The Impact of Delay Variations on TCP Performance

Michael Scharf
Institut für Kommunikationsnetze und Rechnersysteme
Universität Stuttgart
scharf@ikr.uni-stuttgart.de

ITG FG 5.2.1 Workshop, Hamburg
20. Feb. 2004
Characteristics of mobile networks
Impact of delay variations on TCP
Modeling the RTT estimation in TCP
Model validation
Optimization approaches
Conclusions and future work
Characteristics of mobile networks

Network architecture (simplified)

- Few packet losses due to highly persistent link layer
- Rather low bandwidth, but high latency
- Variable delays and significant jitter
  - Retransmission of radio blocks (ARQ mechanism)
  - Cell handovers and link outages
  - Radio resource preemption by voice traffic

Impact of delay variations on TCP performance?
Transmission Control Protocol (TCP)

- Window-based, reliable transport protocol
  - Receiver advertised window
  - Congestion window

- Error recovery
  - Fast retransmit/Fast recovery mechanism
  - Retransmission timeouts

- Different variants: TCP Reno, NewReno, SACK, ...

Impact of delay variations on TCP (1)
Impact of delay variations on TCP (2)

Potential effects

- Spurious TCP timeouts = timeouts even though no packets are lost
  - Go-back-N mechanism unnecessarily retransmits segments
  - Needless reduction of congestion window
  - TCP may waste bandwidth or underutilize the available resources
Impact of delay variations on TCP (2)

Potential effects

- Spurious TCP timeouts = timeouts even though no packets are lost
  - Go-back-N mechanism unnecessarily retransmits segments
  - Needless reduction of congestion window
  - TCP may waste bandwidth or underutilize the available resources

- Mis-estimation of available network capacity by TCP
  - Buffer overflows if over-estimated
  - Poor throughput if under-estimated
Impact of delay variations on TCP (2)

Potential effects

- Spurious TCP timeouts = timeouts even though no packets are lost
  - Go-back-N mechanism unnecessarily retransmits segments
  - Needless reduction of congestion window
  - TCP may waste bandwidth or underutilize the available resources

- Mis-estimation of available network capacity by TCP
  - Buffer overflows if over-estimated
  - Poor throughput if under-estimated

- Packet reordering
  - May trigger spurious fast retransmits
  - Usually prevented by reliable link layer
Spurious timeouts - An example

Institut für Kommunikationsnetze und Rechnersysteme

Universität Stuttgart
RTT sampling by TCP

Default method:

- One measurement per RTT
- Low sampling rate
- No measurement on retransmitted segments (Karn’s algorithm)
RTT sampling by TCP

Default method:
- One measurement per RTT
- Low sampling rate
- No measurement on retransmitted segments (Karn’s algorithm)

Timestamps (RFC 1323):
- Additional 12 byte TCP header option
- Samples with every new ACK
- Measurements on retransmitted segments
RTO calculation

- **Tradeoff necessary**
  - Frequent spurious timeouts if value too small (aggressive timer)
  - Long idle times if value too large (conservative timer)

- **Algorithm according to RFC 2988:**

  \[
  \text{RTTVAR: } v(n) = \frac{3}{4} \cdot v(n-1) + \frac{1}{4} \cdot |s(n-1) - x(n)|
  \]

  \[
  \text{SRTT: } s(n) = \frac{7}{8} \cdot s(n-1) + \frac{1}{8} \cdot x(n)
  \]

  \[
  \text{RTO: } R(n) = \max(s(n) + 4 \cdot v(n), m)
  \]

- **Recommendation for minimum:** \( m = 1 \text{ sec} \)

- **Coarse timer granularity in many protocol stacks**
Assumptions

- Single bottleneck: Radio link
- Main parameters
  - Service rate $\mu$
  - Latency $\tau$
  - Buffer size $B > \mu \cdot \tau$
- TCP bulk data transfer
  - Single TCP connection over radio link
  - Greedy source
- Not limited by receiver advertised window
  - Typical saw-tooth behavior with cycles
Modeling the RTT estimation in TCP (4)

