Adaptive, Best-Effort Congestion Control Mechanisms for Real-Time Communications on the Internet

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What are we doing?
- Trying to understand how “broken” the Internet is today
- Trying to understand how to design real-time multimedia applications for the Internet

Why are we doing this?
- We want to understand if we should spend our efforts building a better Internet, making “smarter” applications, or both

How are we doing this?
- Developing real-time communications and computation middle-ware
- Building real-time applications with experimental communications software
- Evaluating their performance on controlled and production networks
- Running long-term performance studies on the Internet
- Evaluating their performance on controlled and production networks
- Running long-term performance studies on the Internet

Outline
- Our driving problem — realizing distributed, immersive, virtual laboratories
  - The UNC nanoManipulator system
- The continuous media congestion control problem
- 2-Dimensional media scaling techniques
- Experimental results for Internet videoconferencing
Advanced scientific instruments have computer-based or computer-enhanced interfaces.

Treating these systems as distributed systems enables...

- Better user interfaces
- Remote operation of instruments
- Multi-user and collaborative operation
- Sharing of instruments and specialized computing equipment

Example — Atomic Force Microscopes

The UNC nanoManipulator system

- A virtual environment interface to a scanning-probe microscope
- Provides telepresence on sample surfaces scaled 1,000,000:1
Distributed Virtual Laboratories
Networking challenges

Graphics Engine & Host Processor
Internetwork
Visual Feedback
Intel-based Microscope Controller
Intel-based PHANToM Controller
Force Feedback

AFM Control Processing
Internetwork
80 Kbps ("touch mode")
816 Kbps ("scan mode")
48 Kbps ("touch mode")
250 Mbps (max)

User Interface & Application Processing
96 Kbps
Hand Tracking & Feedback Control
1.05 Gbps (max)

3D Graphics Processing

Distributed Virtual Laboratories
nM distribution scenarios

➤ Scientific collaboration over Integrated Services networks
➤ Equal distribution of graphics, tracking, and microscope hardware

Duke OC-48 Sonet Node
MCNC OC-48 Sonet Node
NCSU OC-48 Sonet Node
The North Carolina GigaPOP

➤ Scientific collaboration over high-speed, best effort internetworks
➤ Co-located graphics & microscope hardware, remote tracking & user interface
➤ Co-located microscope hardware, tracking & user interface, remote graphics engine
Distributed Virtual Laboratories

$nM$ distribution scenarios

➤ Scientific collaboration over Integrated Services networks
➤ Scientific collaboration over high-speed, best effort internetworks
➤ Educational outreach over the Internet
  ➤ Co-located graphics & microscope hardware, remote tracking & user interface

Adaptive, best-effort congestion control for real-time communications

Outline

➤ Our driving problem — realizing distributed, immersive, virtual laboratories
  ➤ The UNC \textit{nanoManipulator} system
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Cont. Media Congestion Control

Effect of packet loss on UNC campus

Cont. Media Congestion Control

Effect of packet loss across 16 hops
Cont. Media Congestion Control
The UNC approach

➤ Operating principle:
Network elements that cannot reserve, or support real-time allocation of resources, will persist for the foreseeable future.

➤ Focus on adaptive, best-effort transmission...
Treat the network as a black box – Assume only that sufficient bandwidth exists for some useful execution of the system

➤ ... with real-time media control at the endpoints

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Cont. Media Congestion Control
The UNC approach

➤ Congestion in the small: delay-jitter

Elastic queueing to manage the trade-off between low latency playout and gap-rate

➤ Congestion in the large: packet loss

Adaptive media scaling and packaging to decrease network queueing (latency) and minimize packet loss

Congestion Control
The nature of congestion

➤ What causes congestion?
  ➤ Did our multimedia stream(s) cause the network to be congested?
  ➤ Are there simply too many connections competing for too little bandwidth?
Congestion Control

The nature of congestion

➤ How can we make the best use of the (time varying) bandwidth that is available to our streams?
  ➤ How can we determine what this bandwidth is?
  ➤ How can we track how it changes over time?
  ➤ How can we match our application’s output to the available bandwidth?

