Overview

- QoS
  - Motivation
  - Integrated services
  - Adaptive applications
  - Differentiated services
- Video streaming
  - Background
  - Olympics study
  - Video control plane

Motivation

- Internet currently provides one single class of "best-effort" service
  - No assurances about delivery
- Existing applications are elastic
  - Tolerate delays and losses
  - Can adapt to congestion
- Future "real-time" applications may be inelastic

QoS and Video Streaming

- Assigned reading:
  - Video control plane
  - Bird's Nest: Sections 1-2
- Optional reading:
  - Coolstream
  - Live Video Streaming with Dynamic Application End-points
**Inelastic Applications**

- Continuous media applications
  - Lower and upper limit on acceptable performance.
  - BW below which video and audio are not intelligible.
  - Internet telephones, teleconferencing with high delay (200 - 300ms) impair human interaction.
- Hard real-time applications
  - Require hard limits on performance.
  - E.g. control applications.

**Why a New Service Model?**

- What is the basic objective of network design?
  - Maximize total bandwidth? Minimize latency?
  - Maximize user satisfaction – the total utility given to users.
- What does utility vs. bandwidth look like?
  - Must be non-decreasing function.
  - Shape depends on application.

**Utility Curve Shapes**

- Elastic
- Hard real-time
- Delay-adaptive

Stay to the right and you are fine for all curves.

**Admission Control**

- If $U$(bandwidth) is concave
  - elastic applications
    - Incremental utility is decreasing with increasing bandwidth.
    - Is always advantageous to have more flows with lower bandwidth.
    - No need of admission control; This is why the Internet works!
Utility Curves – Inelastic traffic

Does equal allocation of bandwidth maximize total utility?

Admission Control

- If $U$ is convex $\rightarrow$ inelastic applications
  - $U$(number of flows) is no longer monotonically increasing
  - Need admission control to maximize total utility
- **Admission control** $\rightarrow$
  deciding when the addition of new people would result in reduction of utility
  - Basically avoids overload

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Components of Integrated Services

1. **Type of commitment**
   - What does the network promise?
2. Packet scheduling
   - How does the network meet promises?
3. Service interface
   - How does the application describe what it wants?
4. Establishing the guarantee
   - How is the promise communicated to/from the network
   - How is admission of new applications controlled?
QoS Framework

Traffic Enforcement

Packet Scheduling

Admission Control

Type of Commitments

- **Guaranteed** service
  - For intolerant and rigid applications
  - Fixed guarantee, network meets commitment as long as clients send at match traffic agreement

- **Predicted** service
  - For tolerant and adaptive applications
  - Two components
    - If conditions do not change, commit to current service
    - If conditions change attempt to deliver consistent performance

- **Datagram/best effort service**

Components of Integrated Services

1. **Type of commitment**
   - What does the network promise?

2. **Packet scheduling**
   - How does the network meet promises?

3. **Service interface**
   - How does the application describe what it wants?

4. **Establishing the guarantee**
   - How is the promise communicated to/from the network
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Scheduling for Guaranteed Traffic

- Use **token bucket filter** to characterize traffic
  - Described by rate $r$ and bucket depth $b$
  - Can also be used to do traffic enforcement by reshaping the traffic at the network ingress

- Use **WFQ** at the routers
  - Parekh’s bound for
    - Worst case queuing delay = $b/r$
Token Bucket Filter

Operation:
- If bucket fills, tokens are discarded
- Sending a packet of size P uses P tokens
- If bucket has P tokens, packet sent at max rate, else must wait for tokens to accumulate

Token Bucket Operation

- Tokens enter bucket at rate $r$
- Bucket depth $b$: capacity of bucket
- Tokens enter bucket

Token Bucket Characteristics

- On the long run, rate is limited to $r$
- On the short run, a burst of size $b$ can be sent
- Amount of traffic entering at interval $T$ is bounded by:
  - Traffic = $b + r^*T$
- Information useful to admission algorithm

Token Bucket Specs

- Flow A: $r = 1$ MBps, $B = 1$ byte
- Flow B: $r = 1$ MBps, $B = 1$ MB
DiffServ

- Analogy:
  - Airline service, first class, coach, various restrictions on coach as a function of payment
- Best-effort expected to make up bulk of traffic, but revenue from first class important to economic base (will pay for more plentiful bandwidth overall)
- Not motivated by real-time! Motivated by economics and assurances

Basic Architecture

- Agreements/service provided within a domain
  - Service Level Agreement (SLA) with ISP
- Edge routers do traffic conditioning
  - Perform per aggregate shaping and policing
  - Mark packets with a small number of bits; each bit encoding represents a class or subclass
- Core routers
  - Process packets based on packet marking and defined per hop behavior: default, expedited forwarding, and assured forwarding
- More scalable than IntServ
  - No per flow state or signaling

Edge Router Input Functionality

classify packets based on packet header

Traffic Conditioning
**Comparison**

<table>
<thead>
<tr>
<th></th>
<th>Best-Effort</th>
<th>Diffserv</th>
<th>Intserv</th>
</tr>
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<tbody>
<tr>
<td>Service</td>
<td>• Connectivity</td>
<td>• Per aggregation isolation</td>
<td>• Per flow isolation</td>
</tr>
<tr>
<td></td>
<td>• No isolation</td>
<td>• Per aggregation guarantee</td>
<td>• Per flow guarantee</td>
</tr>
<tr>
<td></td>
<td>• No guarantees</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service Scope</td>
<td>• End-to-end</td>
<td>• Domain</td>
<td>• End-to-end</td>
</tr>
<tr>
<td>Complexity</td>
<td>• No set-up</td>
<td>• Long term setup</td>
<td>• Per flow setup</td>
</tr>
<tr>
<td>Scalability</td>
<td>• Highly scalable</td>
<td>• Scalable (edge routers maintain per aggregate state; core routers per class state)</td>
<td>• Not scalable (each router maintains per flow state)</td>
</tr>
</tbody>
</table>

