Rate-Based versus Queue-Based Models of Congestion Control

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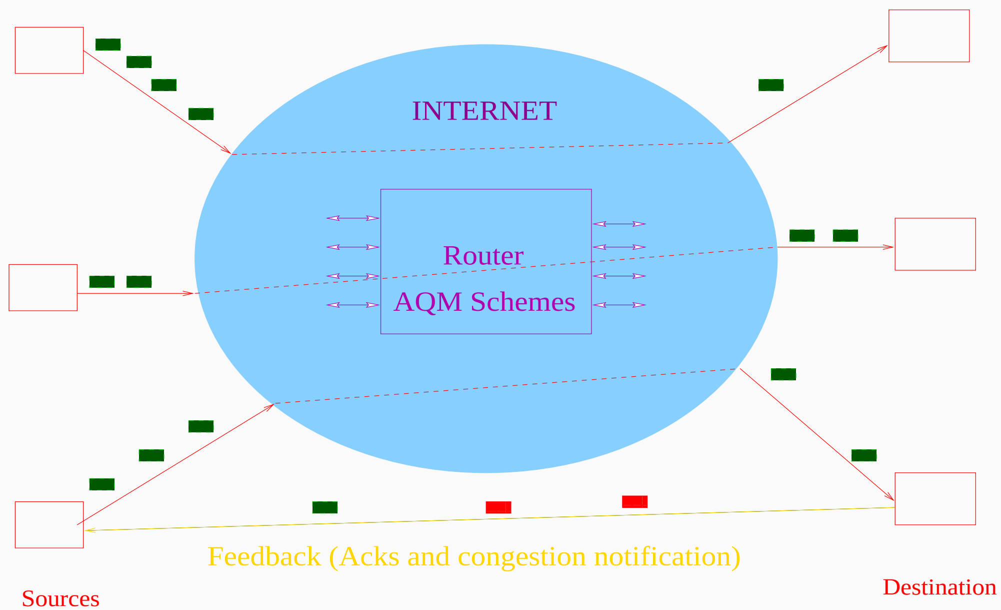
The End-to-End Paradigm of Internet



- Routers react to the aggregate flow passing through it
- Routers drop/mark (set ECN bit to 1) packets during congestion

  → Explicit Congestion notification (ECN)
- Queueing delays can be made negligible with ECN mechanism

Models of Congestion Control

- Rate update of sources described by suitable differential or difference equations (deterministic models)

  $\longrightarrow$ Rate Based Models:

  The fraction of packets marked by a router modeled as p(total rate into the link)

  $\longrightarrow$ Queue Based Models:

  The fraction of packets marked by a router modeled as p(queue length)

- However, there are sources of uncertainties (randomness):

  $\longrightarrow$ Unresponsive flows, probabilistic marking, windowing effects

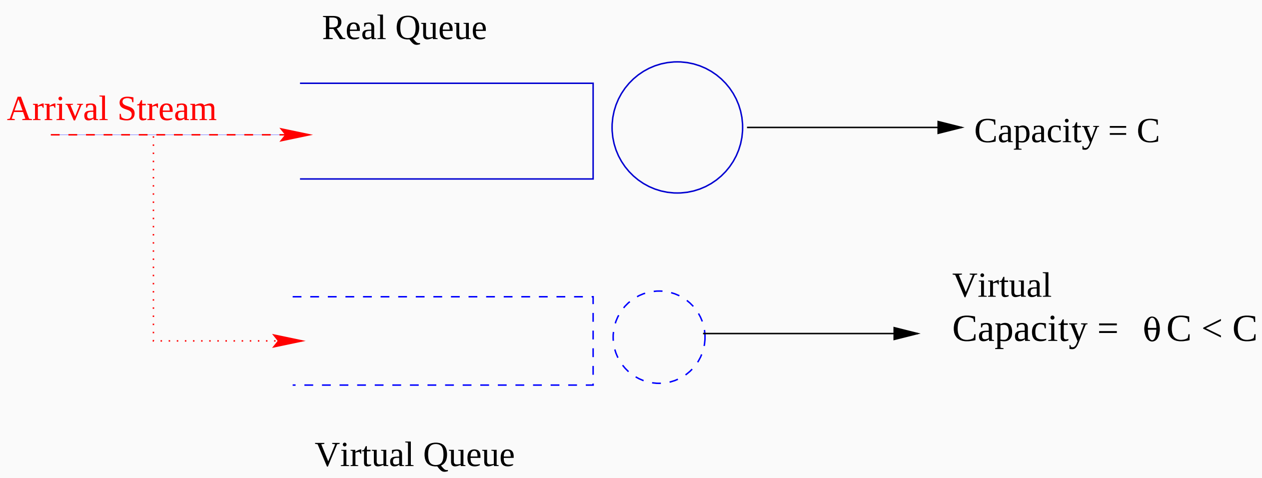
  $\longrightarrow$ The deterministic models can be viewed as the limiting model of the average flow rate

- Most AQM schemes are queue-length based.

