On Scalable Modeling of TCP Congestion Control Mechanism for Large-Scale IP Networks

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Background: Large-Scale Networks

- Emergence of large-scale networks
  - Communication networks is becoming larger and more complex
  - e.g., network with 10,000 nodes and 100,000 flows
- Urgent need for analysis technique of large-scale networks
  - Ensure stability, reliability, and robustness
  - Allow future network expandability and design
  - Asses impact of network failures and natural disasters

Background: Conventional Techniques for Networks Analysis

- Mathematical analysis
  - Queuing theory is a powerful tool for small-scale networks, but…
  - Not applicable to large-scale networks
- Simulation
  - Several network simulators are available, but…
  - Not applicable to large-scale networks
- Still limited to small-scale networks

Challenges

- How statistical/dynamical behavior of large-scale networks can be analyzed?
  - Statistical behavior
    - e.g., throughput, average delay, packet loss probability
  - Dynamical behavior
    - e.g., convergence time, ramp-up time, overshoot
- Must be scalable and accurate for complex large-scale networks

Possible Solutions

- Mathematical analysis
  - Advanced queuing systems
    - e.g., BCMP network
  - Fluid-based modeling
- Simulation
  - Parallel/distributed simulator
    - e.g., PDNS (Parallel/Distributed NS)
  - Fluid-based simulation
    - e.g., SSF (Scalable Simulation Framework)

Objective

- Propose an analysis method for large-scale networks
  - Analyze both statistical and dynamical behaviors
  - Applicable to complex closed-loop networks
  - Scalable to large-scale networks
  - Accurate in diverse network parameters

Key Ideas

- Extend existing fluid-based modeling approach
- Model network components as SISO systems
  - TCP congestion control mechanism
  - RED router
  - Link propagation delay
- Join SISO systems for building entire network model
- Perform steady-state analysis and numerical simulation

SISO: Single Input and Single Output

Modeling TCP Congestion Control Mechanism

- x(t): input (arrival rate of ACK packets)
- y(t): output (transmission rate of data packets)
- R: round-trip time
- z(t) = y(t - R) - x(t)

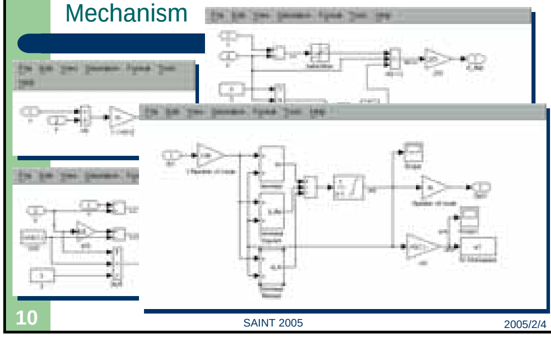
$$\begin{aligned}\dot{y} &= g(x(t), y(t), R) \\ &= \frac{x(t)}{y(t) R^2} - \frac{2}{3} y(t) z(t) \{1 - p_{TO}(t)\} \\ &\quad - \left\{ \frac{4}{3} y(t) - \frac{1}{R} \right\} z(t) p_{TO}(t)\end{aligned}$$

additive increase

multiplicative decrease

TCP timeout

Block Diagram of TCP Congestion Control Mechanism



Modeling RED Router

- x(t): input (packet arrival rate)
- y(t): output (packet departure rate)
- minth, maxth, maxp, wq: RED control parameters

$$\begin{aligned}y(t) &= h(x(t), p(t), c(t)) \\ &= \min(c(t), (1 - p(t))\, x(t))\end{aligned}$$

$$p(t) = \frac{2 p_b(t)}{1 + p_b(t)}$$

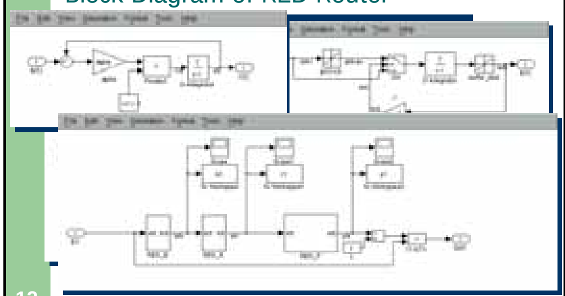
$$\dot{r} = -\alpha\, c(t) (r(t) - b(t))$$

