Optimizing Live Game Streaming Platforms Using Segment-of-Interests

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Outline

- Introduction & Motivation
- System Overview
- SoI Detector
- Resource Allocator
- Evaluation
- Conclusion

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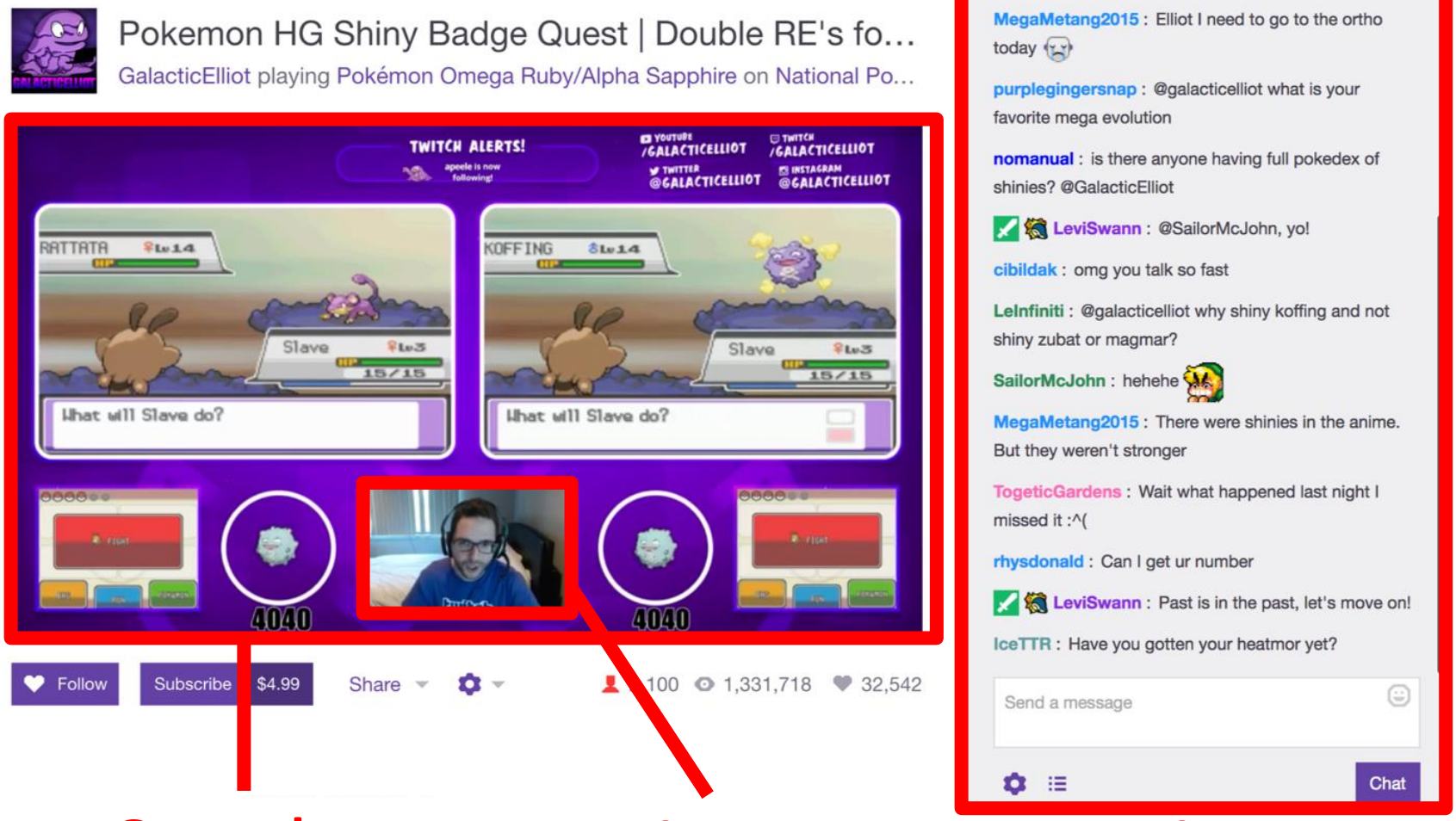
Twitch