Rate-Based versus Queue-Based Models

- Give very different conditions for stability
- In many examples, one is stable for large enough bandwidth-delay product, the other stable for small bandwidth-delay product
- Which is the right model for the Internet?
- Do different parameter choices of an AQM scheme produce different models?

Review: Virtual-Queue Based Marking



- Virtual Queue adds packet whenever there is an arrival
- Packets drained at a lower rate of $\tilde{C} = \theta \times Capacity\ (\theta < 1)$

  $\longrightarrow$ Helps to detect incipient congestion

  $\longrightarrow$ Packets from controlled flows can still overflow due to the presence of uncontrolled flows and other uncertainties

- How to choose θ to meet a target buffer overflow probability?

Our Objective

- Provide suitable discrete-time stochastic models which capture the various uncertainties

- Goal is to answer the following questions:

  $\longrightarrow$ Given a parameter choice, what is the right kind of limiting deterministic model for the average flow-rate?

  $\longrightarrow$ How should the AQM parameters be chosen to achieve low-loss, low-delay and high-utilization?

- Study the robustness of a virtual-queue based marking.

Large System Modeling

- Bottleneck router accessed by N controlled flows, N unresponsive flows

  $\longrightarrow$ Unresponsive flows modeled as stochastic disturbances

- Capacity of the link Nc

  $\longrightarrow$ To have reasonable bandwidth per flow

- Source updates rate every c time-units

- Link processes packets N times faster

Model for Arrival Process into the Link

- The link operates at a much faster time-scale, takes $\frac{1}{Nc}$ time to drain a packet
  $\longrightarrow$ We want to model the arrival process into the link over this time interval

- Suppose x_r is the rate of the r^{th} controlled flow (which is updated every c time-units). Assume:

  $\longrightarrow$ The number of arrivals into the link in time $\frac{1}{Nc}$ is Poisson($\frac{x_r}{Nc}$)

  $\longrightarrow$ Motivation: To model various sources of uncertainties

Marking Mechanism: AQM scheme

- If the queue length is b, a packet is marked with probability

$$f(b) = 1 - \exp(-\gamma^{(N)} b) \qquad \textbf{(REM)}$$

- We study two different scalings of $\gamma^{(N)}$
  $\rightarrow \gamma^{(N)} = \frac{\gamma}{N}$
  $\rightarrow \gamma^{(N)} = \gamma$
- The technique is quite general, can be used with other AQM mechanisms
- We concentrate on VQ based marking. Real Queue based marking can be recovered by setting $\theta = 1$

Discrete-Time Stochastic Models

- Consider N proportionally-fair controllers accesing a bottleneck router

  $\longrightarrow$ Called the N^{th} system

- In the N^{th} system, the dynamics of the r^{th} source is given by

$$x_r^{(N)}[k+1] = x_r^{(N)}[k] + \kappa(w - M_r[k])$$

- M_r is the number of packets marked in the update interval

  $\longrightarrow$ It is a random variable and function of the queue-length $b[k]$

Large Number of Flows Limit

- Under appropriate conditions

$$x^{(N)}[k] = \frac{1}{N} \sum_{r=1}^{N} x_r^{(N)}[k]$$

converges (as $N \to \infty$) in an appropriate sense to

$$x[k+1] = x[k] + \kappa(w - M[k])$$

$\longrightarrow$ What is $M[k]$?

Main Results

- If $f(b) = 1 - \exp(-\gamma b)$

  $\rightarrow M[k] = x[k]\, p(x[k])$, a function of the rate

  $\rightarrow p(x)$ is the equivalent rate-based marking function (precise closed form expression in the paper)

- If $f(b) = 1 - \exp(-\gamma b/N)$

  $\rightarrow M[k] = x[k]\, p_q(q[k], x[k])$, a joint function of the rate and scaled queue length

  $\rightarrow p_q(q, x)$ is the equivalent marking function (precise closed form expression in the paper)

  $\rightarrow$ When $x \approx x^*$ and $\gamma << 1$, $p_q(q, x) \approx 1 - \exp(-\gamma q)$

