Analysis and Improvement of the End-user Over-The-Top Video Streaming Experience

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Ph.D. Dissertation Defense

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Overview

- This presentation introduces *YouSlow* (“YouTube Too Slow!?”), as a new QoE monitoring system for adaptive bitrate video streaming

- Using YouSlow, we analyze video QoE in YouTube by monitoring video abandonment rate for various viewing interruptions such as video ads, rebufferings and bitrate changes during playback

My work on video streaming

Video streaming traffic analysis

- Analyzed video streaming traffic behavior over wireless networks (WIFI, 3G and LTE) under varying network conditions on different device platforms

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Improving over-the-top (OTT) video delivery

- Developed round-trip time (RTT)-based CDN server selection algorithm
- Showed a feasibility of using software-defined networking (SDN) for dynamic QoS / QoE aware video streaming

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Video QoE analysis

- Developed YouSlow as a new approach to monitoring video QoE
- Quantified viewing interruptions by monitoring abandonment rate

Outline

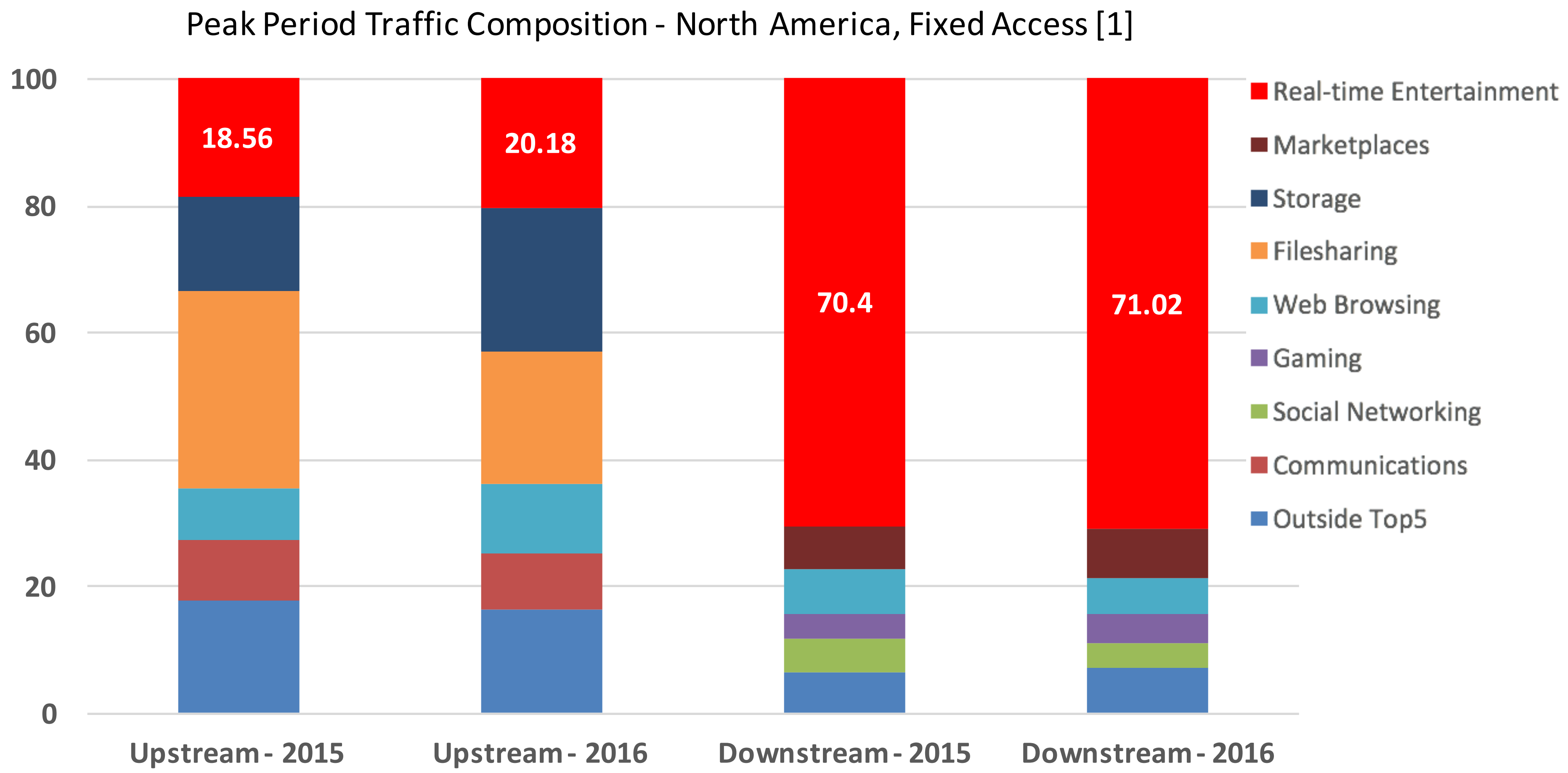
- Background – online video streaming
  - Video streaming traffic in 2016
  - A brief history of video streaming
  - QoS and QoE in video streaming

- YouTube Too Slow!? – YouSlow
  - YouSlow platform
  - YouTube statistics and QoE analysis

- Other projects and publications

Background – Online Video Streaming

Video streaming traffic is still on the rise (1/2)



[1] Sandvine – 2016 Global Internet Phenomena

Video streaming traffic is still on the rise (2/2)

Top 10 peak period applications – North America, Fixed Access [1]

Upstream		Downstream		Aggregate	
BitTorrent	18.37%	Netflix	35.15%	Netflix	32.72%
YouTube	13.13%	YouTube	17.53%	YouTube	17.31%
Netflix	10.33%	Amazon Video	4.26%	HTTP - OTHER	4.14%
SSL - OTHER	8.55%	HTTP - OTHER	4.19%	Amazon Video	3.96%
Google Cloud	6.98%	iTunes	2.91%	SSL - OTHER	3.12%
iCloud	5.98%	Hulu	2.68%	BitTorrent	2.85%
HTTP - OTHER	3.70%	SSL - OTHER	2.53%	iTunes	2.67%
Facebook	3.04%	Xbox One Games Download	2.18%	Hulu	2.47%
FaceTime	2.50%	Facebook	1.89%	Xbox One Games Download	2.15%
Skype	1.75%	BitTorrent	1.73%	Facebook	2.01%
	69.32%		74.33%		72.72%

[1] Sandvine – 2016 Global Internet Phenomena

A brief history of video streaming

Datagram streaming

- Use UDP for transport
- Problems with firewalls common
- Microsoft's Media Server (MMS) [36], Adobe's Real Time Messaging Protocol (RTMP) [39], Real player's Progressive Networks (PNM/PNA) [37], Real-time Transport Protocol (RTP) [38]

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Progressive Download

- Use HTTP for transport
- Use ordinary web servers
- Firewall friendly
- Stream single bitrate only – playout interruptions common
- Easy to implement

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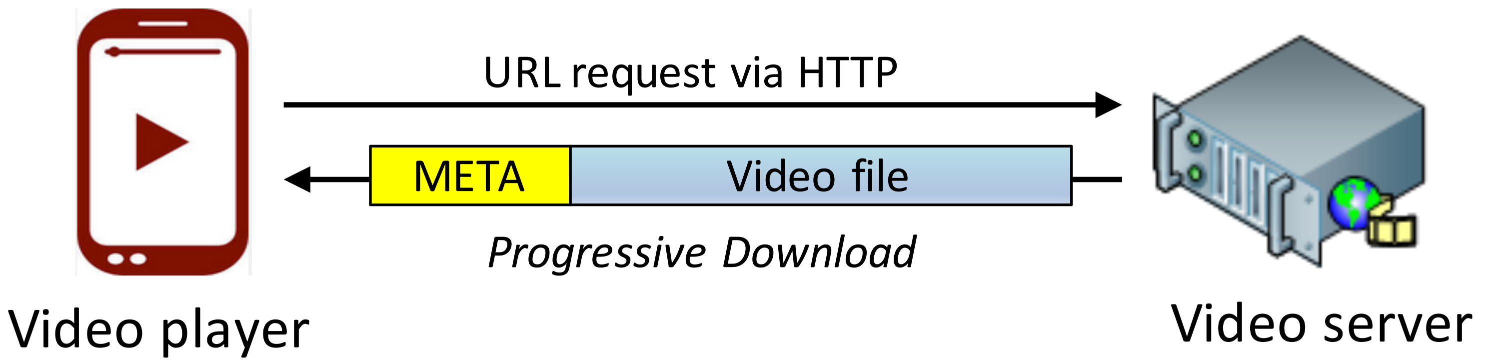
Adaptive bitrate streaming

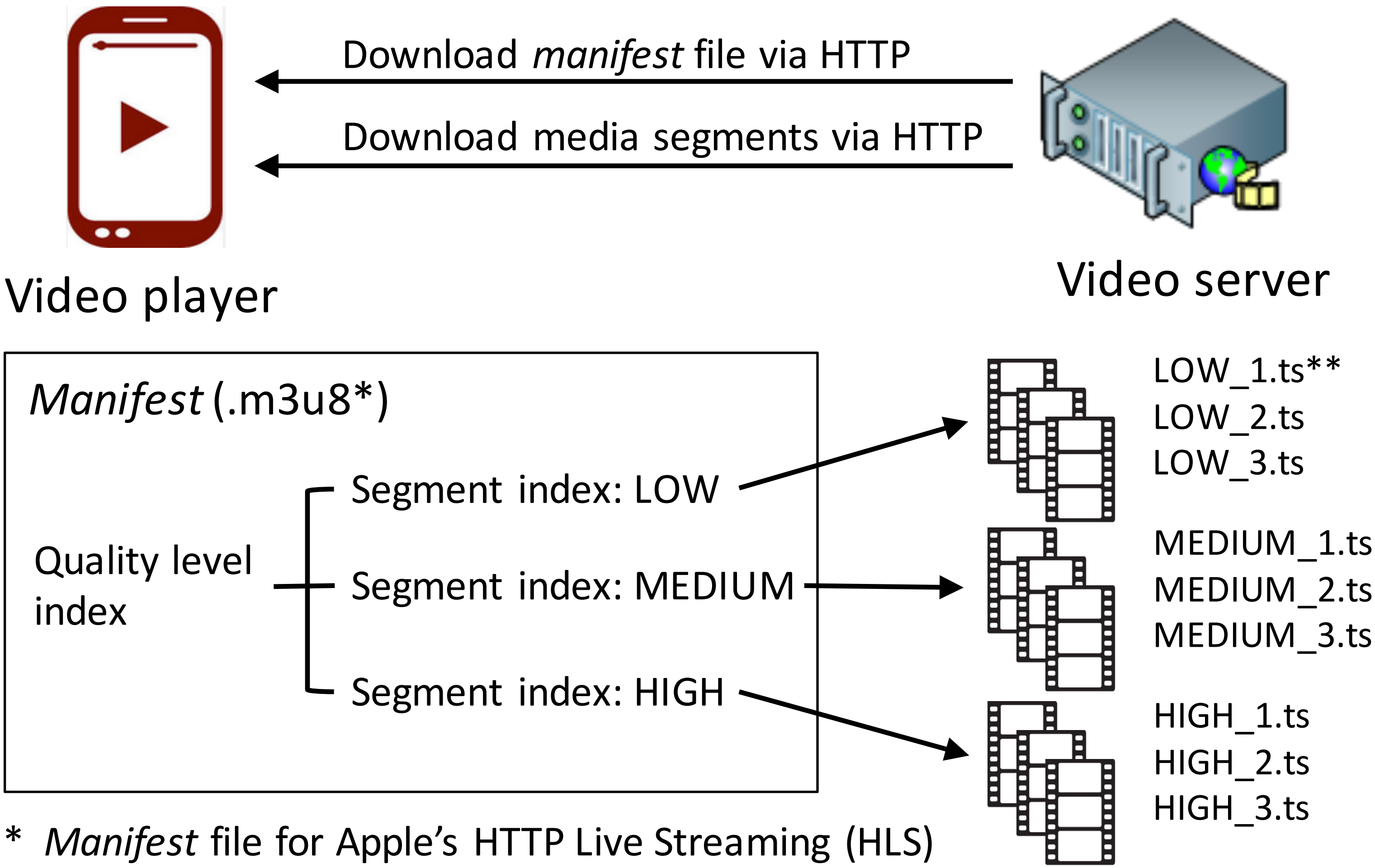
- Use HTTP for transport
- Use special or ordinary web servers
- Firewall friendly
- Use bitrate adaption technology
- Apple's HLS [40], Microsoft's SS [41], Adobe's HDS [42], MPEG-DASH [43]

Progressive download



- Video contents are delivered to clients progressively via HTTP
- Content is streamed and played as it is downloaded on a hard drive
  - Metadata located at the beginning of the file
- Easy to implement and no special web servers required
- All clients must download videos at the same quality regardless of the network conditions and the performance of clients' devices

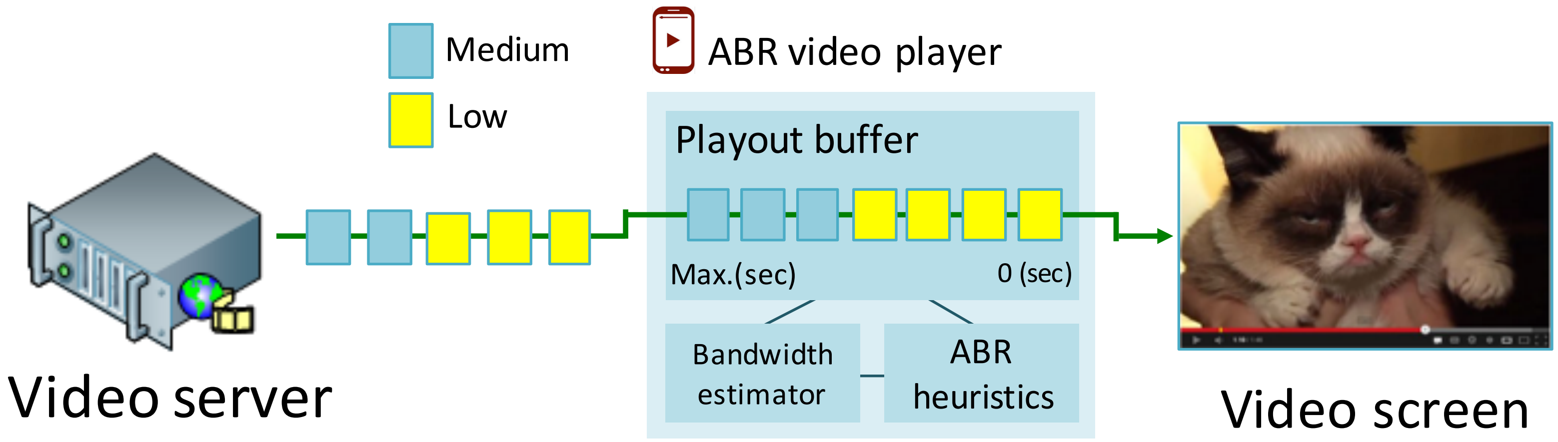
Adaptive bitrate streaming



* *Manifest* file for Apple's HTTP Live Streaming (HLS)