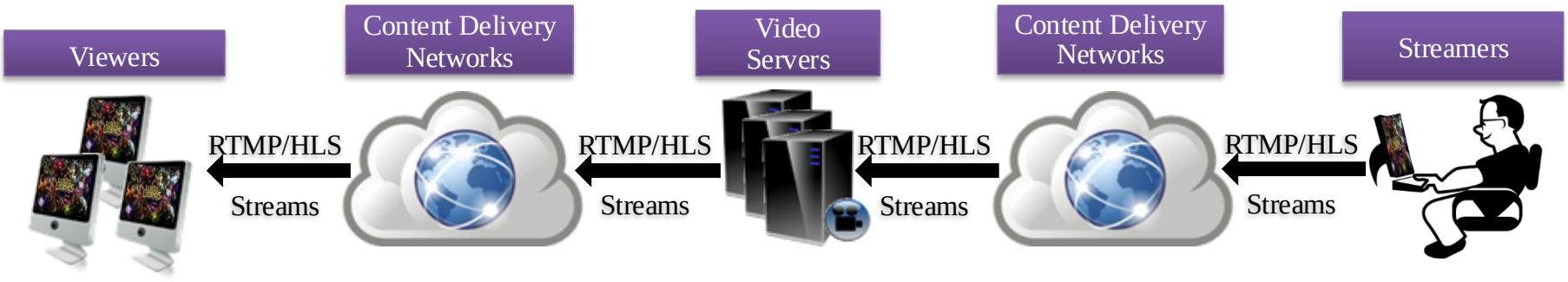


Gameplay

Webcam image

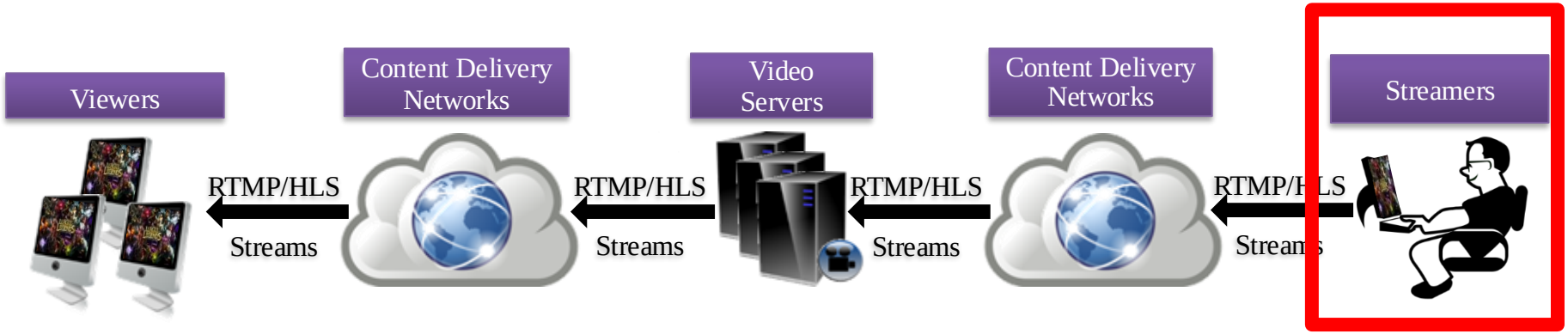
Chat

How Does Live Game Streaming Work?



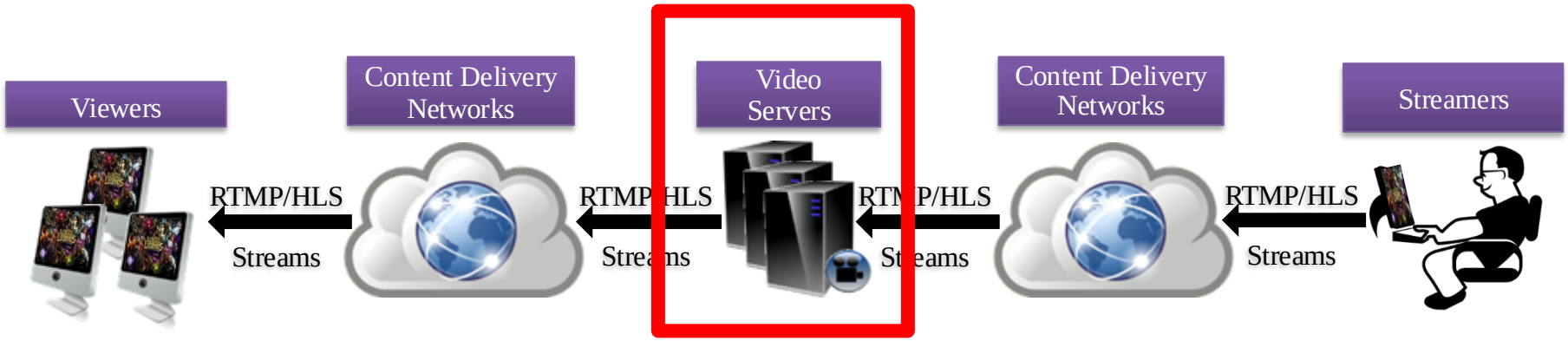
Streamer

- Streamer: send the game stream to video servers
  - Often with streaming software such as OBS
  - Using protocols such as RTMP, HTTP Live Streaming