Simulation Results

- Router accessed by multiple TCP flows and multiple uncontrolled flows

  $\longrightarrow$ ON-OFF model for unresponsive flows

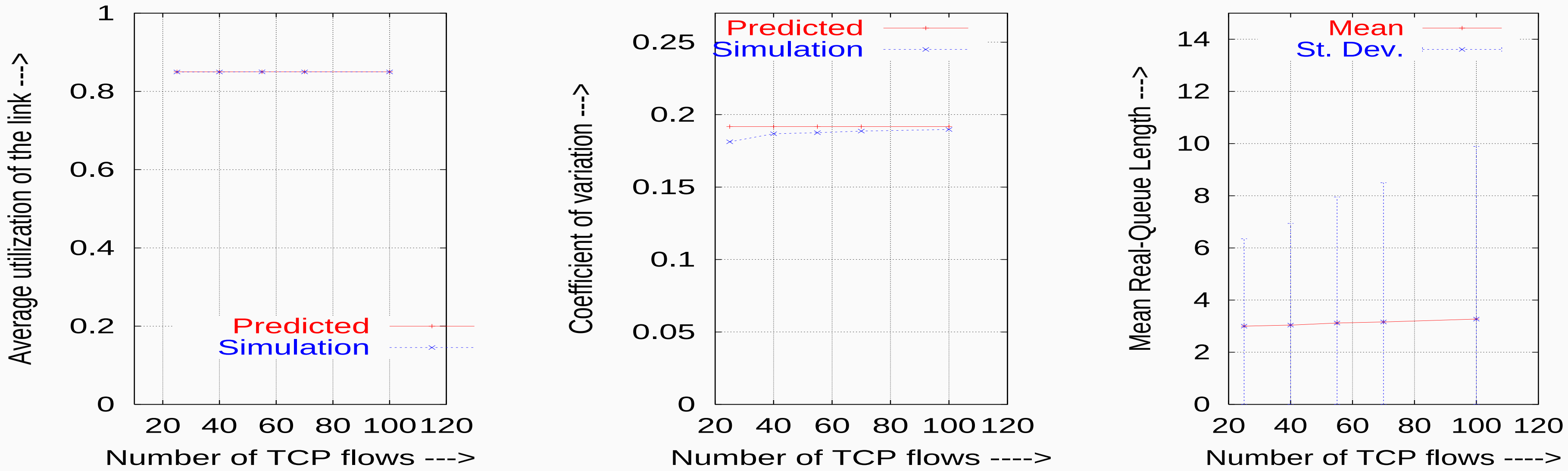
- We are interested in:

  $\longrightarrow$ Link utilization

  $\longrightarrow$ Variance of the arrival process as computed over time to serve $b = 32$ packets

  $\longrightarrow$ Queue length at the real queue

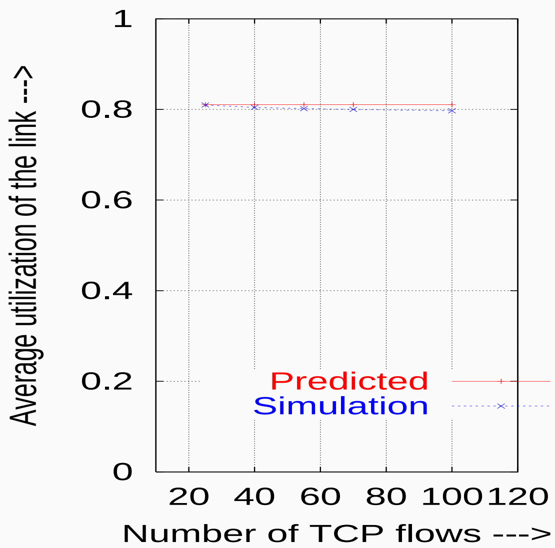
Results: VQ Based REM with $\gamma^{(N)} = \frac{\gamma}{N}$ and TCP Flow Control