** In Apple's HLS, each segment typically contains 10 seconds of data

Adaptive bitrate streaming



- Player changes video bitrate based on various factors such as:
  - Real-time available network bandwidth
  - Remaining playout buffer level of the player
  - Screen resolution and video rendering capabilities (GPU) of the client device

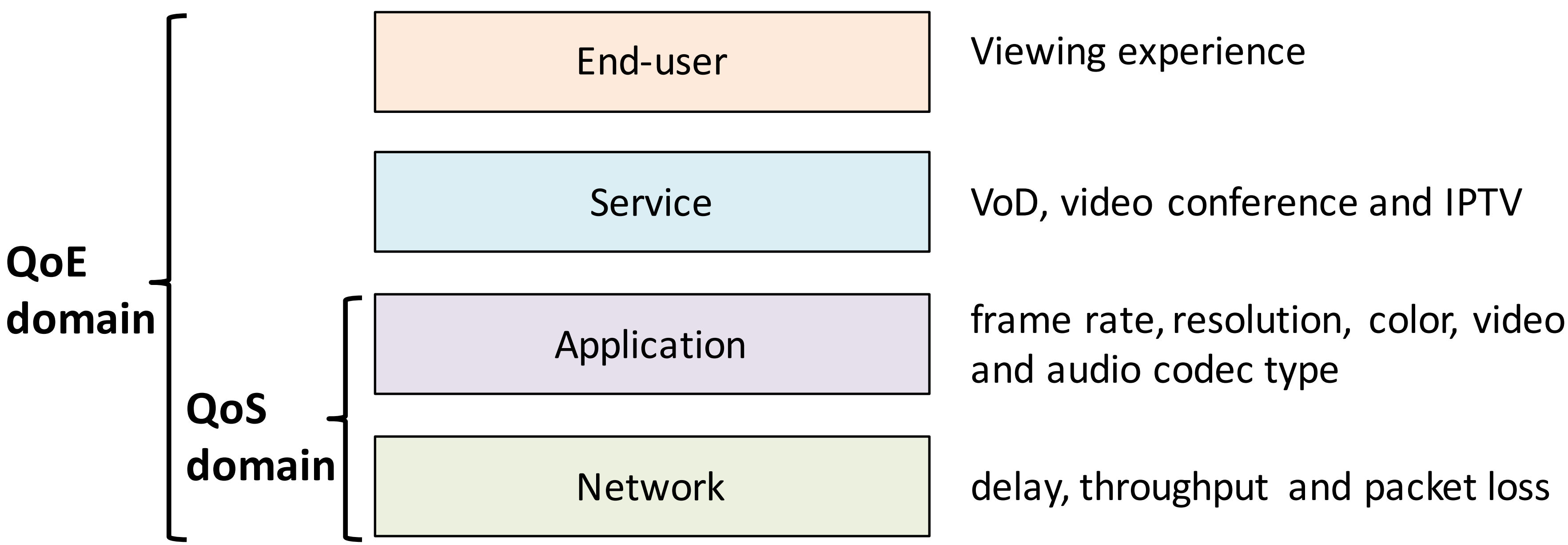
- Apple HTTP Live Streaming (HLS), Microsoft IIS Smooth Streaming (SS), Adobe HTTP Dynamic Streaming (HDS) and Dynamic Adaptive Streaming over HTTP (DASH)

Adaptive bitrate comparison chart

Feature	Adobe HDS	Apple HLS	Microsoft SS	MPEG-DASH
Deployment on ordinary HTTP servers		✓		✓
Flexible DRM support	✓	✓	✓	✓
HTML5 support				✓
Agnostic to video and audio codecs				✓
HEVC Ready (UHD/4K)				✓
Typical segment duration	2-4s	10s	2-4s	Flexible

[2] Bitmovin - MPEG-DASH vs. Apple HLS vs. Microsoft Smooth Streaming vs. Adobe HDS

QoS and QoE in video streaming



Methods for QoE measurement and prediction

Video QoE

Subjective methods

- Perceived service quality subjectively measured by human beings
- laboratory test platform and crowdsourcing platform - a survey-based metric using mean opinion score (MOS) [6,11,12]

Objective methods

- Model a quantitative metric to estimate QoE based on media, service, and transmission parameters
- ITU-T E-Model [7], PESQ [8], PSQA [9], USI [10]

Problems of using existing QoS / QoE methods

QoS-based methods

- Focus on finding network impairments, do not accurately reflect the viewing experience

Subjective QoE methods

- Testing environment requires strict control
- It is difficult to automate
- It is costly and time-consuming
- References [13-16]

Objective QoE methods

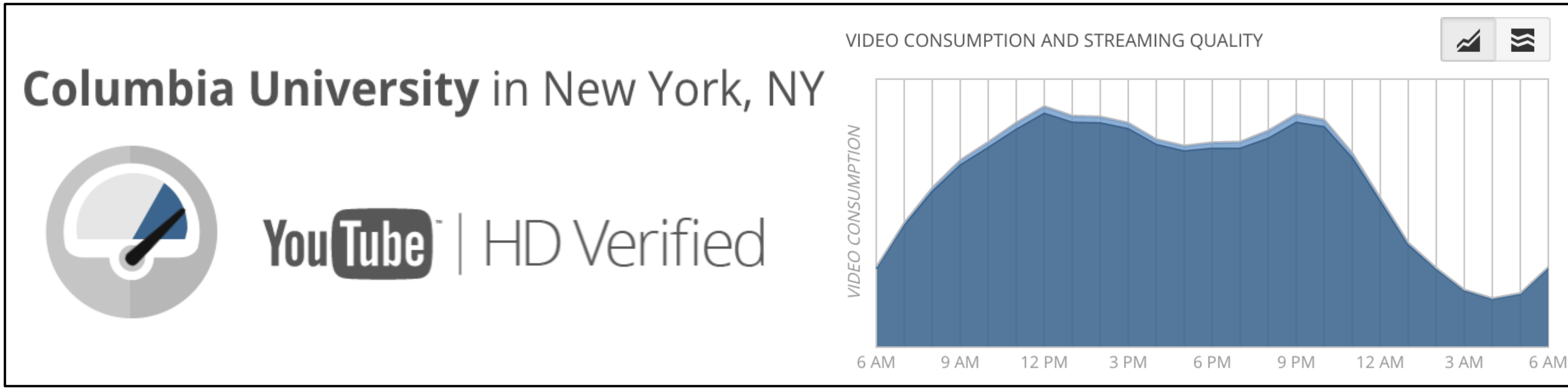
- It is hard to develop and model
- Any modification made to current objective methods may require new tests to derive new statistical models
- References [15,16]

Common QoE metrics in video streaming

Start-up delay	• Time from the instant a play button is clicked to when the player actually starts to play the main video
Rebuffering	• Video stalling or buffer underrun • Occurs when the playback rate is higher than what the network can handle
Avg. bitrate	• Average played bitrate during playback
Bitrate change	• Bitrate increases or decreases while a video is being played

Video quality report by OTT service providers

Google Video Quality Report – A friendly, consumer focused report card [4]



Netflix ISP Speed Index – Focused on ISP QoE rankings [5]

ISP LEADERBOARD - JULY 2016 SHOW SMALLER ISPS

RANK	ISP	SPEED Mbps		PREVIOUS Mbps	RANK CHANGE	TYPE Fiber Cable DSL Satellite Wireless
1	Verizon - FiOS	3.61		3.61		
2	Bright House	3.59		3.60		
3	Optimum	3.55		3.56		

YouTube Too Slow!?

YOUSLOW

Goal of YouSlow project

- Build a comprehensive platform for the analysis of video QoE in online video streaming services that deliver videos over the Internet using ABR streaming technologies

- YouSlow currently supports YouTube

YouSlow platform

End-user device

Chrome plug-in

YouSlow app.

https://dyswis.cs.columbia.edu/youslow/

User-friendly QoE report

Monitor playback events from within video players

- Initial buffering
- Pre-roll ads length
- Bitrate change
- Rebuffering
- Video buffering status
- ISP and location info.*

Video QoE analysis metrics

- Initial buffering
- Video ads
- Bitrate change
- Rebuffering
- Abandonment

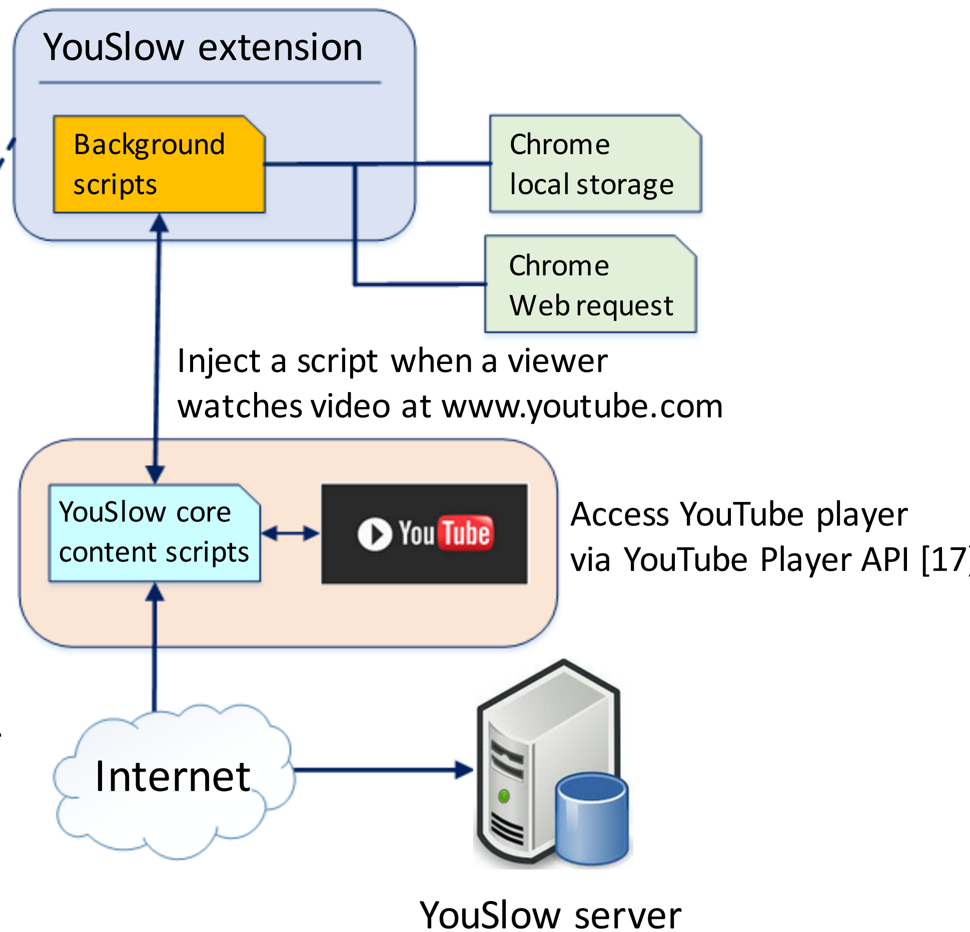
QoE report metrics

- Avg. played bitrate
- Avg. rebuffering ratio
- Avg. HTTP latency
- Others

* MaxMind: IP Geolocation

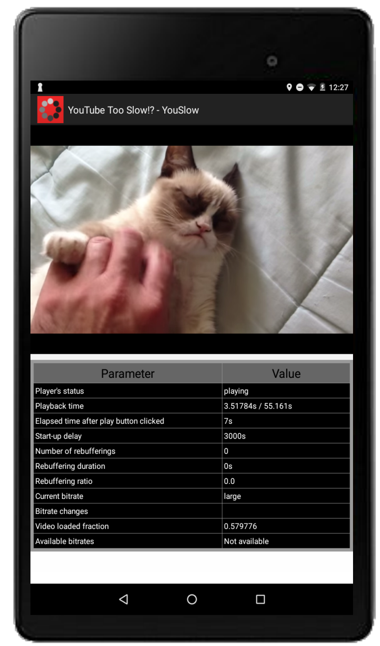
YouSlow Chrome extension

- Obtain various playback status directly from the video players e.g., start-up latency, quality changes, rebuffering status, location and ISP info.



