A Hybrid Model of Adaptive Video Streaming Control Systems

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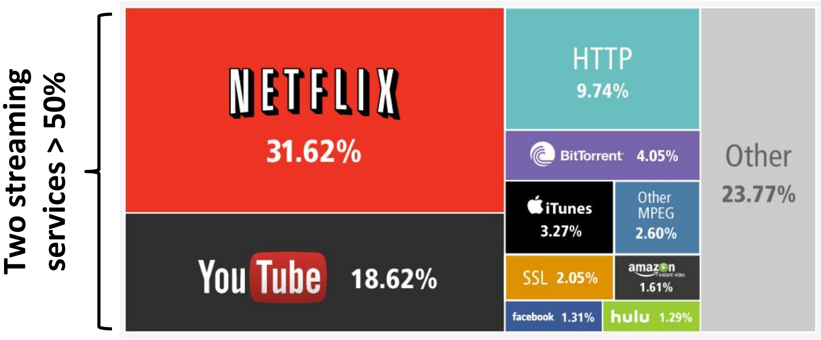
Introduction

- Video will represent ∼80% of Internet global traffic by 2018, up from ∼60% in 2013 (source Cisco)
- Users are moving from traditional TV broadcasting to Internet based video services

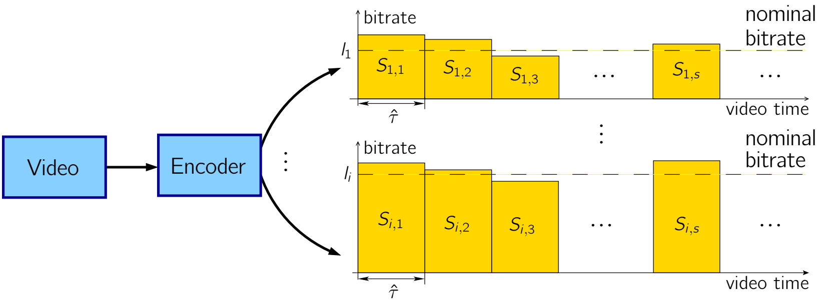


(Source statista.com)

The Challenge

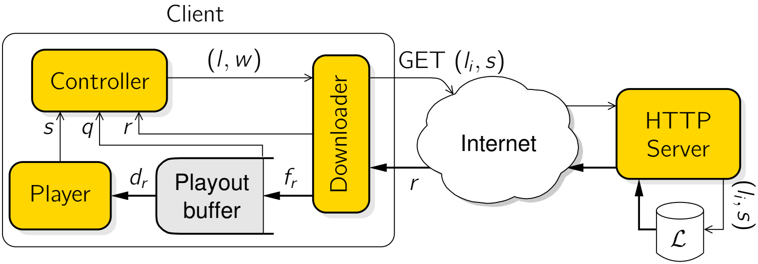
- Provide an experience **at least** as good as traditional TVs on a heterogeneous set of devices (tablets, smartphones, smart TVs)
- **Playback interruptions** due to buffer depletion must be avoided (highly detrimental for QoE)
- Video bitrate should be as high as possible to increase visual quality
- Legacy systems (until ∼2010) encoded video at **fixed bitrate**
- Modern video streaming systems can vary the video bitrate and resolution to adapt to:
  - Time-varying Internet available bandwidth
  - Device resolution

The mainstream Multi-Bitrate Approach



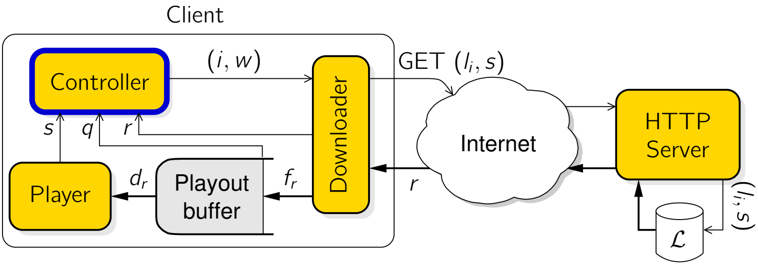
- The video is encoded into a number of versions, the **video levels**, at different (nominal) bitrates l_i
- Each video level is temporally divided into segments of **fixed duration** $\hat{\tau}$
- $S_{i,s}$ is the actual size produced by the encoder for segment s and level i. Actual bitrate is $S_{i,s}/\hat{\tau}$

A video streaming control streaming in a nutshell



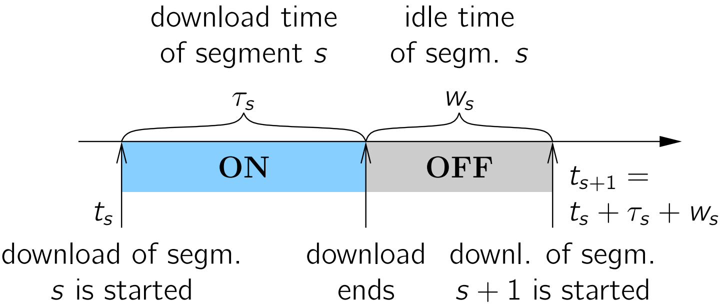
The client fetches video segments at a video bitrate l_i decided by the controller from an HTTP server