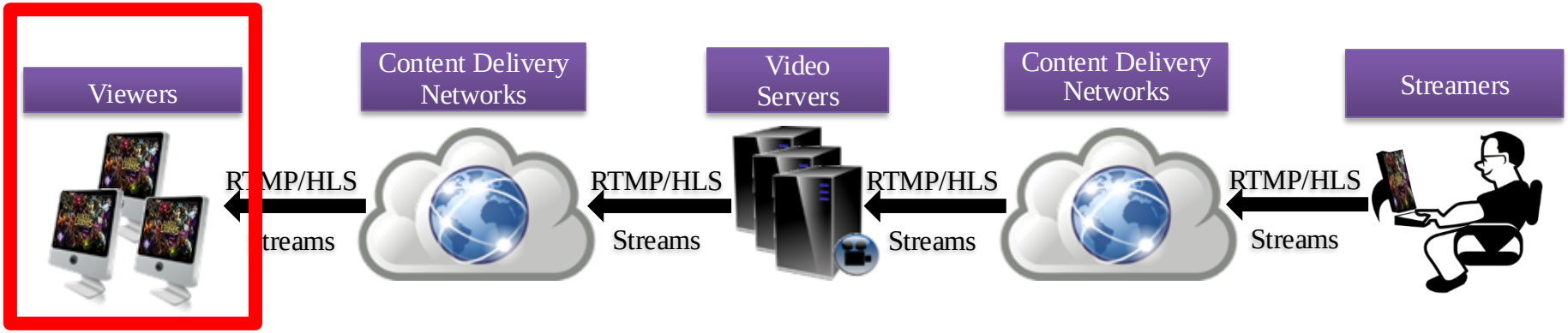
Video Servers

- Relay the stream to viewers
  - Transcode them if necessary



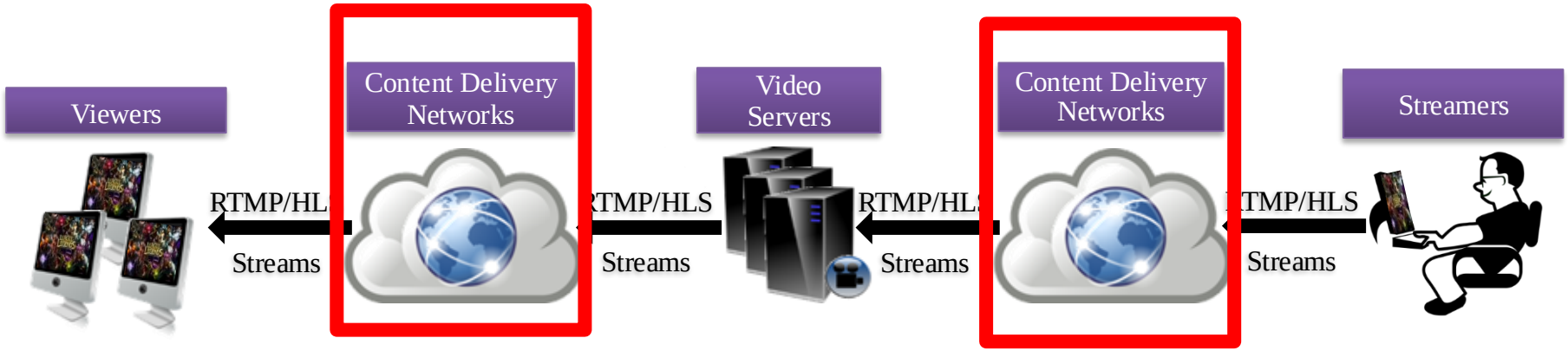
Viewers

- Watch the stream with video players



Content Delivery Networks

- Streams often go through CDNs
  - Companies such as Twitch need to pay for the bandwidth (to CDN companies such as Akamai)



