge, UK, July 1998. Available at http://www.cs.columbia.edu/~hgs/papers/Schu9807_Comparison.ps.gz

J. Sedayao, "World Wide Web Network Traffic Patterns." IEEE COMPCON´95 Technologies for the Information Superhighway, San Francisco, CA, USA, Mar. 1995, pp. 8-12

F. Smith, F. Hernandez Campos, K. Jeffay, D. Ott, "What TCP/IP protocol headers can tell us about the Web, Proc. ACM Sigmetrics/Performance, Cambridge, MA, USA, 2001, pp. 245–256

A. Woodruff, P.M. Aoki, E. Brewer, P. Gauthier, L.A. Rowe, " An investigation of documents from the World Wide Web." Computer Networks and ISDN Systems 28, May 1996, pp. 963-980. Available at http://epoch.cs.berkeley.edu:8000/~woodruff/inktomi/

Self similarity and models for fractal traffic

P. Abry, D. Veitch, P. Flandrin, "Long-Range Dependence: Revisiting Aggregation with Wavelets." Journal of Time Series Analysis 19(3) May 1998, pp. 253-266. Available at http://www.serc.rmit.edu.au/~darryl/A2.ps

R. Adler, R.E. Feldman, M.S. Taqqu, "A Practical Guide to Heavy Tails." Birkhäuser, Boston, Basel, Berlin, 1998

V. Bolotin, J. Coombs-Reyes, D. Heyman, Y. Levy, D. Liu, "IP Traffic Characterization for Planning and Control." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 425-436

M. Caglar, K.R. Krishnan, I. Saniee, "Estimation of Traffic Parameters in High-Speed Data Networks." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 867-876

M.E. Crovella, A. Bestavros, "Explaining World Wide Web Traffic Self-Similarity." Tech. Rep. TR-95-015, Boston University, CS Dept, Aug. 1995. Available at ftp://cs-ftp.bu.edu/techreports/95-015-explaining-web-self-similarity.ps.Z

M.E. Crovella, A. Bestavros, "Self Similarity in WWW traffic: Evidence and possible causes." Proc. ACM SIGMETRICS'96. Available at http://cs-www.bu.edu/faculty/best/res/papers/sigmetrics96.ps

A. Feldmann, A.C. Gilbert, W. Willinger, T.G. Kurtz, "The Changing Nature of Network Traffic: Scaling Phenomena." ACM SIGCOMM Computer Communication Review 28(2) Apr. 1998, pp. 5-29

A. Feldmann, W. Whitt, "Fitting mixtures of exponentials to long-tail distributions to analyze network performance models." Performance Evaluation 31, 1998, pp. 245-279

A. Feldmann, A.C. Gilbert, W.Willinger, "Data networks as cascades: Investigating the multifractal nature of Internet WAN traffic." Proc. SIGCOMM'98, Vancouver, BC, Canada, Sep. 1998, pp. 42-55

L.J. Forys, A. Erramilli, J.L. Wang, "New Traffic Analysis and Engineering Methods for Emerging Technologies." Proc. GLOBECOM'95, New York, NY, USA, Nov. 1995, pp. 848-854

R.G. Garroppo, S. Giordano, M. Isopi, M. Pagano, "On the Implications of the OFF Periods Distribution in Two-State Traffic Models." IEEE Communications Letters 3(7) Jul. 1999, pp. 220-222

M. Greiner, M. Jobmann, C. Klüppelberg, "Telecommunication Traffic, Queueing Models, and Subexponential Distributions." Queueing Systems, 1998

M. Grossglauser, J.-C. Bolot, "On the Relevance of Long-Range Dependence in Network Traffic." Proceedings of ACM Sigcomm'96. Available at http://www.inria.fr/rodeo/personnel/mgross/WWW/Papers/sigcomm96.ps.gz

D.P. Heyman, D. Liu, "Assessing the Effects of Short-Range and Long-Range Dependence on Overflow Probabilities. "Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

P. Huang, A. Feldmann, W. Willinger, "A Non-Intrusive Wavelet-Based Approach to Detecting Network Performance Problems." Proc. ACM Internet Measurement Workshop 2001