Switch Fabric

 Canonical Adaptive Congestion Control

Video bit-rate scaling

➤ Temporal scaling
  ➤ Reduce the resolution of the stream by reducing the frame rate

➤ Spatial scaling
  ➤ Reduce number of pixels in an image

➤ Frequency scaling
  ➤ Reduce the number of DCT coefficients used in compression

➤ Amplitude scaling
  ➤ Reduce the color depth of each pixel in the image

➤ Color space scaling
  ➤ Reduce the number of colors available for displaying the image

Unc Adaptive Congestion Control

2-Dimensional media scaling

➤ Canonical approach to congestion
  ➤ Reduce (video) bit-rate

➤ Alternate approach
  ➤ View congestion control as a search of a 2-dimensional \( \text{bit-rate} \times \text{packet-rate} \) space

➤ Scale bit- and packet-rates simultaneously to find a sustainable operating point

Bit- and Packet-Rate Scaling

An analytic model of media scaling

Capacity constraints
  ➤ the network is incapable of supporting the desired bit rate in any form

Access constraints
  ➤ the network can not support the desired bit rate with the current packaging scheme
Bit- and Packet-Rate Scaling
An analytic model of media scaling

➤ Reduce the packet-rate to adapt to an access constraint
  ➤ Change the packaging or send fewer video frames
  ➤ Primary Trade-off: higher latency (potentially)

➤ Reduce the bit-rate to adapt to a capacity constraint
  ➤ Send fewer video frames or fewer bits per video frame
  ➤ Primary Trade-off: lower fidelity

2-Dimensional Media Scaling
Finding a sustainable operating point

➤ Initial operating point:
  (high quality, 12 fps)

➤ First adaptation:
  (high quality, 10 fps)
  ➤ congestion persists

➤ Second adaptation:
  (medium quality, 10 fps)
  ➤ congestion relieved

➤ First probe:
  (medium quality, 12 fps)

➤ Second probe:
  (medium quality, 14 fps)
2-Dimensional Media Scaling
Dealing with effects of fragmentation

➤ The problem
➤ A sender can only (directly) effect the message rate, not the packet rate

➤ Does fragmentation render message-rate scaling obsolete?

2-Dimensional Media Scaling
Does it work?

➤ Campus-sized internets?
➤ The Internet?

2-Dimensional Media Scaling
Does it work?

➤ Experiments
➤ Baseline – UDP transmission, no adaptations
➤ 1-Dimensional media scaling (video bit-rate scaling)
➤ Audio and video media scaling & packaging

➤ Metrics
➤ Delivered media frame rate (throughput)
➤ Packet loss
➤ Media stream latency
➤ Adaptations performed over time

2-D Scaling on the UNC Campus
Performance with no media scaling

Throughput (frames/sec)
Packet Loss
Audio Latency (ms)
Video Latency (ms)
2-D Scaling on the UNC Campus
Performance with video scaling only

Throughput (frames/sec)
Packet Loss
Audio Latency (ms)
Video Latency (ms)

2-D Scaling on the UNC Campus
Video scaling v. no adaptation

Throughput (frames/sec)
Packet Loss
Audio Latency (ms)

2-D Scaling on the UNC Campus
Performance with 2-dimensional scaling

Throughput (frames/sec)
Packet Loss
Audio Latency (ms)
Video Latency (ms)

2-Dimensional Media Scaling
Does it work?

➤ Campus-sized internets — yes!
➤ It “solves” the first-mile/last-mile problem
➤ The Internet? — well...
➤ Does our necessary condition for success hold?
➤ Does it hold often enough to be useful?
➤ How much “room” is there for 2-D scaling in most codecs?
Sustainability Results
Adaptive methods on the Internet

➤ Results of an Internet performance study from UNC to UVa
  ➤ Repeated trials from 10 am to 7 PM weekdays
  ➤ Trials separated by at least two hours
  ➤ Scattered over three months

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<th>Not Sustainable</th>
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<td>67%</td>
<td>33%</td>
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<tr>
<td>12:00-14:00</td>
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<td>16:00-18:00</td>
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<td>18:00-20:00</td>
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<td>56%</td>
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<tr>
<td>Percentage</td>
<td>39%</td>
<td>61%</td>
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Adaptive, best-effort congestion control for real-time communications

Summary
➤ Real-time applications must be adaptive to be effective on the Internet
➤ Simple middleware adaptations are sufficient for accommodating most Internet pathologies within “the intranet”
  ➤ Biasing how a bit-stream is partitioned into packets is more effective than reducing the bit-stream

Will best-effort techniques scale?
Router-based congestion control

➤ Recursively apply endpoint media adaptations in the network
  ➤ Delay-jitter management adaptations
  ➤ Congestion/flow control adaptations
➤ Compare performance against CBQ gateways
  ➤ RED packet discard for TCP
  ➤ “Delete Oldest & Advance” discard for multimedia