Modeling approach

- RTO calculation is a non-linear filter
- Approximation: Linear input function $x(n)$
- Number of samples per cycle:
  
  $N = f(\mu, \tau, B, \text{sampling method})$

- RTO duration $R(n)$ can be determined analytically
RTT sampling rate

- Path capacity: \( C = \lceil B + 1 + \mu \cdot \tau \rceil \)
- Delayed Acknowledgements mechanism: \( b \) segments per ACK
- Samples per cycle for default measurements

\[
N = b \left\lceil \frac{1}{2} (C + 1) + 2 \right\rceil
\]

- Samples per cycle for timestamps

\[
N = \left\lceil \frac{3}{8} (C + 1)^2 + \frac{C}{b} + 1 \right\rceil
\]
Numerical results
Numerical results

- RTO characteristics highly depends on sampling rate
- Algorithm more aggressive if timestamps are used ($N \gg 10$)
- RFC 2988 and timestamps do not harmonize well
Model validation (1)

Simulation setup

- Various network configurations (GPRS, UMTS)
- Parametrization of RTT estimator
  - With and w/o timestamps
  - Granularity 10 ms or 200 ms
Selected examples

Without timestamps

Model matches quite well to simulation results

With timestamps
Model validation (3)

Different GPRS and UMTS scenarios

Fine timer granularity

![Graph showing RTO duration normalized by \( x_{\text{max}} \) as a function of the number of samples per cycle \( N \). The graph compares model and simulation results, highlighting \( R \), \( R_{\text{max}} \), and \( R_{\text{min}} \).]
Different GPRS and UMTS scenarios

Fine timer granularity vs. Coarse timer granularity

Discrepancies for coarse timer granularity
Performance degradation by spurious timeouts

Spurious timeouts are triggered by off periods of duration $T_{\text{off}} > R_{\text{max}}$
Performance degradation by spurious timeouts

Spurious timeouts are triggered by off periods of duration \( T_{off} > R_{max} \)

Impact only significant in case of frequent delay variations
Optimization approaches

Architectures

Modification of TCP algorithms
- Numerous approaches
- Spurious packet filter
- ACK Regulator
- ACK Buffering
- M-TCP
- Active queue management
- Eifel Algorithm
- F-RTO
- D-SACK
- Freeze TCP

Protocol helper / protocol booster
- Mobile terminal
- GGSN
- Fixed terminal

Split connection
- Example: WAP
Conclusions

- Mobile networks are characterized by variable delays
  - Spurious TCP timeouts degrade performance
  - Sensitivity of TCP to delay variations depends on RTT estimator
- Model for RTT estimation of TCP
  - RTO duration as a function of path parameters
  - Significant impact of RTT sampling rate
  - Timestamps and RFC 2988 do not harmonize well
- Quantification of risk of spurious timeouts
  => Only delay variations of the order of seconds are critical

Future work

- Simulations with more sophisticated UMTS radio link models
- Verification by measurements
The Impact of Delay Variations on TCP Performance

Michael Scharf
Institut für Kommunikationsnetze und Rechnersysteme
Universität Stuttgart
scharf@ikr.uni-stuttgart.de

ITG FG 5.2.1 Workshop, Hamburg
20. Feb. 2004
Modification of TCP algorithms

- **Sender-based**
  - Eifel Algorithm (RFC 3522)
  - F-RTO (P. Sarolahti et. al.)
  - D-SACK (RFC 2883)
- **Receiver-based**
  - Freeze TCP (Goff et. al.)

Protocol helper / protocol booster

- **Filtering of segments**
  - Spurious packet filter (Schüler et. al.)
  - Active queue management (Sågfors et. al.)
- **Manipulation of acknowledgments**
  - ACK Regularor (Chan&Ramjee)
  - ACK Buffering (Huang&Chang)
  - M-TCP (Brown&Singh)

Numerous split connection approaches
Eifel algorithm

- Eliminates retransmission ambiguity by timestamps
- Can detect spurious timeouts
- Improved reaction to spurious timeouts
  - No go-back-N
  - Congestion window restored
  - RTT estimation reinitialized