J.K. Jerkins, A.L. Neidhardt, J.L. Wang, A. Erramilli, "Operations Measurements for Engineering Support of High-Speed Networks with Self-Similar Traffic." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 895-906

W.E. Leland, M.S. Taqqu, W. Willinger, D.V. Wilson, "On the Self-Similar Nature of Ethernet Traffic." Proc. ACM SIGCOMM´93, San Francisco, CA, USA, 1993, pp. 183-193

I. Norros, A. Simonian, D. Veitch, J. Virtamo, "A Benes formula for the fractional Brownian storage." COST 242 Technical Document (95)004, Version 2, May 1995. Available at http://www.serc.rmit.edu.au/~darryl/COST.ps

K. Park, W. Willinger, Eds. "Self-Similar Network Traffic and Performance Evaluation." Wiley, New York, 2000

M. Roughan, D. Veitch, M. Rumsewicz, "Computing Queue-Length Distributions for Power-Law Queues." Proceedings of Infocom'98. Available at http://www.serc.rmit.edu.au/~darryl/Infocom98_camera.ps

M. Roughan, D. Veitch, "A Study of the Daily Variation in the Self-Similarity of Real Data Traffic." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 67-76

M. Roughan, D. Veitch, P. Abry, "Real-Time Estimation of the Parameters of Long-Range Dependence." IEEE/ACM Trans. Networking 8(4)2000 pp. 467–478

Z. Sahinoglu, S. Tekinay, "On Multimedia Networks: Self-Similar Traffic and Network Performance." IEEE Comm. Mag. Jan. 1999, pp. 48-52

S. Sarvotham, R. Riedi, R. Baraniuk, „Connection-level Analysis and Modeling of Network Traffic", Proc. ACM Internet Measurement Workshop 2001

H.-P. Schwefel, L. Lipsky, "Performance Results for Analytic Models of Traffic in Telecommunication Systems, Based on Multiple On-Off Sources with Self-Similar Behavior." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 55-65

D. Starobinski, M. Sidi, "Modeling and Analysis of Heavy-Tailed Distributions via Classical Teletraffic Methods." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 45-54

E. Van den Berg, "Parameter Estimation for Long Range Dependent Data: Single Fine vs. Multiple Coarse Measurements." Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

D. Veitch, "Novel Models of Broadband Traffic." Proc. GLOBECOM'93, Houston, TX, USA, Dec.1993

D. Veitch, P. Abry, "A Wavelet Based Joint Estimator of the Parameters of Long-Range Dependence." IEEE Trans. Information Theory 45(3) Apr. 1999.

W. Willinger, M.S. Taqqu, A. Erramilli, "A bibliographical guide to self-similar traffic and performance modeling for modern high-speed networks." in F.P. Kelly, S. Zachary, I. Ziedins, "Stochastic Networks: Theory and Applications" Royal Statist. Lecture Note Series, Clarendon Press, Oxford, UK, 1996

W. Willinger, M.S. Taqqu, R. Sherman, D.V. Wilson, "Self-Similarity Through High-Variability: Statistical Analysis of Ethernet LAN Traffic at the Source Level." IEEE/ACM Transactions on Networking 5(1) Feb. 1997, pp. 71-86

W. Willinger, V. Paxson, "Where Mathematics meets the Internet." Notices of the American Mathematical Society 45(8) Sep. 1998, pp. 961-970. Available at ftp://ftp.ee.lbl.gov/papers/internet-math-AMS98.ps.gz

Measurement and modelling of Dial-up traffic / User Behavior

A. Adya, P. Bahl, L. Qiu, "Analyzing the Browse Patterns of Mobile Clients", Proc. ACM Internet Measurement Workshop

V.A. Bolotin, "New Subscriber Traffic Variability Patterns for Network Traffic Engineering." Proc. 15th International Teletraffic Congress (ITC 15), V. Ramaswami, P.E. Wirth, Eds., Washington DC, USA, June 1997, pp. 867-878

V.A. Bolotin, Y. Levy, D. Liu, "Characterizing Data Connection and Messages by Mixtures of Distributions on Logarithmic Scale." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 887-894

J. Charzinski, "Good News about Heavy Tails", IEEE Conf. High Perf. Switching and Routing (ATM2000), Heidelberg, Germany, June 2000.