$$\dot{b} = \begin{cases} x(t) - c(t) & \text{if } b(t) > 0 \\ (x(t) - c(t))^+ & \text{if } b(t) = 0 \end{cases}$$

$$p_b(t) = \begin{cases} 0 & \text{if } r(t) < min_{th} \\ \frac{max_p}{max_{th} - min_{th}} (r(t) - min_{th}) & \text{if } min_{th} \le r(t) < max_{th} \\ \frac{1 - max_p}{max_{th}} r(t) - (1 - 2 max_p) & \text{if } max_{th} \le r(t) < 2 max_{th} \\ 1 & \text{if } r(t) \ge 2 max_{th} \end{cases}$$

packet marking probability

Block Diagram of RED Router



Modeling Link Propagation Delay

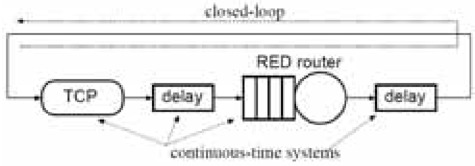
- x(t): input (packet arrival rate)
- y(t): output (packet departure rate)
- τ: propagation delay of the link

$$y(t) = x(t - \tau)$$

constant delay component

Modeling Entire Network

- Connect independent SISO systems
- Example: case of a single TCP flow and RED router



Steady State Analysis: Main Results

- TCP packet output rate

$$\frac{d}{dt} y_n^T(t) = g(x_n^T(t), y_n^T(t), R_n(t))$$

- RED packet output rate

$$y_m^R(t) = h(x_m^R(t), p_m(t))$$

- TCP throughput

$$T_n = y_n^*$$

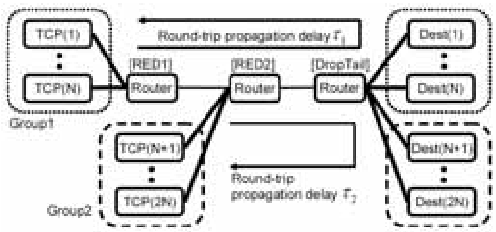
- TCP round-trip time

$$RTT_n = \sum_{l \in L_n} \tau_l + \sum_{m \in D_n} \frac{\overline{q}_m^*}{c_m^*}$$

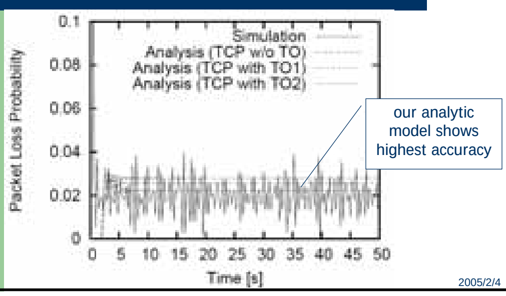
- TCP packet loss probability

$$P_n = 1 - \prod_{m \in D_n} (1 - p_m^*)$$

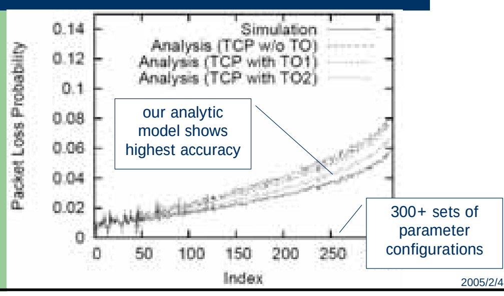
Numerical Examples: Network Model



Numerical Examples: Packet Loss Probability



Numerical Examples: Comparison in Diverse Network Parameters



Conclusion

- Proposed an analysis method for large-scale networks
  - Modeled network components as SISO systems
    - TCP congestion control mechanism
    - RED router
    - Link propagation delay
  - Connect SISO systems for modeling entire network
- Analyzed both statistical and dynamical behaviors
  - Scalable to large-scale networks
  - Accurate in diverse range of network parameters

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Future Works

- Build analytic model for other network components
  - Transport-layer protocols
    - e.g., TCP Vegas, TCP SACK, HighSpeed TCP, DCCP, TFRC, SCTP
  - AQM (Active Queue Management) mechanisms
    - e.g., PI-controller, SRED, DRED, BLUE, FRED
- Implement a fluid-based simulator
  - Can simulate large-scale networks
  - Compatible with ns2 simulation script

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