available in the chrome web store

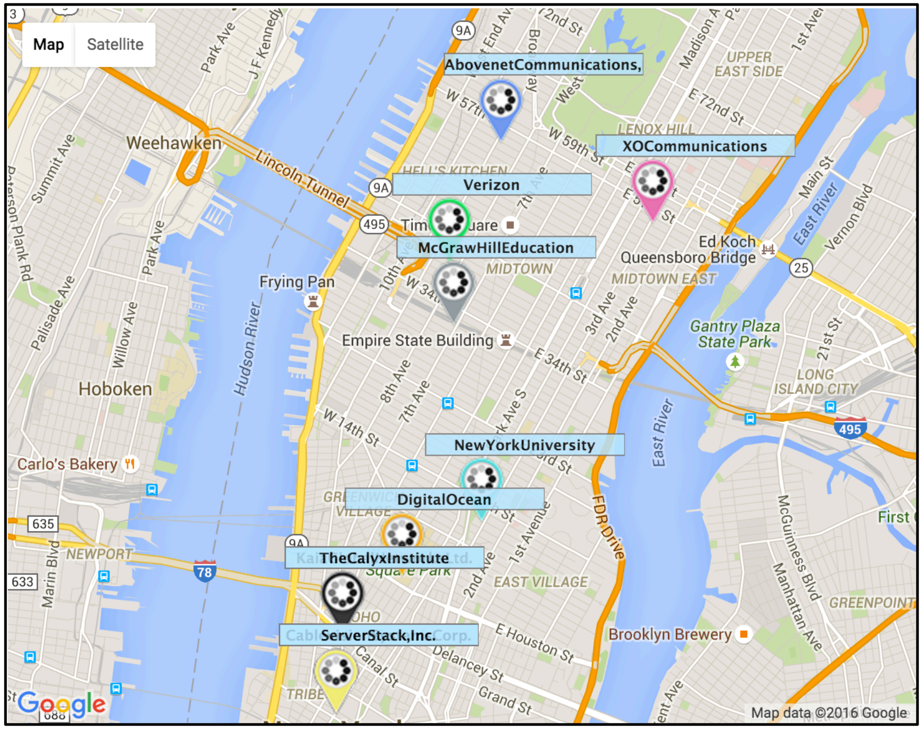
YouSlow mobile application



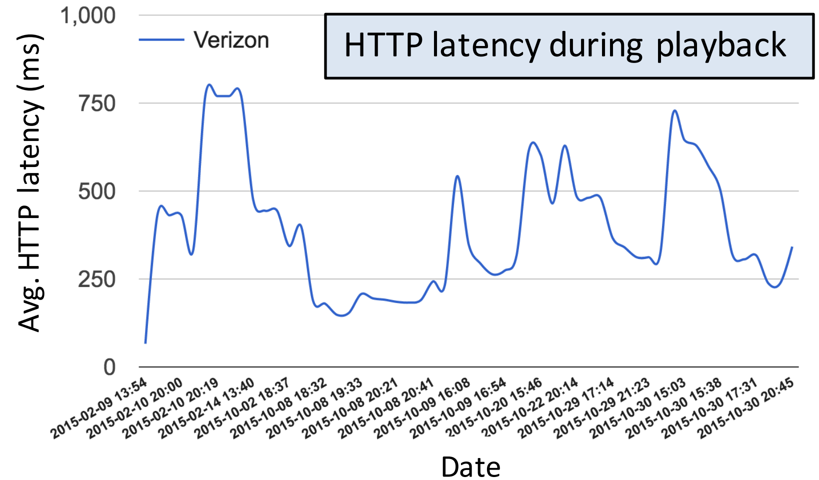
- YouSlow mobile applications (ver.1.0) for iOS and Android released via YouSlow homepage

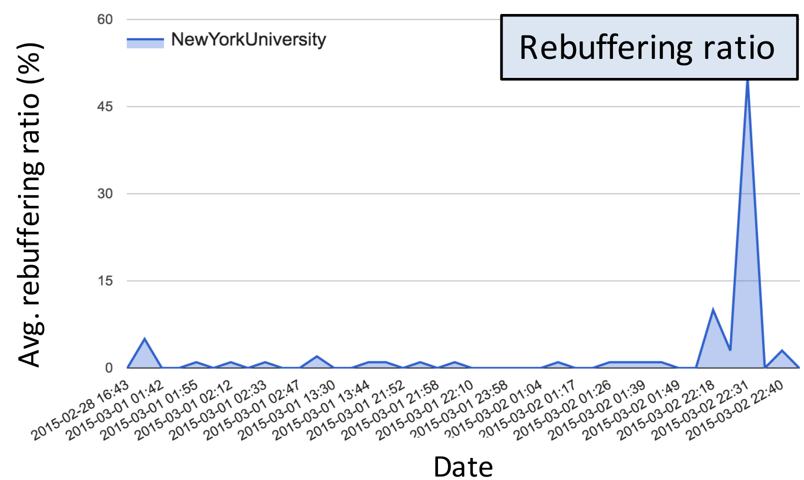
YouSlow monitoring site

https://dyswis.cs.columbia.edu/youslow/



- Approximate location of events
- Played bitrates and avg. HTTP latency
- Rebuffering ratio





YouTube Statistics

YOUSLOW

Dataset

- We analyzed a total of 1,471,958 YouTube views collected from February 2015 to July 2016 from more than 1,000 viewers in 117 countries
- Dataset only includes the video sessions where the viewers watched YouTube videos using the Chrome browser on desktops or laptops

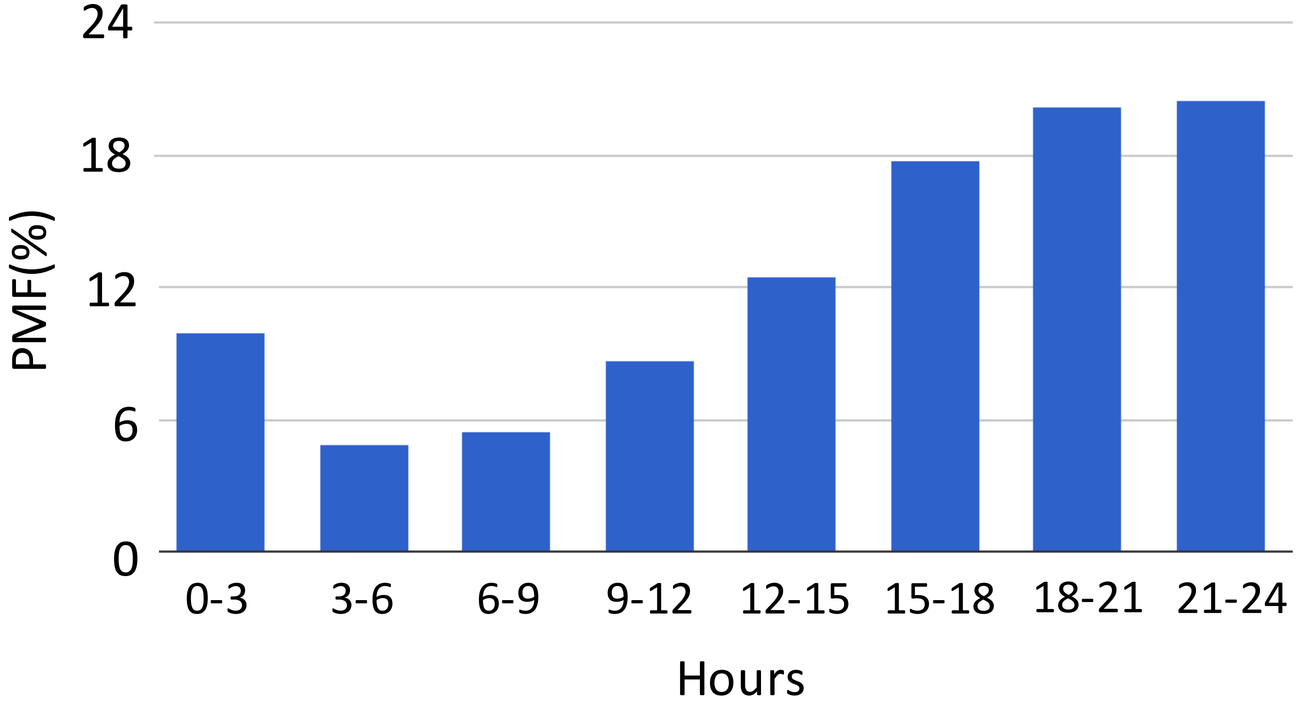
Top 10 countries

Country	Count
United States	503010
United Kingdom	107482
India	99424
Malaysia	75808
Germany	59630
South Korea	56484
Indonesia	55052
Canada	46463
Philippines	32560
Italy	31675

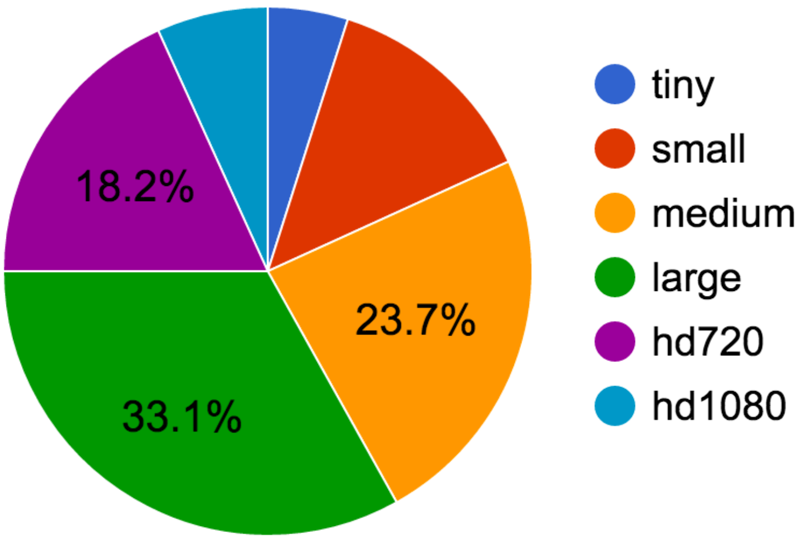
Top 10 ISPs

ISP	Country	Count
Comcast	United States	93469
AT&T	United States	90049
Verizon	United States	58610
CharterCommunications	United States	53375
DeutscheTelekomAG	Germany	46125
TimeWarnerCable	United States	43319
TMNet,InternetServiceProvider	Malaysia	42659
PTTelekomunikasiIndonesia	Indonesia	27214
NationalInternetBackbone	India	22781
PhilippineLongDistanceTelephoneCompany	Philippines	22638

Distribution of YouTube access time

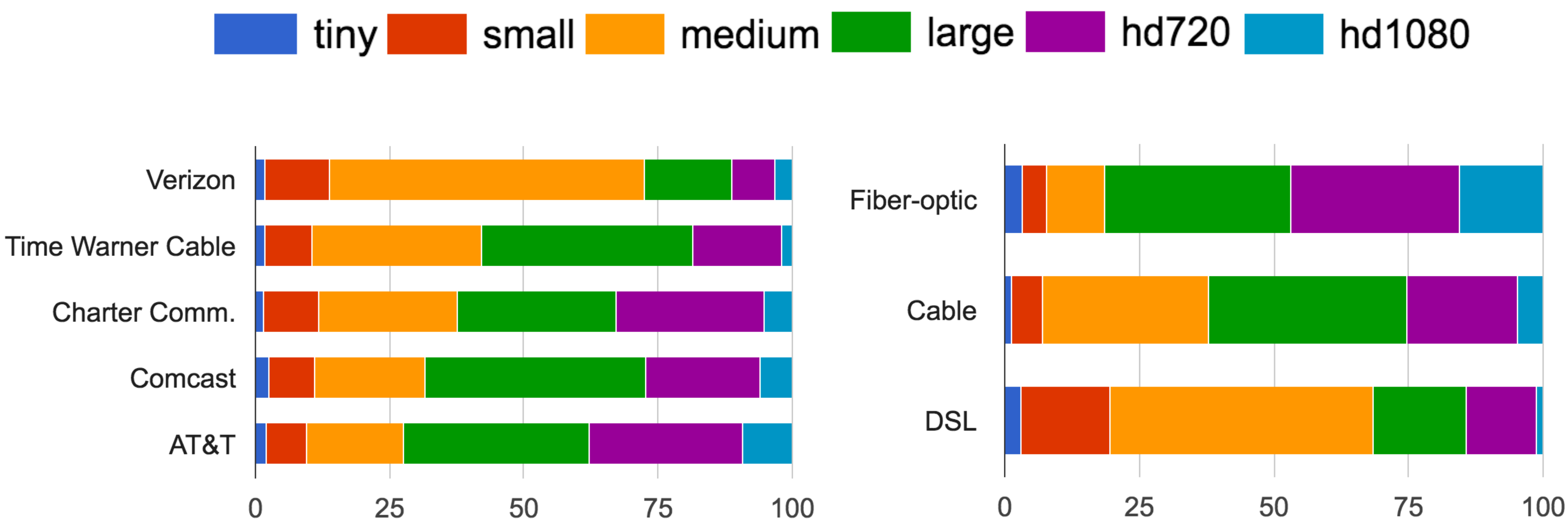


Distribution of YouTube played bitrates



Type	Video bitrate	Resolution
highres	35 - 45 Mbps	3840 × 2160
hd1440	10 Mbps	2560 × 1440
hd1080	8,000 kbps	1920 × 1080
hd720	5,000 kbps	1280 × 720
large	2,500 kbps	854 × 480
medium	1,000 kbps	640 × 360
small	400 kbps	426 × 240
tiny	80 kbps	256 × 144

Comparison of YouTube played bitrates

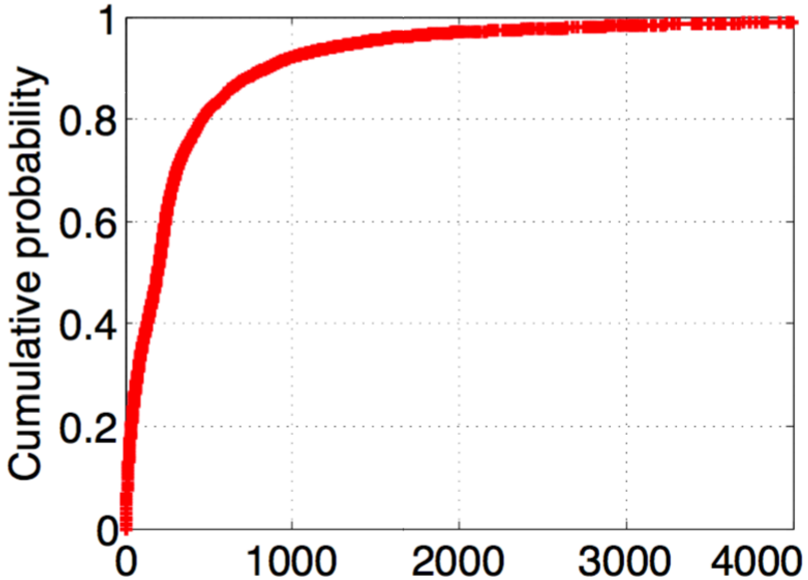


U.S. ISPs

Different types of Internet connections

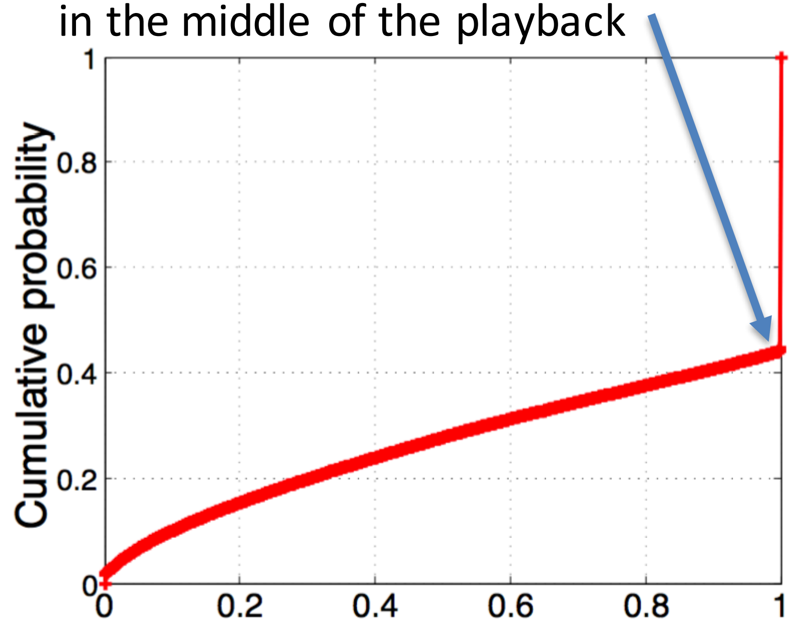
Audience retention and video loaded fraction