J. Färber, S. Bodamer, J. Charzinski, "Statistical Evaluation and modelling of Internet dial-up traffic." Proc. SPIE Performance and Control of Network Systems III, Boston, MA, USA, Sep. 1999

A.A. Fredericks, "Impact of Holding Time Distributions on Parcel Blocking in Multi-Class Networks with Application to Internet Traffic on PSTN's." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 877-886

J.J. Gordon, K. Murty, A. Rayes, "Overview of Internet Traffic Issues on the PSTN." Proc. 15th International Teletraffic Congress (ITC 15), V. Ramaswami, P.E. Wirth, Eds., Washington DC, USA, June 1997, pp. 643-652

J. Kilpi, I. Norros: "Call Level Traffic Analysis of a Large ISP." Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

S. Morgan, "The Internet and the Local Telephone Network: Conflicts and Opportunities." IEEE Comm. Mag. Jan. 1998, pp. 42-48

P. Orenstein, "A preliminary analysis of Work-at-Home Traffic Characteristics." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 907-918

TCP and TCP models

M. Allman, "On the Generation and Use of TCP Acknowledgements." ACM SIGCOMM Computer Communication Review 28(5) Oct. 1998, pp. 4-21

Å. Arvidsson, P. Karlsson, "On Traffic Models for TCP/IP." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 457-466

H. Balakrishnan, V.N. Padmanabhan, "How Network Asymmetry Affects TCP." IEEE Communications Magazine 39(4) 2001 pp. 60–67

C. Barakat, E. Altman, "Performance of Short TCP Transfers." Proc. Networking 2000, Paris, France, May 2000, pp. 567–579

T. Bonald, "Comparison of TCP Reno and TCP Vegas via Fluid Approximation", INRIA Rapport de Recherche No. 3563, Nov. 1998

C.P. Charalambos, V.S. Frost, J.B. Evans, "Performance of TCP Extensions on Noisy High BDP Networks." IEEE Commun. Letters 3(10)1999 pp. 294–296

S. Floyd, "A Report on Recent Developments in TCP Congestion Control." IEEE Communications Magazine 39(4) 2001 pp. 84–90

S. Low, L. Peterson, L. Wang, "Understanding TCP Vegas: A Duality Model." Proc. ACM Sigmetrics / Performance 2001, Cambridge, MA, USA, June 2001, pp. 226–235.

M. Mathis, J. Semke, J. Mahdavi, T. Ott, "The Macroscopic Behavior of the TCP Congestion Avoidance Algorithm." ACM Computer Communication Review 27(3), July 1997

J.C. Mogul, G. Minshall, "Rethinking the TCP Nagle Algorithm." ACM Computer Communication Review 31(1)2001 pp. 6–20

J. Padhye, V. Firoiu, D. Towsley, J. Kurose: ``Modeling TCP Throughput: A Simple Model and its Empirical Validation'' ACM Computer Communication Review (Proc. ACM Sigcomm'98), Vol. 28 No. 4, Oct. 1998, http://www.acm.org/sigcomm/sigcomm98/tp/paper25.pdf

H.-P. Schwefel, "Behavior of TCP-like elastic traffic at a buffered bottleneck router." Proc. IEEE Infocom, Anchorage, AK, USA, April 2001. Available at http://wwwjessen.informatik.tu-muenchen.de/~schwefel/TCP_paper.ps.gz

I. Yeom, A.L.N. Reddy, "Modeling TCP Behavior in a Differentiated Services Network." IEEE/ACM Trans. Networking 9(1)2001 pp. 31–46

Measured Performance

M. Allman, "Measuring End-to-End Bulk Transfer Capacity", Proc. ACM Internet Measurement Workshop 2001

P. Barford, M. Crovella, "Measuring Web Performance in the Wide Area." ACM Perf. Eval. Review 27(2)1999 pp. 37–48

P. Barford, M. Crovella, "A Performance Evaluation of Hyper Text Transfer Protocols." Proc. ACM Sigmetrics, Atlanta, GA, USA, May 1999