The Controller



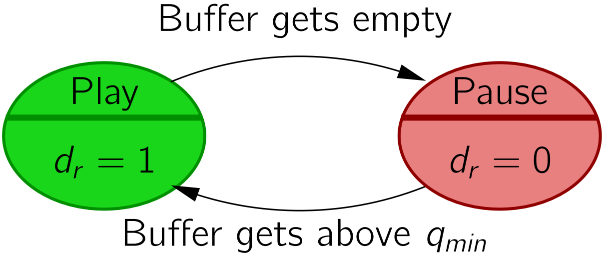
- The controller's output has two components:
    1. The index $i \in \{1, \ldots, N\}$ of the video level to be downloaded
    2. The idle time w to be waited between two consecutive segments download
- Control actions can be actuated only when a new segment **download is triggered** (event driven)

The Downloader



- The downloader serves as the actuator and fetches video segments from the HTTP server
- It pushed video segments as soon as they are downloaded (at time $t_s + \tau_s$)

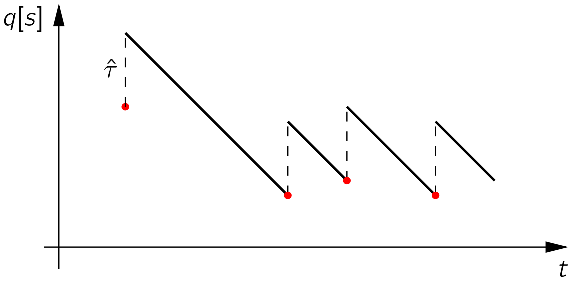
The Player



Two possible states:

- **Pause**: video playback is paused (drain rate $d_r = 0$) to allow the buffer to be filled
- **Play**: the player drains the buffer at rate $d_r = 1$ and plays the video

The playout buffer



- It is **drained continuously** by the player at a rate d_r
- It is **impulsively filled** by a fixed amount $\hat{\tau}$ (segm. duration) on completion of a segment download
- Net increment (decrement) of queue length due to the download of a segment:

$$q(t_s + \tau_s) - q(t_s) = \hat{\tau} - \int_{t_s}^{t_s+\tau_s} d_r(\xi) d\xi$$

Hybrid Dynamical Systems modeling framework

A hybrid system can be described by four elements [HDS]:

$$\mathscr{H} : \begin{cases} \dot{x} = f(x, u, r) & (x, u, r) \in \mathcal{C}, \\ x^{+} = g(x, u, r) & (x, u, r) \in \mathcal{D} \end{cases}$$

- **Flow set**: $\mathcal{C}$ where the state x “flows” (evolves continuously)
- **Jump set**: $\mathcal{D}$ where the state x “jumps” (time discrete evolution)
- **Flow map**: f modelling time-continuous evolution
- **Jump map**: g modelling time-discrete evolution

[HDS] R. Goebel, R.G. Sanfelice, A.R. Teel, “Hybrid Dynamical, Systems: modeling, stability, and robustness”, Princeton University Press, 2012

State, input, disturbance

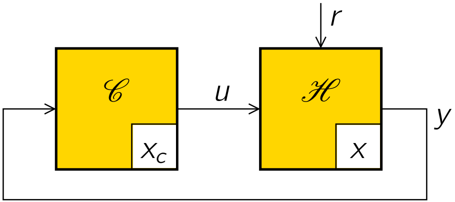
State $x = \begin{bmatrix} q \\ d_r \\ \Delta \\ \tau \\ \sigma \\ s \end{bmatrix}$

- **Playout buffer length** (s) [PB]
- Draining rate [P]
- Segment downloaded bytes [D]
- Idle timer (s) [D]
- Downloader state (1=ON,0=Idle) [D]
- Segment index [D]

Input $u = \begin{bmatrix} i \\ w \end{bmatrix}$

- Video level $i \in \{1, \ldots, N\}$
- Idle duration (s)

Disturbance r available bandwidth (bytes/s)



Jump set $\mathcal{D}$

$\mathcal{D}$ is the union of the sets:

$$
\begin{aligned}
\mathcal{D}_{\text{feed}} &= \{(x,u,r) \in \mathcal{X} \times \mathcal{U} \times \mathbb{R}_{\geq 0} : \Delta = S_{i,s}\} \\
\mathcal{D}_{\text{dwnl}} &= \{(x,u,r) \in \mathcal{X} \times \mathcal{U} \times \mathbb{R}_{\geq 0} : \tau = w \wedge \sigma = 0\} \\
\mathcal{D}_{\text{empty}} &= \{(x,u,r) \in \mathcal{X} \times \mathcal{U} \times \mathbb{R}_{\geq 0} : q = 0 \wedge d_r = 1\} \\
\mathcal{D}_{\text{play}} &= \{(x,u,r) \in \mathcal{X} \times \mathcal{U} \times \mathbb{R}_{\geq 0} : q \geq q_{\text{min}} \wedge d_r = 0\}
\end{aligned}
$$