Avg. audience retention is 6:36 minutes and the median is 2:39 minutes



*Audience retention (sec)

About 42% of viewers closed videos in the middle of the playback

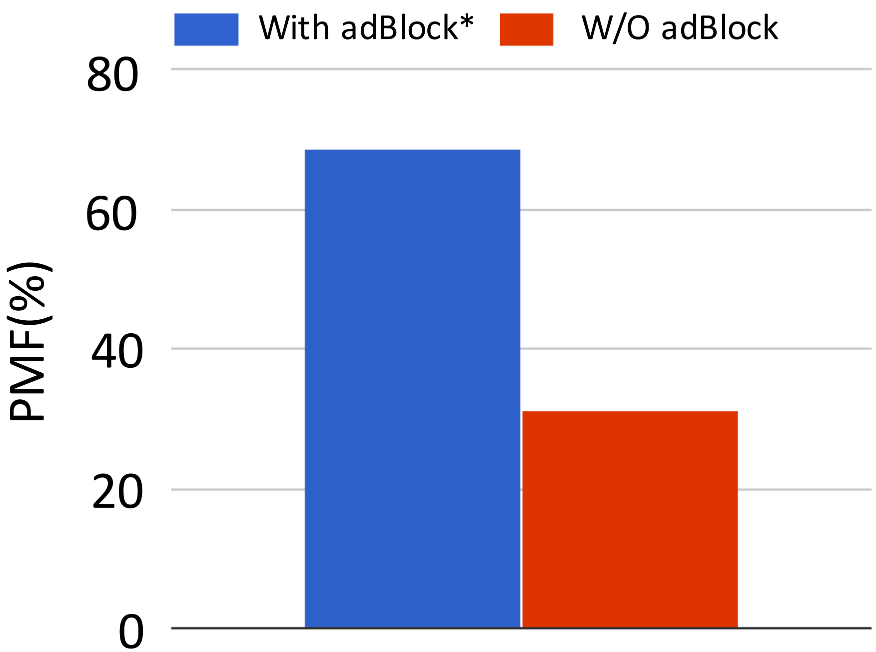


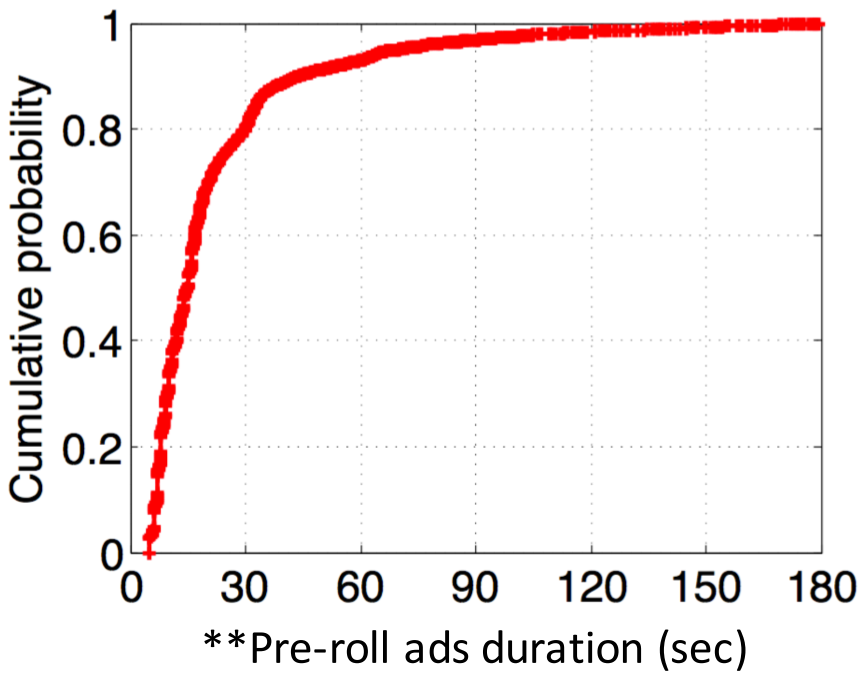
**Video loaded fraction

* The average time amount a viewer is staying with the video

** A number between 0 and 1 that specifies the percentage of the video that the player shows as buffered - higher value means that the viewer is staying longer in the video session

Pre-roll ads in YouTube

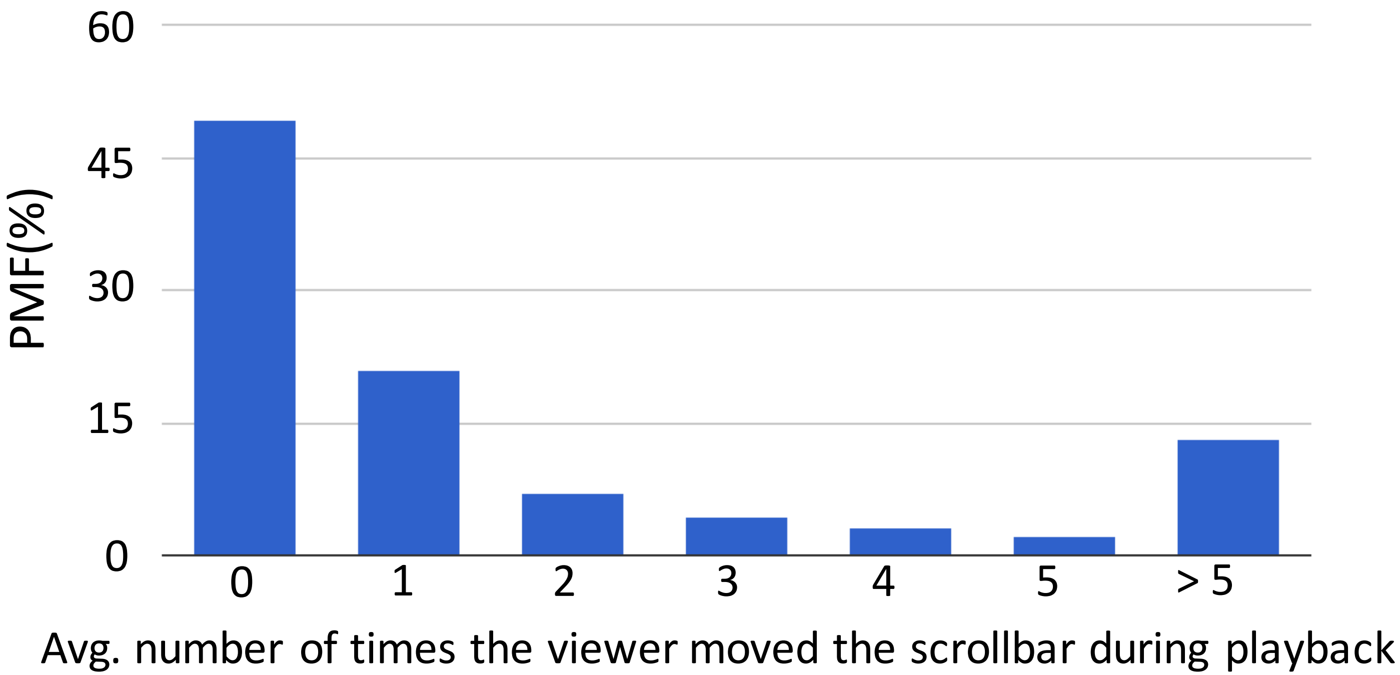




* With adBlock extensions [18], viewers can watch YouTube videos without ads during the entire playback

** How long the viewers watched the pre-roll ads before the main content

Moving a scrollbar during playback



- YouSlow is able to detect if a viewer is moving the scrollbar of YouTube player forwards or backwards during playback.

YouSlow QoE Analysis

YOUSLOW

Video abandonment methodology

- YouSlow returns video abandonment status every video session
  - $+1$: the viewer watched the video until the end
  - -1: the viewer stopped the video during video playback
- Analyze viewing interruptions by computing video abandonment rate depending on various playback events such as pre-roll ads, rebufferings and bitrate changes

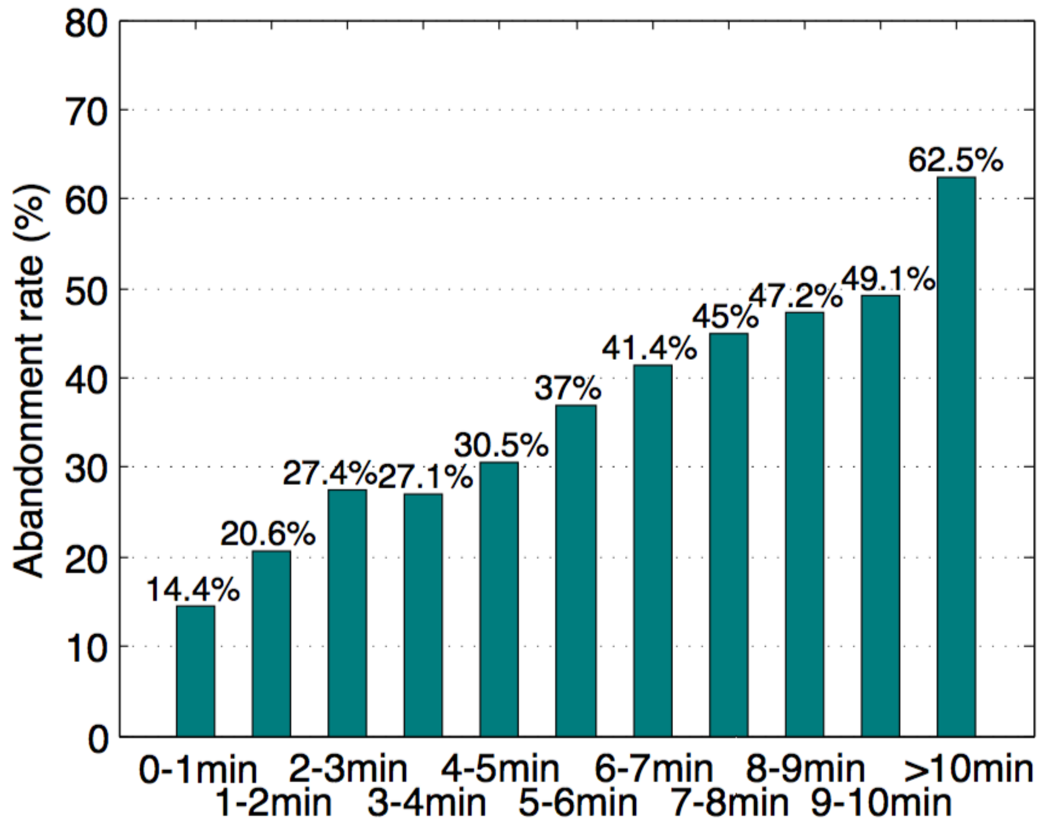
Video abandonment methodology

- Video samples are grouped and analyzed using the following notations:

Unimpaired	No viewing interruptions such as pre-roll ads, long initial buffering (> 1sec), rebufferings and bitrate changes
Ad-free	Experienced no pre-roll ads before the main content
Rebuffered	Suffered from rebufferings in the middle of a playback
Initial buffered	Experienced long initial buffering (> 1sec) at the beginning of playback

Unimpaired

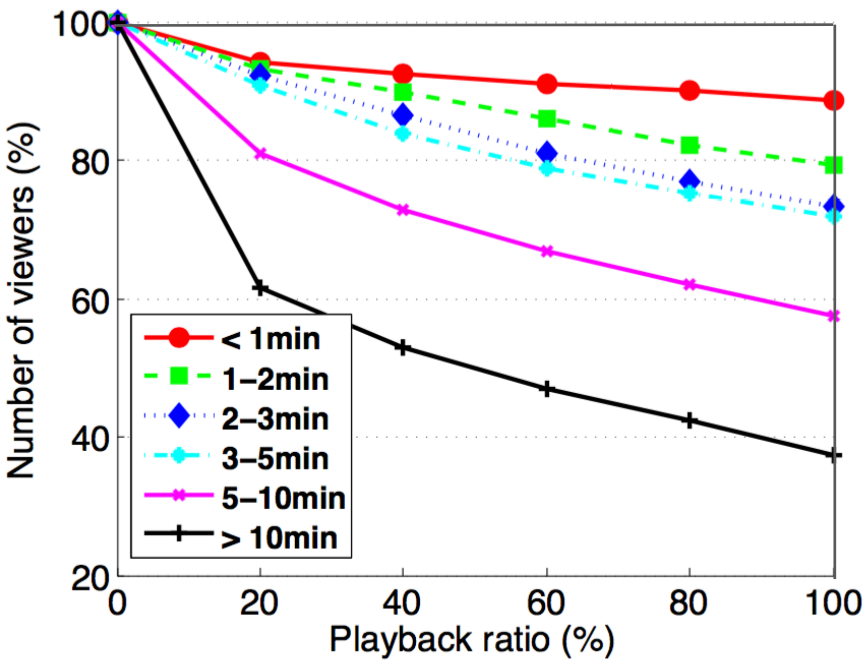
Video duration impact on abandonment rate (1/2)