P. Barford, M. Crovella, "Critical Path Analysis of TCP Transactions." Proc. ACM Sigcomm Stockholm, Sweden, Sep. 2000

E. Cohen, H. Kaplan, "Prefetching the Means for Document Transfer: A New Approach for Reducing Web Latency." Proc. IEEE Infocom Tel Aviv, Israel, March 2000

K.P. Gummadi, S. Saroiu, S.D. Gribble, "King: Estimating latency between arbitrary Internet end hosts.", Proc. Internet Meas. Workshop 2002

M.A. Habib, M. Abrams, "Analysis of Sources of Latency in Downloading Web Pages." Proc. WebNet, San Antonio, USA, Nov. 2000

C. Huitema, S. Weerahandi, "Internet Measurements: the Rising Tide and the DNS Snag." Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

J. Jung, E. Sit, H. Balakrishnan, R. Morris, "DNS Performance and the Effectiveness of Caching", Proc. ACM Internet Measurement Workshop 2001

S. Khirman, P. Henriksen, "Relationship between Quality-of-Service and Quality-of-Experience for

Public Internet Service", Proc. PAM 2002

B. Krishnamurthy, C.E. Wills, "Analyzing Factors that Influence End-to-End Web Performance." Computer Networks 33 (1–6) 2000 pp. 17–32

R. Liston, S. Srinivasan, E. Zegura, “Diversity in DNS Performance Measures”, Proc. ACM Internet Measurement Workshop 2002

T. Zseby, “Deployment of Sampling Methods for SLA Validation with Non-Intrusive Measurements”, Proc. PAM 2002

Dimensioning

S. Bodamer, J. Charzinski: “Evaluation of Effective Bandwidth Schemes for Self-Similar Traffic.” Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

J. Charzinski, “Fun Factor Dimensioning for Elastic Traffic”, COST 257 Tech. Doc. (00)28, Oslo, May 2000. Avail. at http://www-info3.uni-wuerzburg.de/cost/

A. Feldmann, A. Greenberg, C. Lund, N. Reingold, J. Rexford: “Deriving Traffic Demands for Operational IP Networks: Methodology and Experience.” Proc. ACM Sigcomm, Stockholm, Sweden, August 2000

D.P. Heyman, T.V. Lakshman, A.L. Neidhardt, “A New Method for Analysing Feedback-Based Protocols with Applications to Engineering Web Traffic over the Internet” Proc. ACM SIG-METRICS’97, Seattle, WA, USA; ACM Perf. Eval. Review Vol. 25, No. 1, pp. 24–38.

J.G. Klincewicz, J.A. Schmitt, R.T. Wong, “The Design of IP Enterprise Networks with QoS”, Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

K. Lindberger, “Balancing Quality of Service, Pricing and Utilization in Multiservice Networks with Stream and Elastic Traffic” Proc. ITC 16, Edinburgh, UK, June 1999, pp. 1127–1136.

M. Nabe, M. Murata, H. Miyahara, “Analysis and modeling of World Wide Web traffic for capacity dimensioning of Internet access lines.“ Performance Evaluation 34, 1999, pp. 249–271

I. Norros, “On the Use of Fractional Brownian Motion in the Theory of Connectionless Net-works”, IEEE JSAC Vol. 13, No. 6, 1995, pp. 953–962.

Server, Caching and Proxies

M.F. Arlitt, " A Performance Study of Internet Web Servers." Master Thesis, Dep. Computer Science, University of Saskatchewan, Saskatoon, Saskatchewan, S7N 0W0, 1996. Available at ftp://ftp.cs.usask.ca/pub/discus/thesis_arlitt_co.ps.Z

N. Bhatti, A. Bouch, A. Kuchinsky, “Integrating User-Perceived Quality into Web Server Design.“ Comp. Netw. 33 (1–6) 2000 pp. 1–16

J.C. Bolot, P. Hoschka, "Performance Engineering of the World Wide Web: Application to dimensioning and cache design." Computer Networks and ISDN Systems 28, May 1996, pp. 1397-1405

H.-W. Braun, K.C. Claffy, "Web traffic characterization: an assessment of the impact of chaching documents from NCSA´s web server." Computer Networks and ISDN Systems 28, Dec. 1995, pp. 37-51