$\mathcal{D}_{\text{feed}}$	End of download of segment s of level l_i $\Rightarrow$The segment is fed to the buffer
$\mathcal{D}_{\text{dwnl}}$	End of an idle period $\Rightarrow$Triggers the download of the next segment $(s+1)$
$\mathcal{D}_{\text{empty}}$	Queue gets empty $\Rightarrow$ Playback is stopped $(d_r = 0)$
$\mathcal{D}_{\text{play}}$	Queue gets filled $\Rightarrow$ Playback is started $(d_r = 1)$

Continuous and discrete dynamics (f and g)

Continuous dynamics
$(x, u, r) \in \mathcal{C}$

$$\dot{q} = -d_r$$
$$\dot{\Delta} = \sigma r$$
$$\dot{\tau} = 1$$

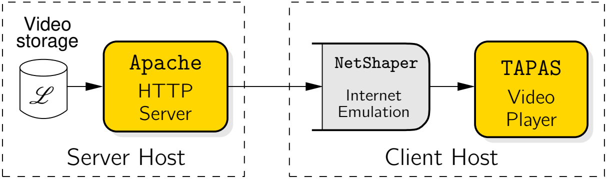
(other variables' derivatives are 0)

Discrete dynamics
$(x, u, r) \in \mathcal{D}$

$$d_r^+ = \begin{cases} 1, & (x, u, r) \in \mathcal{D}_{\text{play}} \\ 0, & (x, u, r) \in \mathcal{D}_{\text{empty}} \end{cases}$$
$$q^+ = q + \hat{\tau} \;\; (x, u, r) \in \mathcal{D}_{\text{feed}}$$
$$\Delta^+ = 0 \;\; (x, u, r) \in \mathcal{D}_{\text{feed}}$$
$$\sigma^+ = \begin{cases} 0 & (x, u, r) \in \mathcal{D}_{\text{feed}} \\ 1 & (x, u, r) \in \mathcal{D}_{\text{dwnl}} \end{cases}$$
$$\tau^+ = 0 \;\; (x, u, r) \in \mathcal{D}_{\text{feed}} \cup \mathcal{D}_{\text{dwnl}}$$
$$s^+ = s + 1 \;\; (x, u, r) \in \mathcal{D}_{\text{feed}}$$

Experimental Validation

- The model is implemented in Matlab through the Hybrid Equations (HyEq) Toolbox by Sanfelice
- Experimental data: gathered through tests on a controlled testbed in lab



- An Internet bottleneck link is emulated by a tool we developed allowing the bandwidth r to be set
- An adaptive video streaming client is implemented using TAPAS (https://github.com/ldecicco/tapas)

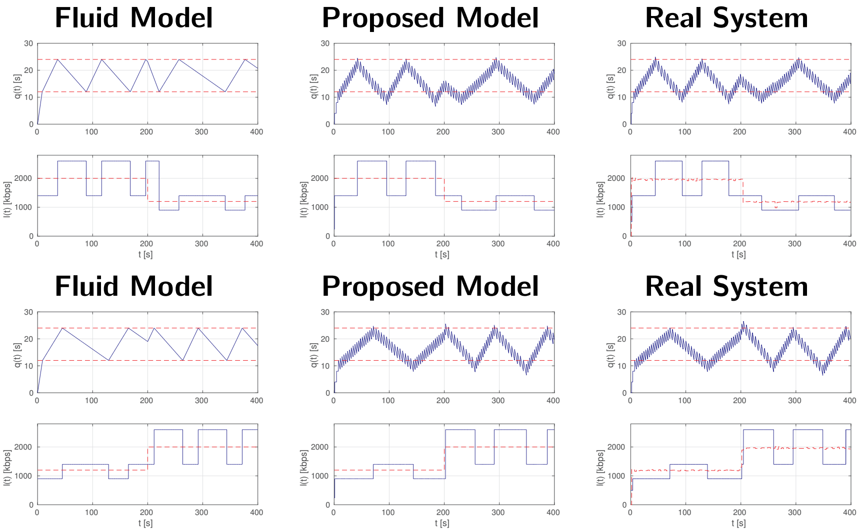
Experimental Validation

- **Employed controller** [ACC15]: a controller keeping the queue length within $[q_L, q_H]$ by throttling the video level between the closest ones $(l_i\ ,\ l_{i+1})$ to the available bandwidth r
- We compare the dynamics of:
  - A fluid flow model of the queue length [ACC15]
  - The proposed Hybrid system model
  - The real system
- The video is the popular benchmark "Sintel" encoded at five nominal bitrates:

$$\mathcal{L} = \{240, 500, 900, 1400, 2600\}\text{kb/s}$$

[ACC15] G. Cofano, L. De Cicco, S. Mascolo, "Characterizing Adaptive Video Streaming Control Systems", in Proc. of ACC, July 2015

Results: step response



Conclusions

- We have proposed a hybrid system modeling adaptive video streaming control systems
- The model accurately predicts the dynamics of real video streaming systems
- The model can be used to:
  - Design control laws and prove properties of the closed loop system (future work)
  - Perform simulations of video streaming systems to aid the design phase of controllers

Thank you!

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Results: step response