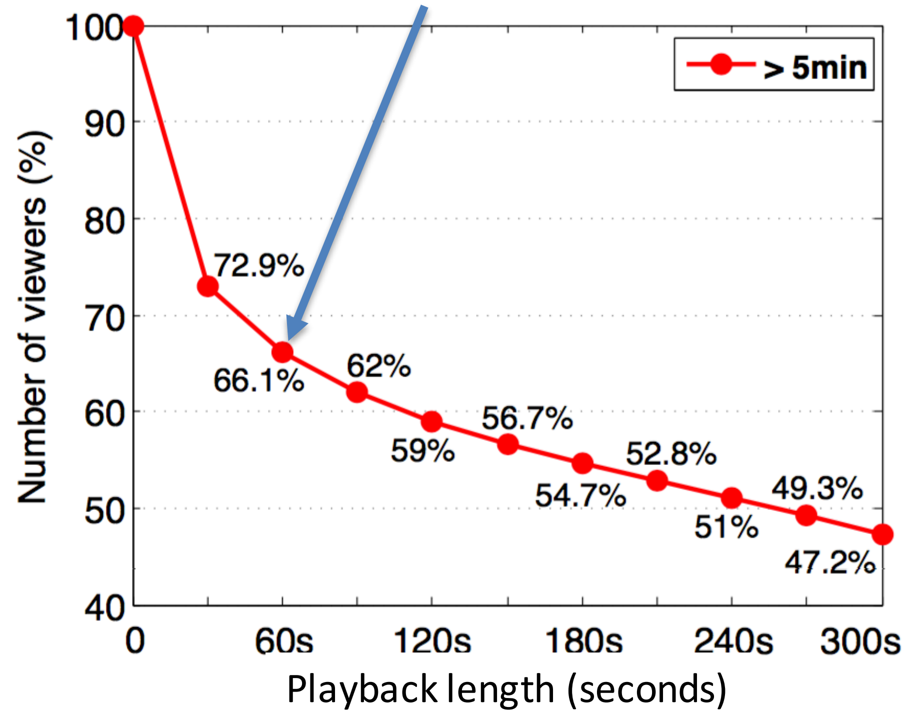
Video duration (minutes)

Unimpaired

Video duration impact on abandonment rate (2/2)

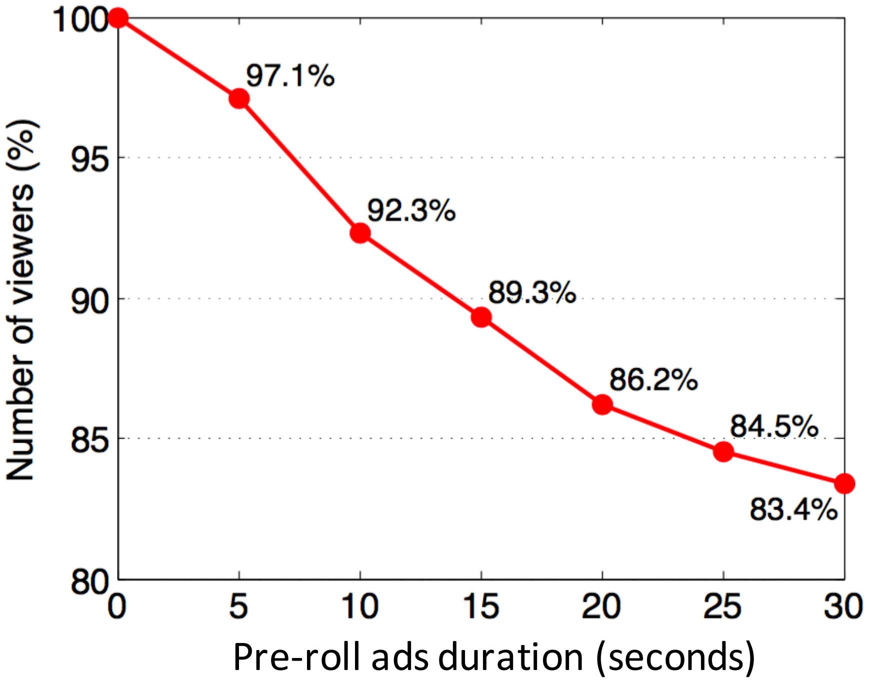


34% of viewers left during the first 60 seconds of video



Pre-roll ads length impact on abandonment rate

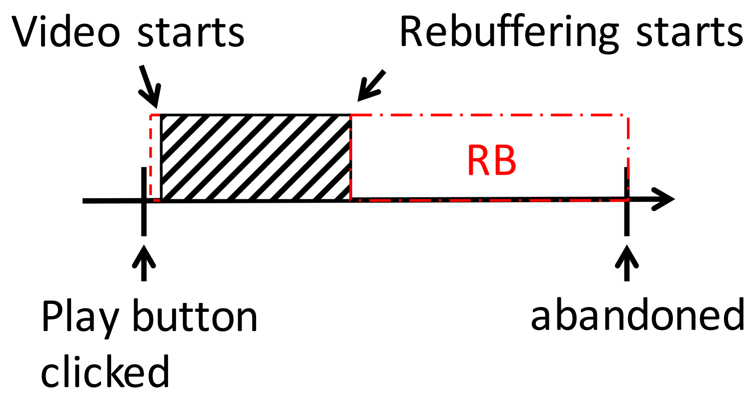
- 24.8% (3,138 / 12,653) of viewers abandoned the videos during the ads



Number of viewers as the pre-roll ad duration increases

- *About 10% of viewers abandoned the YouTube videos when the pre-roll ads lasted for 15 seconds*

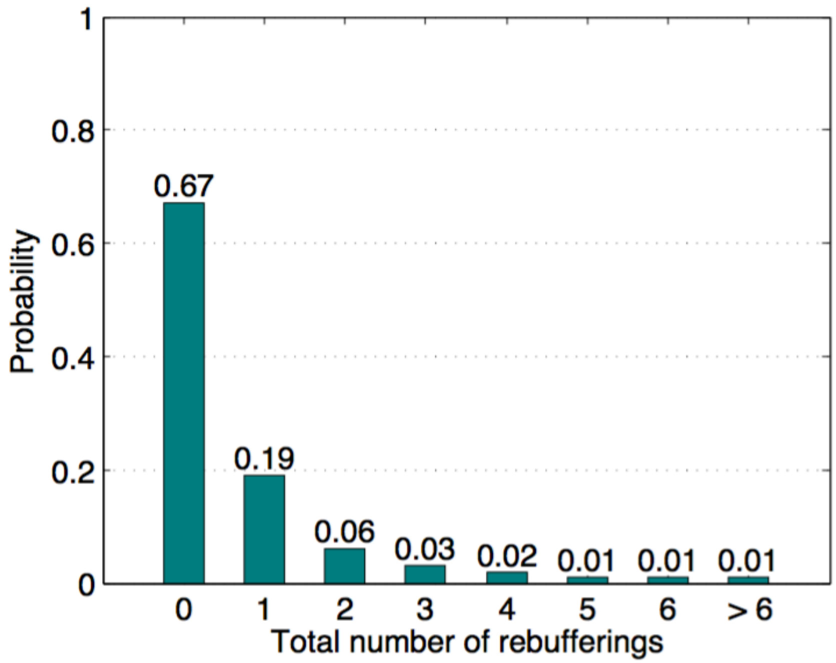
Rebuffering impact on video QoE

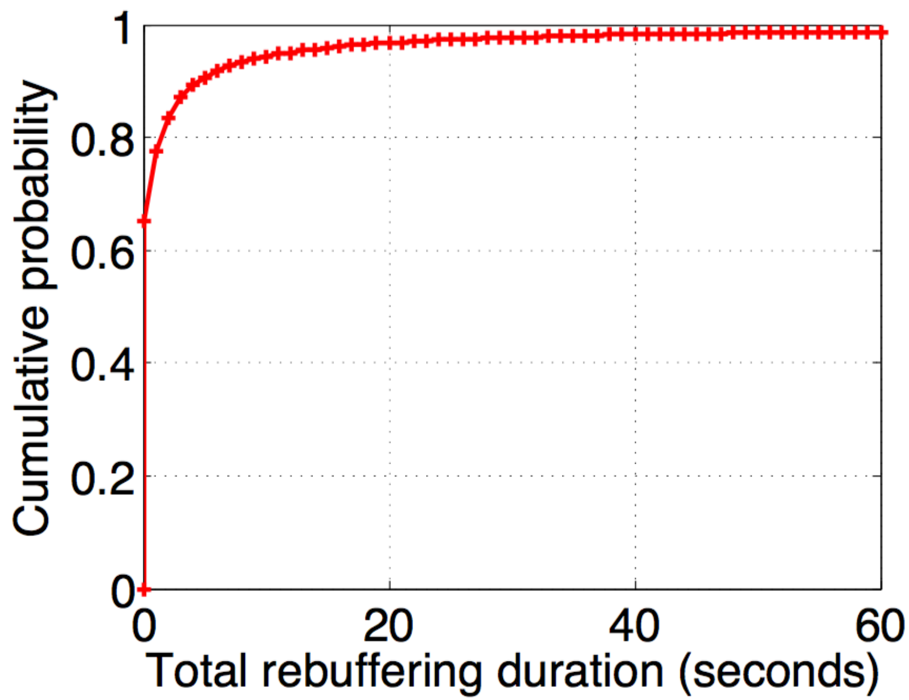


- A rebuffering occurs when an ABR player requests a higher bitrate than what a network can handle

- Rebufferings should be avoided if at all possible in order to enhance video QoE [19-23]
  - Video QoE can vary depending on the number of rebufferings and its duration

YouTube rebuffering statistics

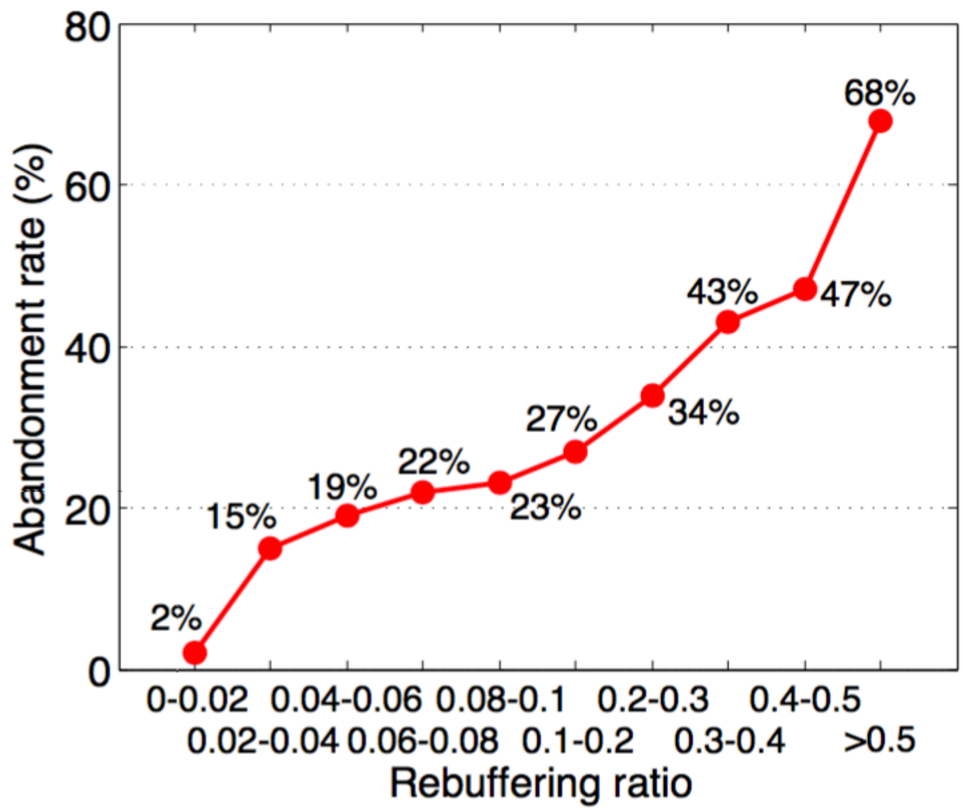




Ad-free | Non-initial buffered | Rebuffered

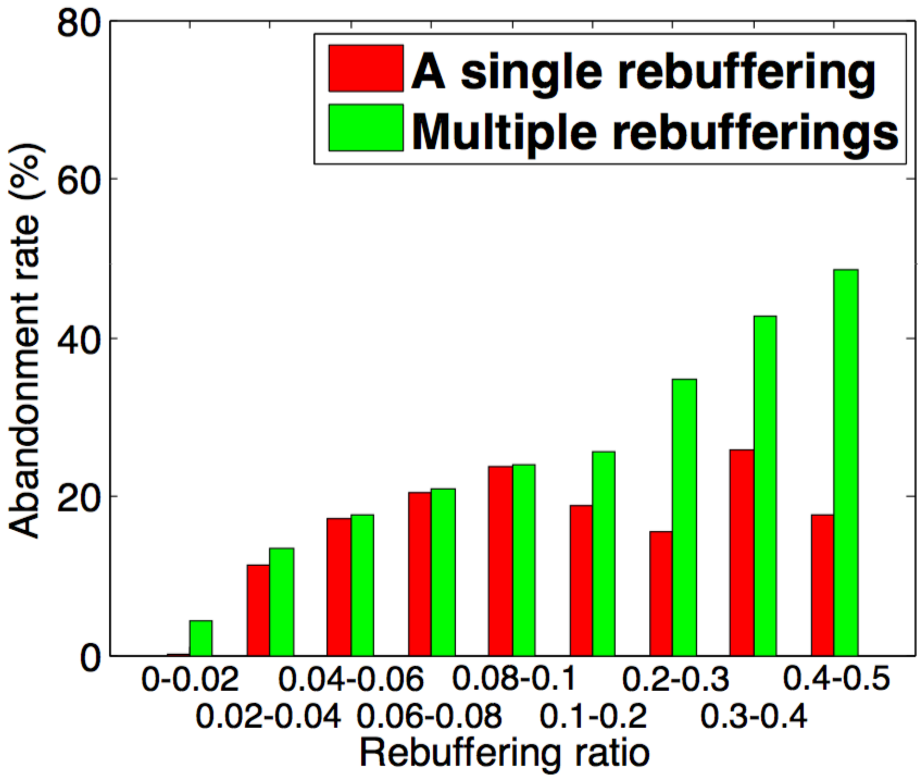
Rebuffering ratio on abandonment rate

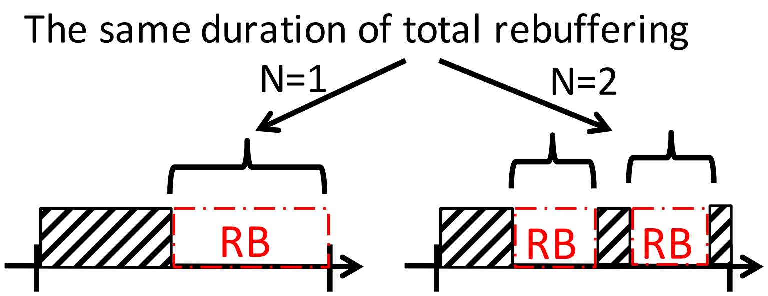
$$\text{Rebuffering ratio} = \frac{\text{Total rebuffering duration (sec)}}{\text{Total playback duration (sec)}}$$