J. Dilley, M. Arlitt, “Improving Proxy Cache Performance: Analysis of Three Replacement Policies.“ IEEE Internet Computing Nov. 1999 pp. 44–50

Y. Fujita, M. Murata, H, Miyahara, "Performance Modeling and Evaluation of Web Systems with Proxy Caching." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 1179-1188

A. Loutonen, K. Altis, "World-Wide Web Proxies." Computer Networks and ISDN Systems 27 Nov. 1994, pp. 147-154

E.M. Nahum, M.-C. Rosu, S. Seshan, J. Almeida, “The Effects of Wide-Area Conditions on WWW Server Performance.” Proc. ACM Sigmetrics / Performance 2001, Cambridge, MA, June 2001, pp. 257–267

D. Neal, "The Harvest Object Cache in New Zealand." Computer Networks and ISDN Systems 28, May 1996, pp. 1415-1430

P.K. Reeser, R.D. van der Mei, R. Hariharan, "An Analytic Model of a Web Server." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 1199-1208

QoS

M. Asawa, "Measuring and Analyzing Service Levels: A Scalable Passive Approach." Proc. Sixth International Workshop on Quality of Service (IWQoS'98), May 1998, pp. 3-12

T. Bonald, J.W. Roberts, “Performance of Bandwidth Sharing Mechanisms for Service Differentiation in the Internet.” Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

T. Bonald, L. Massoulié, “Impact of Fairness on Internet Performance.” Proc. ACM Sigmetrics / Performance 2001, Cambridge, MA, USA, June 2001, pp. 82–91.

J. Charzinski, “Problems of Elastic Traffic Admission Control in an HTTP Scenario.“ Proc. IWQoS, Karlsruhe, Germany, June 2001.

R.A. Guérin, V. Pla, “Aggregation and Conformance in Differentiated Service Networks – A Case Study.” Proc. ITC Specialist Seminar on IP Traffic, Monterey, CA, USA, Sep. 2000

A. Kumar, M. Hegde, S.V.R. Anand, B.N. Bindu, D. Thirumurthy, A.A. Kherani, “Nonintrusive TCP Connection Admission Control for Bandwidth Management of an Internet Access Link.” IEEE Communications Magazine 38(5) 2000 pp. 160–167

L. Massoulié, J. Roberts, "Arguments in favour of admission control for TCP flows." Proc. ITC 16, Edinburgh, UK, June 1999, pp. 33-44

M. May, J.C. Bolot, A. Jean-Marie, C. Diot, “Simple Performance Models of Differentiated Services Schemes for the Internet.” Proc. IEEE Infocom New York NY, USA, March 1999

R. Mortier, I. Pratt, C Clark, S. Crosby, “Implicit Admission Control.” IEEE JSAC 18(12) 2000 pp. 2629–2639

K. Nichols, S. Blake, F. Baker, D. Black, "Definition of the Differentiated Service Field (DS Field) in the IPv4 and IPv6 Headers.", RFC 2474, Dec. 1998

J.W. Roberts, S. Oueslati-Boulahia, “Quality of Service by Flow Aware Networking.” Phil. Trans. Royal Soc. Series A Vol. 358 No. 1773, August 2000

S. Shenker, "Fundamental Design Issues for the Future Internet." IEEE JSAC 13(7), Sep 1995, pp. 1176-1188

L. Zhang, S. Deering, D. Estrin, S. Shenker, D. Zappala, "RSVP: A New Resource ReSerVation Protocol." IEEE Network, Sep. 1993, pp. 8-18

Simulation

M.E. Crovella, L. Lipsky, “Long-Lasting Transient Conditions in Simulations with Heavy-Tailed Workloads.” Proc. Winter Simulation Conf. 1997

S. Floyd, V. Paxson, ”Why We Don’t Know How To Simulate The Internet.” Proc. 1997 Winter Simulation Conference, Atlanta, GA, USA, Dec. 1997. Available at http://www.aciri.org/floyd/papers/wsc97.ps

H.-P. Schwefel, L. Lipsky, M. Jobmann, “On the Necessity of Transient Performance Analysis in Telecommunication Networks.” Feb. 2001. Available at http://wwwjessen.informatik.tu-muenchen.de/~schwefel/itc17.ps.gz