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**Internet Video Today**

- DVD transfer
  - BitTorrent → P2P lecture
- Client-server streaming (“on demand”)
  - Hulu, Netflix, ..
- Synchronized video (“live”)
  - Sports events, IPTV, ...
- Interactive video conferencing
  - Skype, ...
- Latency really matters

**Client-Server Streaming: Adaptation Quality to Link**

- **Long Time Scale**
- **Short Time Scale**
  - Content Negotiation
  - Server Selection
  - Adaptive Media
Problems Adapting to Network State

- TCP hides network state
- New applications may not use TCP
  - Often do not adapt to congestion
  
  Need system that helps applications learn and adapt to congestion

Feedback about Network State

- Monitoring successes and losses
  - Application hints
  - Probing system

  Notification API (application hints)
  - Application calls cm_update(nsent, nrecd, congestion indicator, rtt)

Long History of Research in Video

- Early application Video Conferencing Tool
  - VIC – used the SIP protocol
  - Motivated new TCP friendly congestion ctl
  - Motivated multicast research
  - Adaptive (multi-layer) video streaming
  - Motivated lots of QoS research
  - Video delivery leveraging peer-to-peer

  How much of this is currently in use?

Some Example Systems

- IPTV: delivery of TV using IP technology
  - Multicast and R-UDP over private network
  - QoS limited to small number of flow class

  Video playback over the Internet
  - Uses playback buffers to avoid stalls
  - Tends to burst chunks of data using TCP
  - Rate adaptation is emerging technology

  Video conferencing
  - High quality over VPNs or dedicated lines
  - Best effort systems such as Skype
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Architecture Overview

- Multiple layers of CDN nodes for scalability
  - Run the Adobe Flash Media Software (FMS)
  - Can run in original (top) or edge mode (other)
- FMS provide streaming capability
  - Pause, seek, etc. - similar to DVD players
  - Alternative is HTTP download (next)
- Operations Support Systems control load balancing, billing, …

Video Distribution Architecture

- Multiple layers of CDN nodes for scalability
- Run the Adobe Flash Media Software (FMS)
- Can run in original (top) or edge mode (other)
- FMS provide streaming capability
- Pause, seek, etc. - similar to DVD players
- Alternative is HTTP download (next)
- Operations Support Systems control load balancing, billing, …
Video Quality Matters [Sigcomm’11]
- Quality has substantial impact on viewer engagement
  - Need to ensure uninterrupted streaming at high bitrates
- Buffering ratio is most critical across video traffic types
  - Highest impact for live: 1% of buffering reduced play time by 3min
  - 1% increase in buffering can lead to more than 60% loss in audience over one month

Our Argument
- CDN performance varies widely in time, geography, and ISPs
- Opportunity for significantly improving video Quality by selecting best CDN (and bitrate) for each viewer
- Hence, we argue for a logically **centralized** control plane to dynamically select CDN and bitrate

Our Assumptions:
- Content is encoded at multiple bitrates
- Content is delivered by multiple CDNs

How do We Collect Data?
- Automatic and continuous monitoring of video player
  - Flash: NetStream, VideoElement
  - Silverlight: MediaElement, SmoothStreamMediaElement
  - iOS: MPMoviePlayerElement

CDNs Vary in Performance over Geographies and Time
- Metric: buffering ratio
- One month aggregated dataset
  - Multiple Flash (RTMP) customers
  - Three major CDNs
  - 31,744 DMA-ASN-hour with > 100 streams from each CDN
  - DMA: Designated Market Area
- Percentage of DMA-ASN-hour partitions a CDN has lowest buffering ratio

There is no single best CDN across geographies, network, and time
Washington, DC viewer experience differed greatly...

Comcast viewers got the best streams from CDN 1 51% of the time and only 9% from CDN 2.

Verizon users got the best streams from CDN 1 only 17% of the time and 77% from CDN 2.

There is no single best CDN in the same geographic region or over time.

CDN Streaming Failures Are Common Events

- % of stream failures: % of streams that failed to start
- Three months dataset (May-July, 2011) for a premium customer using Flash

Video Control Plane Architecture

- Coordinator implementing a global optimization algorithm that dynamically select CDN & bitrate for each client based on
  - Individual client
  - Aggregate statistics
  - Content owner policies
  - (CDN/ISP info)

Possible Actions to Improve Quality

- Switch the bitrate
  - Buffering, high frame drops, high start time, ...
  - High available bandwidth, ...
- Switch the CDN
  - Connection error, missing content, buffering on low bitrate, ...
- When to perform switching/selection?
  - Start time selection only
  - Start time selection & midstream switching
Example: Local vs. Global Optimization

What is Next?

- Three lectures on wireless next week

- Three “Choice” lectures:
  - Datacenter networks
  - Sensor Networks
  - Energy efficient wireless

Next Lecture: Data Center Networks

- Lecture starts at 3:30
- Readings
  - Portland
  - Sections 1, 2, and 4 of Incast
  - Sections 1-2 of VL2
- Optional
  - DCTCP