- *More viewers abandoned the videos as the rebuffering ratio increased*

Num. of rebuffering impact on abandonment rate



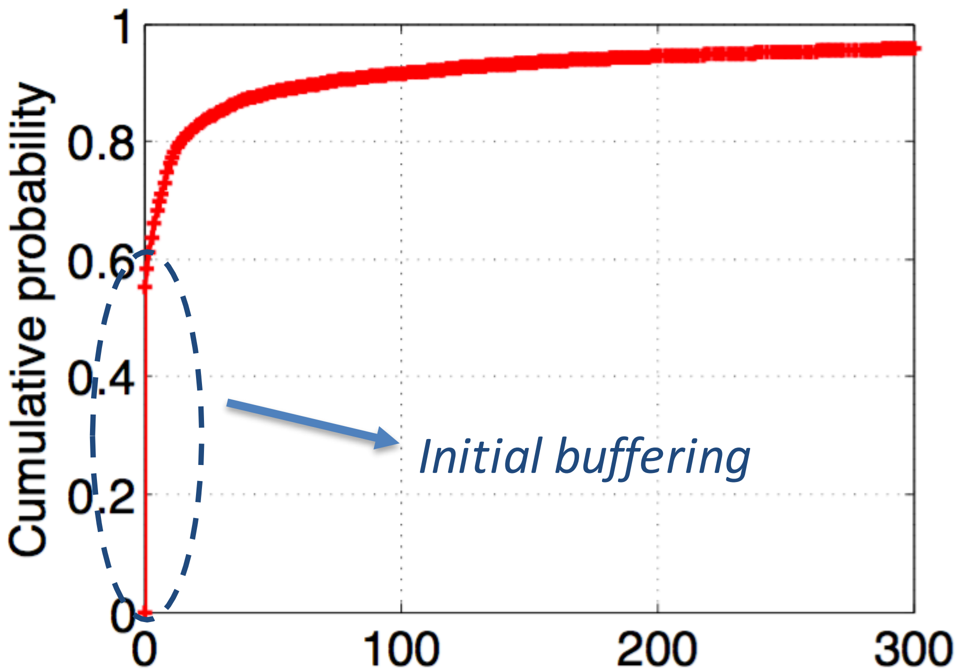


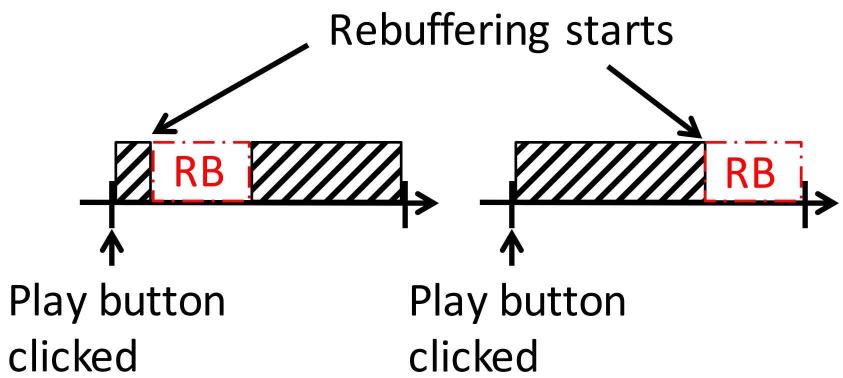
- *Multiple rebufferings cause higher abandonment rates than a single rebuffering*

Ad-free | Initial buffered | Single-rebuffered

Rebuffering early vs. later

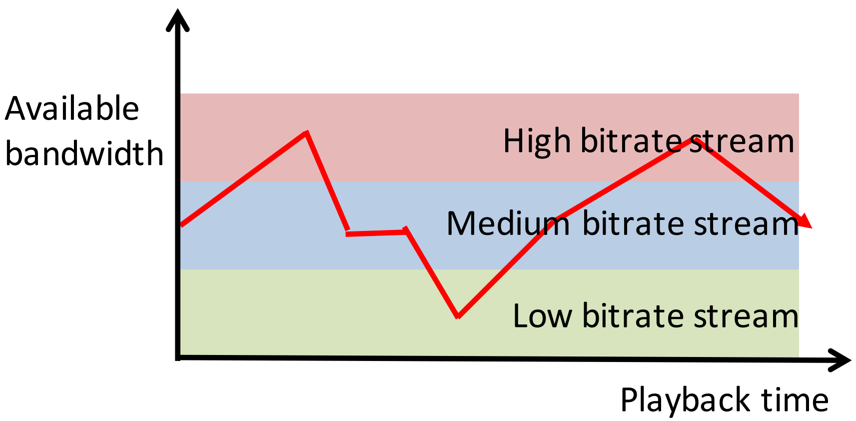
- CDF of number of abandonment for different rebuffering start times

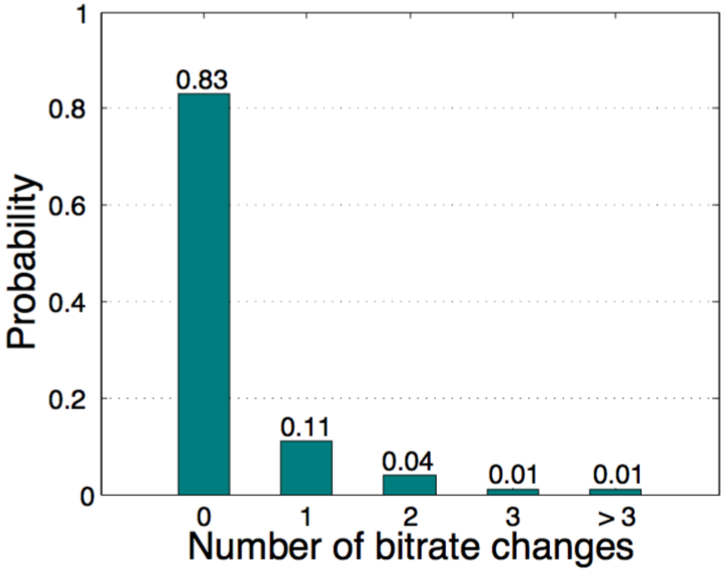




- *Most viewers abandoned the videos when the rebufferings started at the beginning of playback*

Bitrate change impact on video QoE

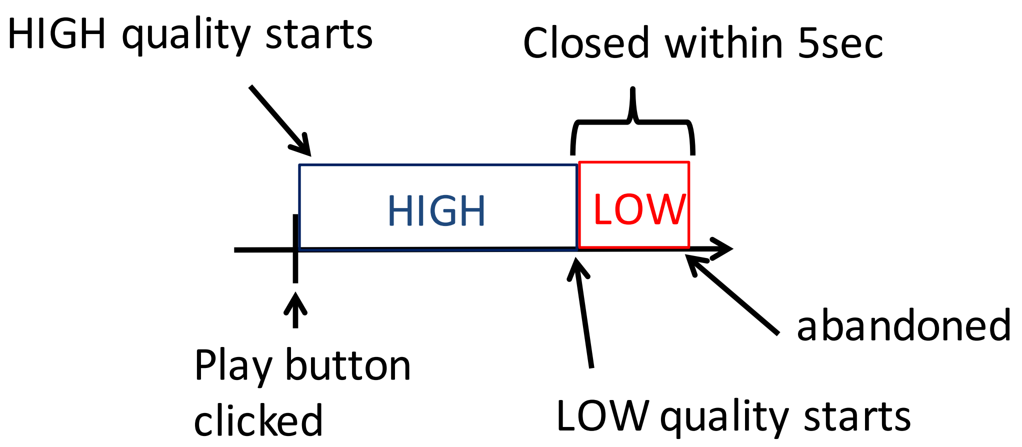




- Frequent bitrate changes can degrade QoE of viewer [24-28]
  - Video QoE can vary depending on the number of bitrate changes and their amplitude (i.e., by how much bitrate increases or decreases)

- Bitrate changes have less impact on video QoE than rebufferings

Bitrate change ratio on abandonment rate (1/2)



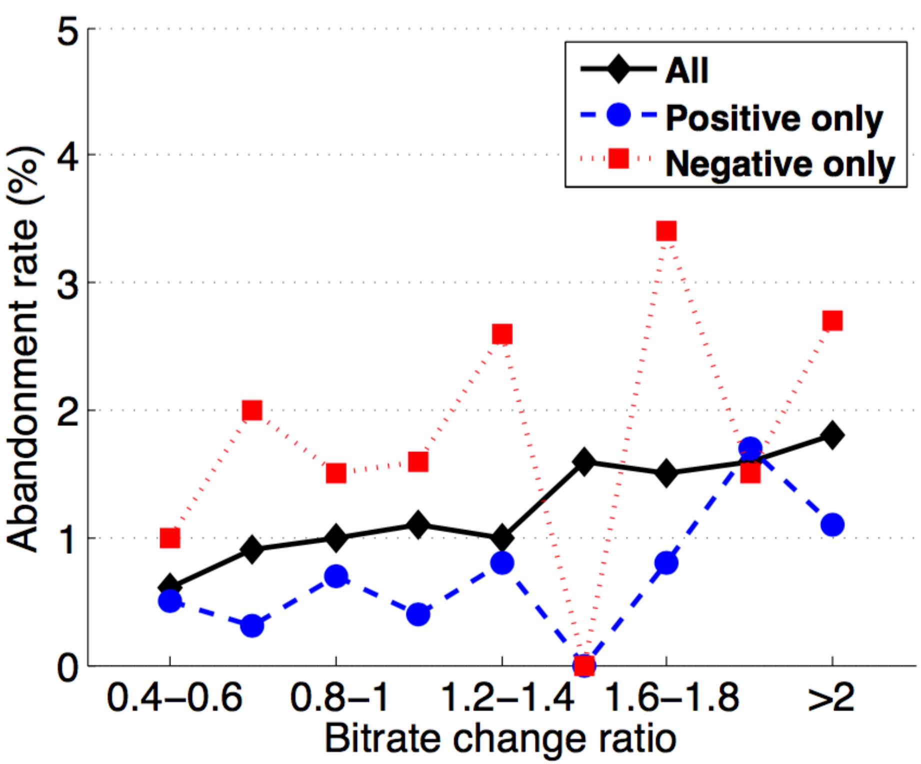
- We only considered the videos as abandoned when they were closed within five seconds after the bitrate was changed in the middle of a playback

Ad-free | Non-initial buffered | Non-rebuffered

Bitrate change ratio on abandonment rate (2/2)

$$\text{Bitrate change (BR) ratio} = \frac{\sum_{i=1}^{\text{Num.of BR changes}} |\log(BR_i/BR_{i-1})|}{\text{Num. of BR changes}}$$

BR_i: newly selected bitrate, BR_{i-1}: previous bitrate (in kb/s)



- *Abandonment rate: Negative > Positive*
- *Viewers prefer constant bitrate to increasing bitrate during playback*

Ad-free | Non-initial buffered | Non-rebuffered

Constant vs. positive vs. negative bitrate change

The impact of a *single bitrate (BR) change* on video loaded fraction

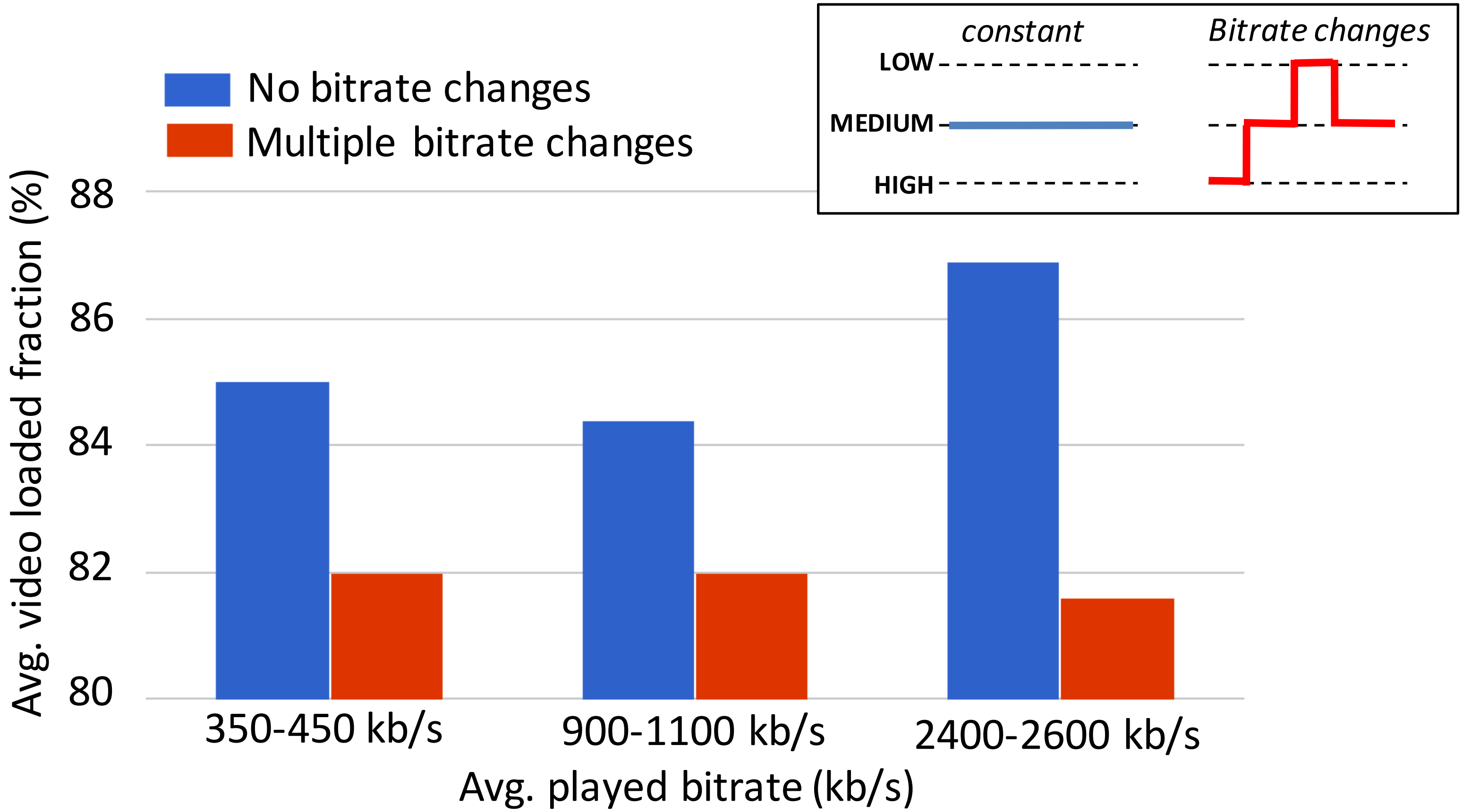
	Starting bitrate		
	small	***medium*** or ***large***	***hd*** or ***highres***
No BR change	0.94	0.95	0.94
Positive	0.9	0.92	0.92
Negative	0.89	0.9	0.89