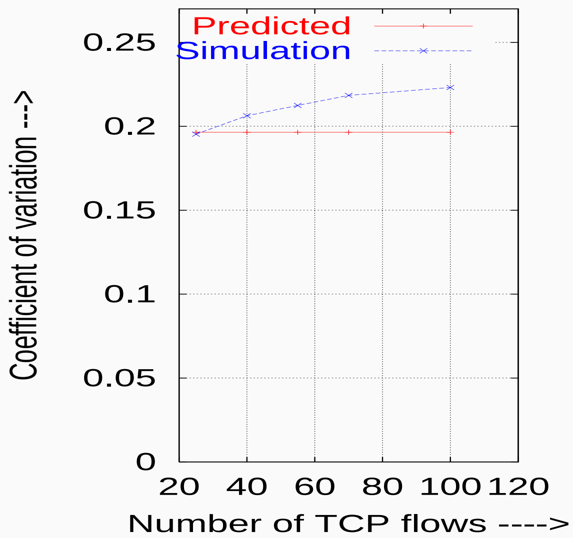


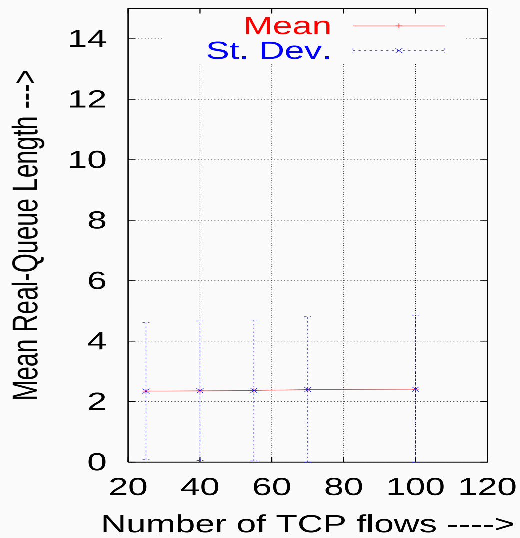
- The variance as predicted by our model is very accurate
- The queue-length is $O(1)$

  $\longrightarrow$ The models can be used to find the buffer size ($O(1)$) required for a given overflow probability and given utilization

Results: VQ Based REM with $\gamma^{(N)} = \gamma$ and TCP Flow Control





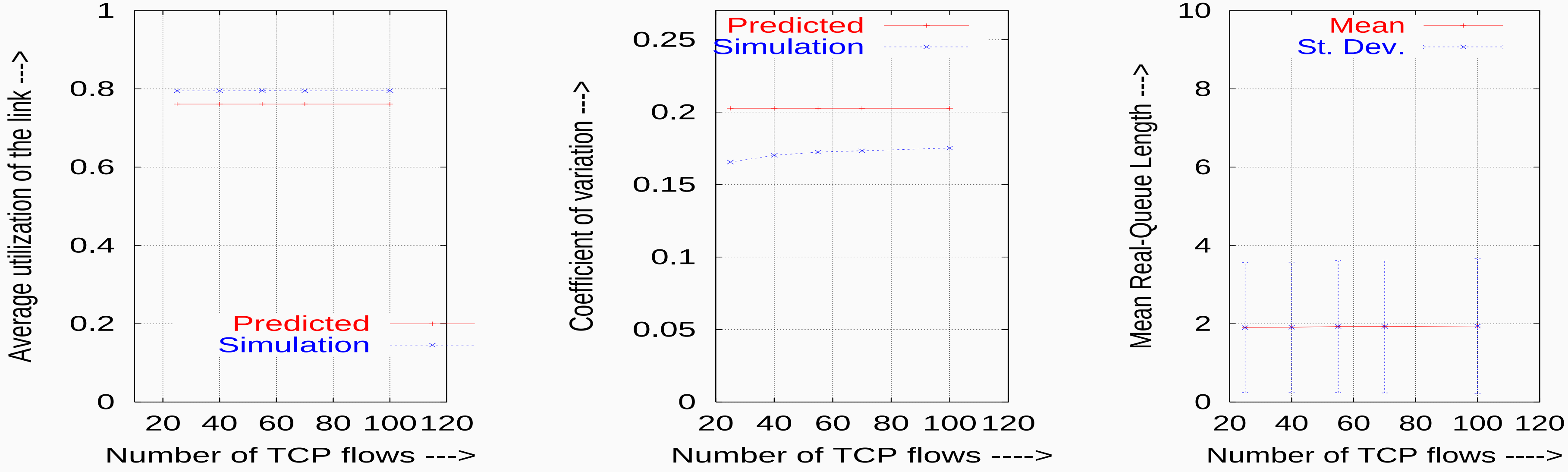


- The utilization and the variance as predicted by our model is very accurate
- The queue-length is $O(1)$

  $\longrightarrow$ Again, we can find the buffer size ($O(1)$) required for a given overflow probability and a given utilization

  $\longrightarrow$ Demonstrates the robustness of virtual-queue based marking

Results: Real-Queue Based REM with $\gamma^{(N)} = \gamma$ and TCP Flow Control



- Our models accurately predict utilization, variance and mean queue length
- With real-queue based marking, an arbitrarily low over-flow probability can be achieved with an $O(1)$ buffer size with $\gamma^{(N)} = \gamma$
- Real Queue based marking with $\gamma^{(N)} = \frac{\gamma}{N}$ gives a queue-length of $O(N)$

Summary

- Depending on how AQM parameters are are scaled, the equivalent model for marking function can be rate-based or jointly rate and queue-length based
- With virtual queue based marking, steady state properties like mean and variance are robust to the choice of parameter
- An $O(1)$ buffer size can achieve a given buffer-overflow probability at a given utilization, if parameters are chosen judiciously

THANK YOU