Video loaded fraction getting slightly lower

- *More viewers abandoned the videos early when the ABR players changed the bitrates regardless of starting bitrates*

Ad-free | Non-initial buffered | Non-rebuffered

Constant vs. bitrate changes



- *Viewers prefer constant bitrate than bitrate changes during playback*

Ad-free

Non-initial buffered

Multiple linear regression analysis on abandonment rate

- Investigate the relationship between the abandonment rate and the rebufferings (RBs) and bitrate (BR) changes

- To concentrate on the impact of rebufferings and bitrate changes during playback, we analyze ad-free and non-initial buffered videos only

Ad-free

Non-initial buffered

Multiple linear regression analysis on abandonment rate

- Using number of rebufferings (RBs) and bitrate (BR) changes

Predictor variable	S	R-sq	R-sq (adj)
(1) only	0.047	59.6%	57.6%
(2) only	0.061	32.6%	29.2%
(1) and (2)	0.033	81.4%	79.4%

(1) Num. of RBs (2) Num. of BR changes

(a) Model summary

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	0.091	0.045	41.52	< 0.0001
Error	19	0.02	0.001		
Total	21	0.112			

(b) Analysis of variance

Term	Coef	SE Coef	T-value	P-value	VIF
Constant	0.1821	0.018	9.92	< 0.0001	
Num. of RBs	0.0246	0.003	7.06	< 0.0001	1.02
Num. of BR changes	0.0374	0.008	4.71	0.0002	1.02

(c) Coefficients

Ad-free | Non-initial buffered

Multiple linear regression analysis on abandonment rate

- Using number of rebufferings (RBs) and rebuffering / bitrate (BR) change ratios

Predictor variable	S	R-sq	R-sq (adj)
(1) only	0.06	91.3%	90.9%
(3) only	0.122	64.3%	62.7%
(1) and (3)	0.049	94.6%	94.0%
(1) and (2)	0.0615	91.4%	90.5%
(1), (2) and (3)	0.05	94.6%	93.7%

(1) RB ratio (2) BR change ratio (3) Num. of RBs

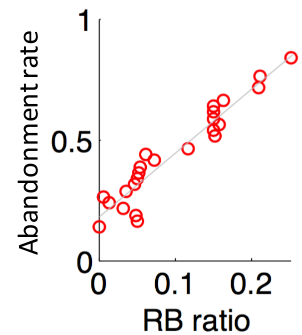
(a) Model summary

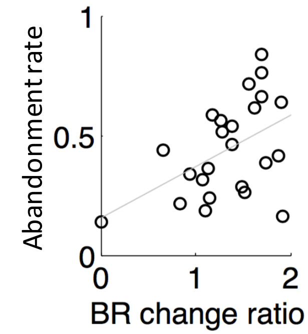
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.872	0.29	115.92	< 0.0001
Error	20	0.05	0.002		
Total	23	0.922			

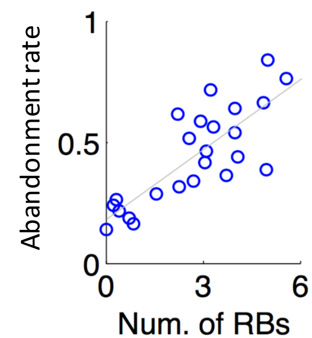
(b) Analysis of variance

Term	Coef	SE Coef	T-value	P-value	VIF
Constant	0.142	0.033	4.28	0.0004	
RB ratio	2.156	0.212	10.17	< 0.0001	2.13
BR change ratio	0.001	0.027	0.07	0.9483	1.32
Num. of RBs	0.031	0.009	3.43	0.0027	2.04

(c) Coefficients





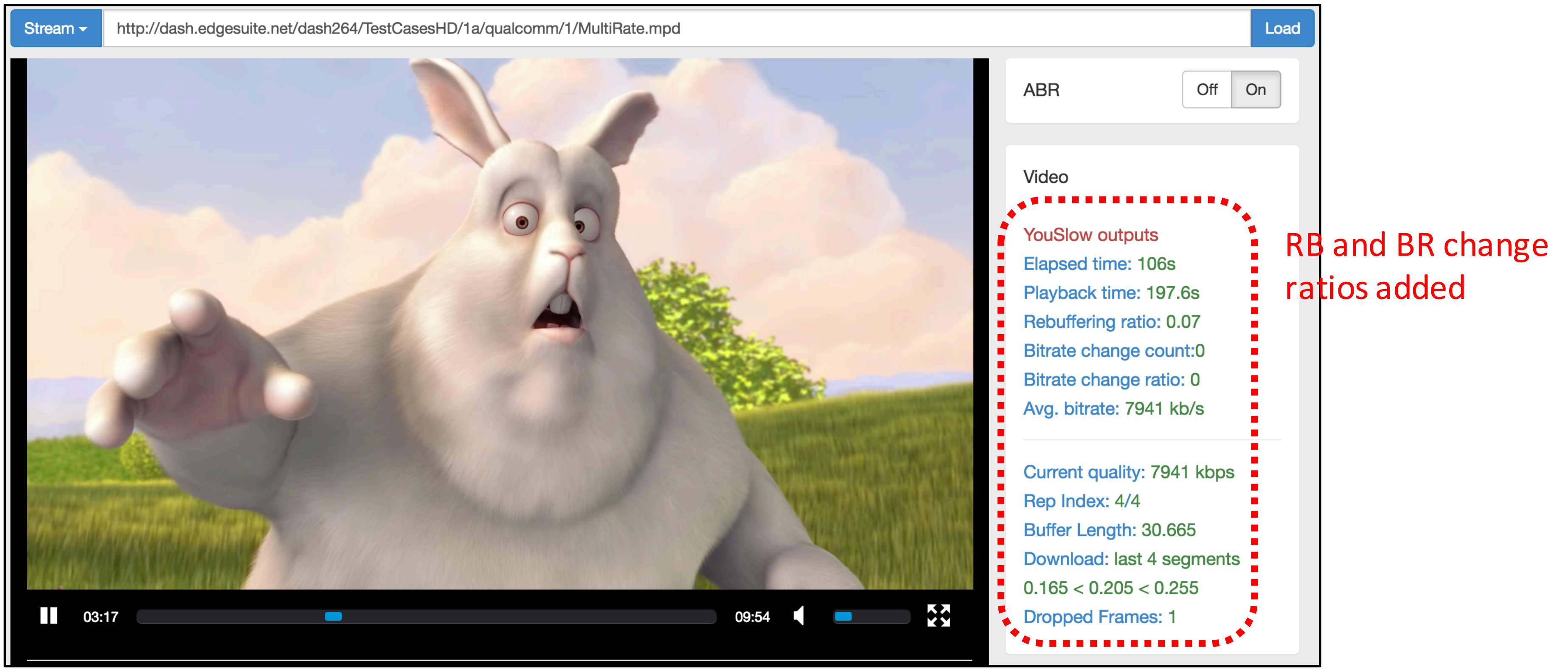


Summary

- Existing QoS /QoE methods are not enough to analyze video QoE
- YouSlow can monitor various video playback status directly from within video players - more time and cost-saving to collect a large number of data samples
- We developed and evaluated QoE metrics regarding start-up delay, video ads, rebufferings and bitrate changes
- Based on YouSlow analysis, we aim to improve the performance of ABR streaming technologies and develop a comprehensive video QoE monitoring system

Making impact: YouSlow on MPEG-DASH

- Improve MPEG-DASH video player based on YouSlow analysis
- Implemented in MPEG-DASH Reference Client Player version 1.5.1
  - Available at https://dyswis.cs.columbia.edu/youslow/



Related work

- Video abandonment analysis
  - Dobrian et al. [29] at Conviva focused on the analysis of initial buffering and rebuffering ratio on video abandonment
  - Shafiq et al. [30] analyzed video abandonment by inspecting video packets from the ISP routers
  - Krishnan et al. [35] investigated the effectiveness of video ads by monitoring their completion and abandonment rates

- Collecting measurements from web browser plug-ins
  - ***Fathom*** [31] - a Firefox plug-in for network measurements
  - ***YoMo*** [32] - a Firefox plug-in to estimate the amount of playtime buffered by the YouTube player

Differences from prior work

- Focus on the analysis of video QoE
  - Obtain various playback events directly from within ABR players
- Easy to collect a large number of samples
  - YouSlow collects about 3,500 YouTube views every day
- Easy to add new video streaming services
  - Other player's JavaScript APIs such as Vimeo can be easily added to YouSlow
- Easy to modify QoE metrics
  - Instantly obtain results after updates
- A user-friendly QoE report
  - Location and ISP-based analysis - avg. played bitrate and rebuffering ratio

Publications on YouSlow

- Video QoE analysis – YouTube Too Slow!? YouSlow
    - **QoE Matters More Than QoS: Why People Stop Watching Cat Videos**
        - Hyunwoo Nam, Kyung-Hwa Kim and Henning Schulzrinne
        - IEEE INFOCOM, San Francisco, USA, April 2016
    - **Generating Realistic YouTube-like Stall Patterns for HTTP Video Streaming Assessment**
        - Martín Varela, Hyunwoo Nam, Henning Schulzrinne and Toni Mäki,
        - IEEE QoMEX, Lisbon Portugal, June 2016
    - **YouSlow: A Performance Analysis Tool for Adaptive Bitrate Video Streaming**
        - Hyunwoo Nam, Kyung-Hwa Kim, Doru Calin and Henning Schulzrinne
        - ACM SIGCOMM Poster, Chicago, USA, August 2014

Other projects on video streaming

- Video traffic analysis over wireless networks
  - **A Traffic Analysis: Badly Designed Video Clients Can Waste Network Bandwidth**
    - Hyunwoo Nam, Bong Ho Kim, Doru Calin, and Henning Schulzrinne
    - IEEE GLOBECOM Workshop, Atlanta, USA, December 2013

- Improving over-the-top (OTT) video content delivery
  - **Towards QoE-aware Video Streaming using SDN**
    - Hyunwoo Nam, Kyung-Hwa Kim, Jong Yul Kim, and Henning Schulzrinne
    - IEEE GLOBECOM, Texas, USA, December 2014
  - **Towards Dynamic Network Condition-Aware Video Server Selection Algorithms over Wireless Networks**
    - Hyunwoo Nam, Kyung-Hwa Kim, Doru Calin, and Henning Schulzrinne
    - IEEE ISCC, Madeira, Portugal, June 2014
  - **Towards Dynamic QoS-aware Over-The-Top Video Streaming**
    - Hyunwoo Nam, Kyung-Hwa Kim, Bong Ho Kim, Doru Calin, and Henning Schulzrinne
    - IEEE WoWMoM in best paper session, Sydney, Australia, June 2014

Other projects (non-video streaming)

- Intelligent content delivery using software-defined networking
  - **Towards Dynamic MPTCP Path Control Using SDN**
    - Hyunwoo Nam, Doru Calin and Henning Schulzrinne
    - IEEE NETSOFT, Seoul, South Korea, June 2016
  - **Intelligent Content Delivery over Wireless via SDN**
    - Hyunwoo Nam, Doru Calin and Henning Schulzrinne
    - IEEE WCNC best paper, New Orleans, USA, March 2015

- Cloud computing and software-defined networks
  - **Flexible Network Address Mapping for Container-based Clouds**
    - Kyung-Hwa Kim, Jae Woo Lee, Michael Ben-Ami, **Hyunwoo Nam**, Jan Janak and Henning Schulzrinne,
    - IEEE NetSoft, London, England, Aplril 2015

Other projects (non-video streaming)

- Network diagnosis and troubleshooting platform
  - **MoT: A Collaborative Network Troubleshooting Platform for the Internet of Things**
    - Kyung-Hwa Kim, **Hyunwoo Nam**, Jin Hyung Park and Henning Schulzrinne
    - IEEE WCNC, Istanbul Turkey, May 2014
  - **DYSWIS: Crowdsourcing a Home Network Diagnosis**
    - Kyung-Hwa Kim, **Hyunwoo Nam**, Vishal Singh, Daniel Song and Henning Schulzrinne
    - IEEE ICCCN, Shanghai China, August 2014
  - **WiSlow: A WiFi Network Performance Troubleshooting Tool for End Users**
    - Kyung-Hwa Kim, **Hyunwoo Nam** and Henning Schulzrinne
    - IEEE INFOCOM, Toronto Canada, April 2014
  - **WiSlow: A Performance Troubleshooting Tool for Wi-Fi Networks**
    - Kyung-Hwa Kim, **Hyunwoo Nam** and Henning Schulzrinne
    - USENIX NSDI poster and demo, Seattle USA, April 2014

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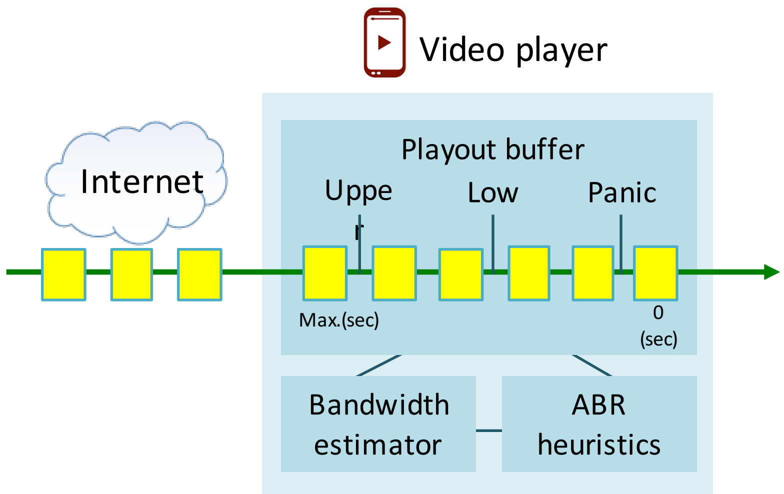
Backup slides

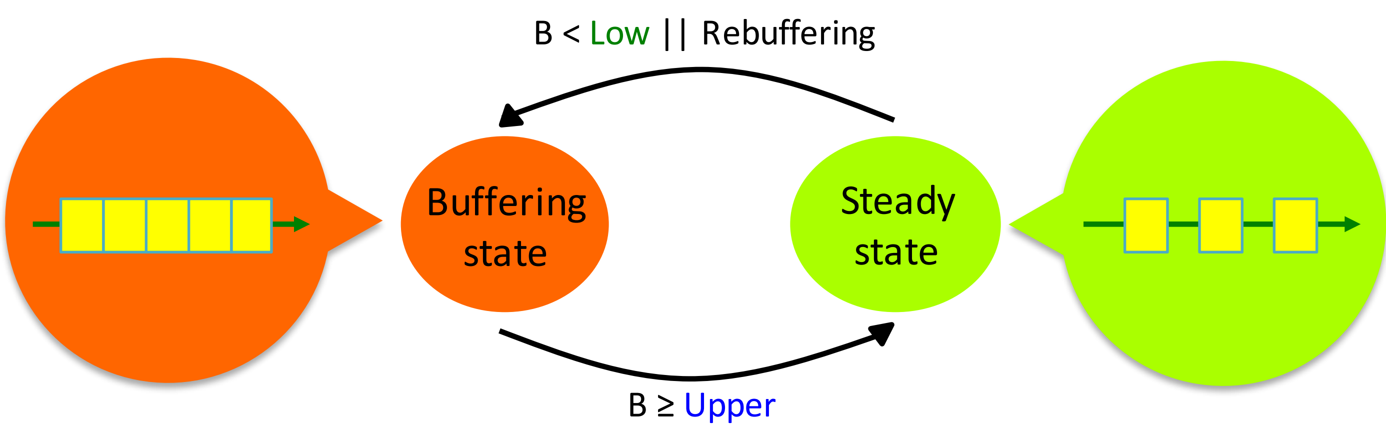
ABR heuristics



Video

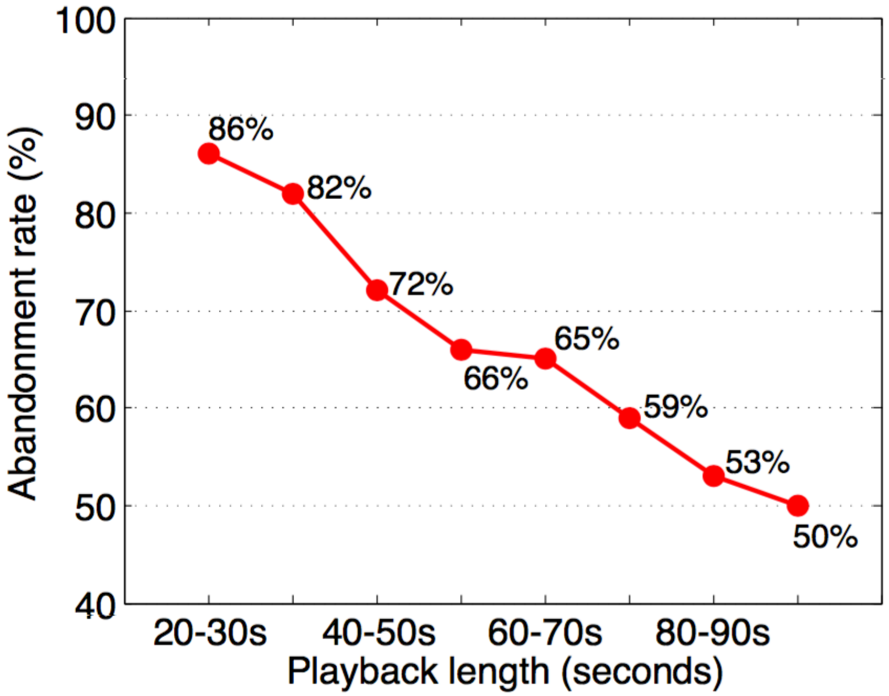
- Degrade bitrate:
  {B < Low || Timeout}
- Upgrade quality:
  {$BW_{avail.}$ > playback rate for next bitrate && B > Upper}
- Request the lowest bitrate:
  {B < Panic||Rebuffering||{$BW_{\downarrow}$ and B<Low}}

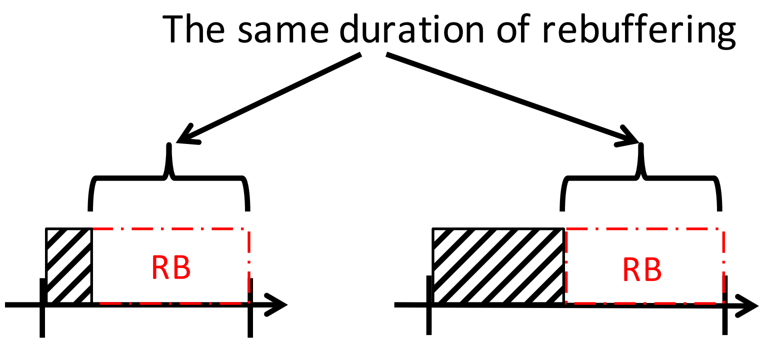
> ➢ B: current playout buffer (sec)
> ➢ Panic, Low and Upper: buffer thresholds



Rebuffering duration on abandonment rate

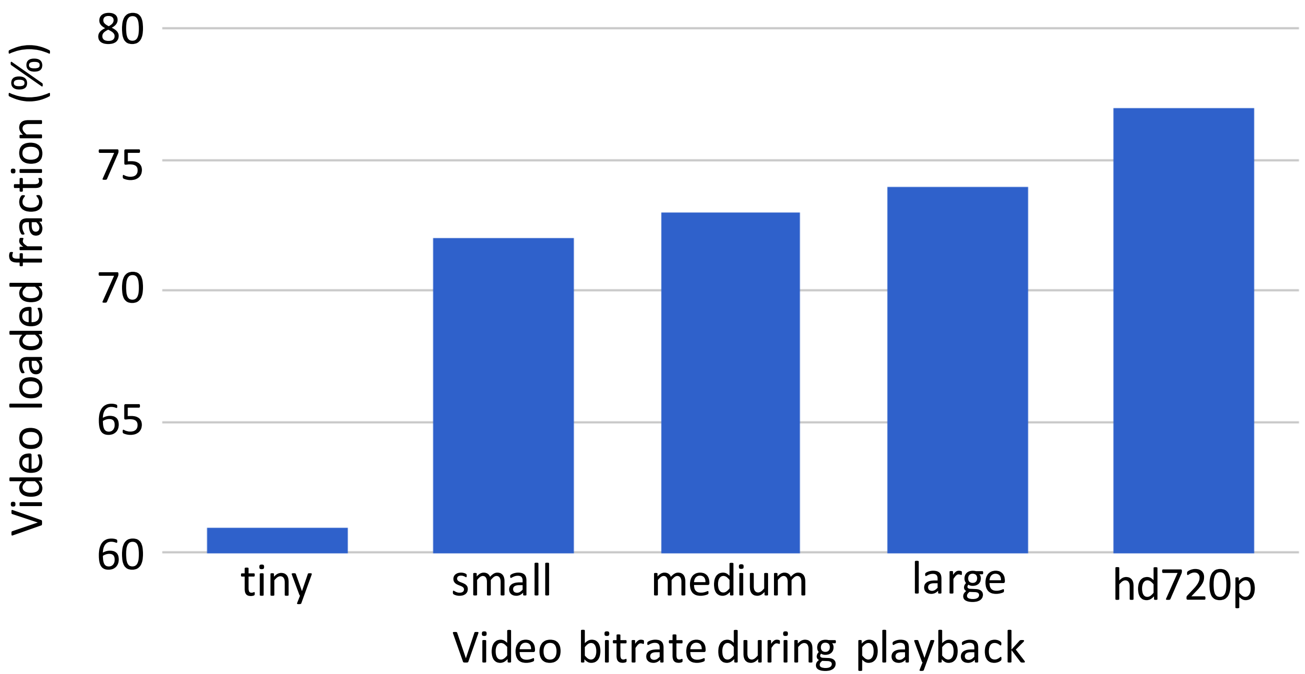
- A total rebuffering duration is not sufficient for modeling QoE metrics.





Abandonment rates for the video sessions where the total rebuffering duration is between 10 and 15s but they have different periods of total playback times (20 through 100s)

Avg. bitrate impact on video loaded fraction



- Concentrating only on the impact of video bitrate, we analyzed the video sessions with no rebufferings and no bitrate changes

Sandvine - Explanation of traffic categories

Traffic Category	Description	Examples
Storage	Large data transfers using the File Transfer Protocol or its derivatives. Services that provide file-hosting, network back-up, and one-click downloads	FTP, Rapidshare, Mozy, zShare, Carbonite, Dropbox
Gaming	Console and PC gaming, console download traffic, game updates	Xbox Live, Playstation 4, Playstation 3, PC games
Marketplaces	Marketplaces where subscribers can purchase and download media including applications, music, movies, books, and software updates	Google Android Marketplace, Apple iTunes, Windows Update
Administration	Applications and services used to administer the network	DNS, ICMP, NTP, SNMP
Filesharing	Filesharing applications that use a peer-to-peer or Newsgroups as a distribution models	BitTorrent, eDonkey, Gnutella, Ares, Newsgroups
Communications	Applications, services and protocols that allow email, chat, voice, and video communications; information sharing (photos, status, etc. between users	Skype, WhatsApp, iMessage, FaceTime, Snapchat
Real-Time Entertainment	Applications and protocols that allow "on-demand" entertainment that is consumed (viewed or heard) as it arrives	Streamed or buffered audio and video (RTSP, RTP, RTMP, Flash, MPEG), peercasting (PPStream, Octoshape), specific streaming sites and services (Netflix, Hulu, YouTube, Spotify,)
Social Networking	Websites and services focused on enabling interaction (chat, communication) and information sharing (photos, status, etc. between users	Facebook, Twitter, Linkedin, Instagram
Tunneling	Protocols and services that allow remote access to network resources or mask application identity.	Remote Desktop, VNC, PC Anywhere, SSL traffic, SSH,
Web Browsing	Web protocols and specific websites	HTTP, WAP browsing

Table 2.3: ABR technologies comparison chart[1]

	Adobe's HDS	Microsoft's SS	Apple's HLS	3GPP/MPEG DASH[2]
Video codec	H.264, VP6	H.264, VC-1	H.264	H.264 + others (agnostic)
Audio codec	AAC, MP3	AAC, WMA	AAC, MP3	AAC + others (agnostic)
Manifest file	.fmf	.ismc	.m3u8	.mpd
Package and segment format	.f4f, .fmf MP4 segments	.ismv MP4 segments	.ts MPEG-2 TS	.mp4 MP4 segments + MPEG-2 TS
File storage on server	Contiguous	Contiguous	Individual file per segment	Contiguous or individual files per segment
Segmentation and delivery	Adobe Interactive Server	Microsoft Internet Information Services	Multiple vendors. Standard HTTP or streaming servers	Multiple vendors. Standard HTTP or streaming servers
Playback	Flash, Air	Silverlight	Apple iOS, Quick Time X	3GPP-Rel 9 or MPEG clients
Protection	Flash Access	PlayReady	AES-128 encryption	Flexible (e.g., OMA [49] or UV [50])
Deployment on ordinary HTTP servers	No	No	Yes	Yes
HTML5 support	No	No	No	Yes
Typical segment duration	2 - 4 seconds	2 - 4 seconds	10 seconds	Flexible

[1] The content in the table is based on the report produced by the Internet Video Archive (IVA) group [51].

[2] HTML5 video players use MSE [36].

Table 2.4: The State of MPEG-DASH 2016[1]

Web browser	Operating system	MSE support	EME support[2]
Chrome 37+	Win 7+, OS X Yosemite+	mp4 AVC, webm VP9 [52]	CENC ClearKey [53], Widevine [54]
Chrome 37+	Android 4.4.4+	mp4 AVC, webm VP9	CENC ClearKey, Widevine
Edge	Win 10	mp4 AVC, webm VP9 (passthrough codec)	PlayReady
Firefox 42+	Win 7+, OS X Yosemite+	mp4 AVC	CENC ClearKey Adobe Primetime
Firefox 42+	Android 5.0+	mp4 AVC	-
Internet Explorer 11	Win 8.1	mp4 AVC	PlayReady
Internet Explorer 11	WinPhone 8.1	mp4 AVC	-
Opera 26+	Win 7+, OS X Maverick+	mp4 AVC, webm VP9	CENC ClearKey
Safari 8+	OS X Yosemite+	mp4 AVC, ts AVC	FairPlay (Netflix only)
Safari Mobile	iOS	-	-

[1] The content in the table is based on the report produced by the Streaming Media magazine [55].

[2] HTML5 web browsers use Encrypted Media Extensions (EME) to support digital rights management (DRM) for media copyright protection [56].