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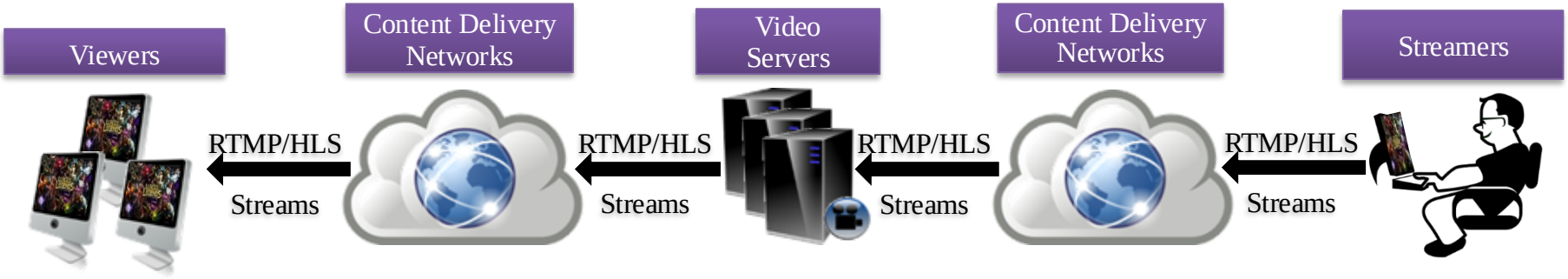


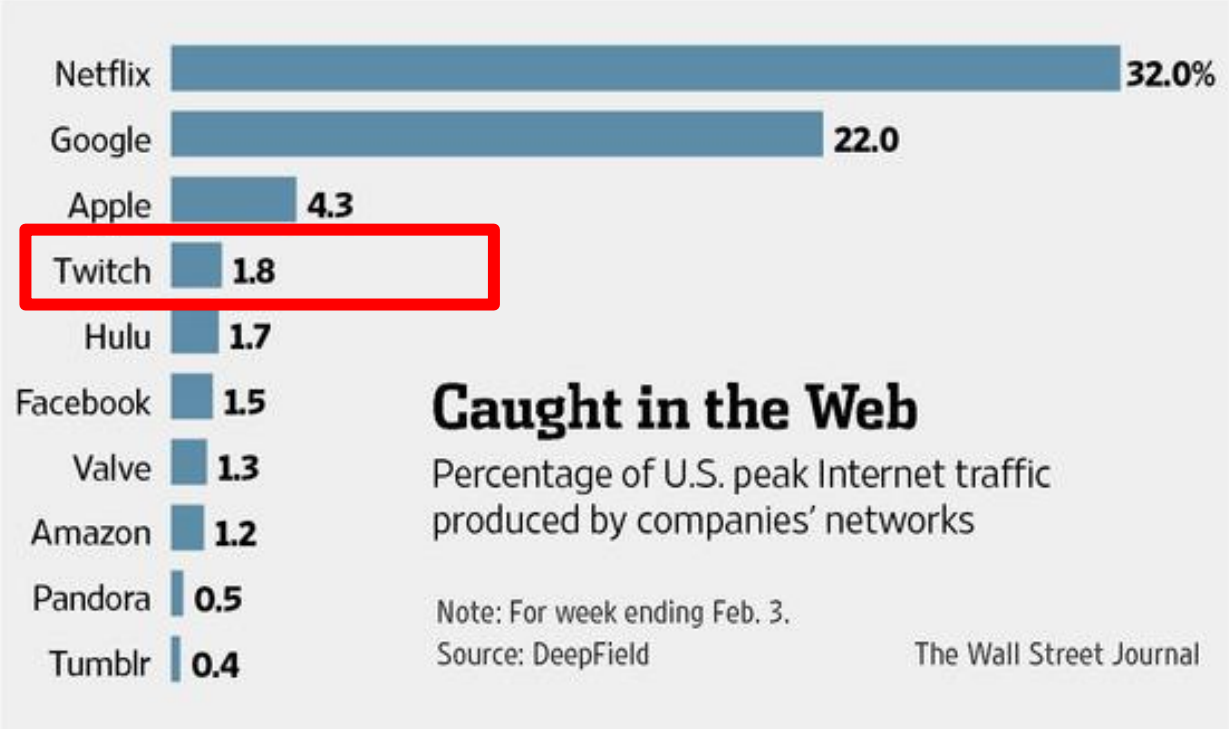
Who are running these services?

Who Are Running These Services?

- Twitch
  - Spin-off from Justin.tv
  - The broadcast platform for most E-sport event
- Ustream
  - The streaming service used by Sony PS4
- YouTube Gaming
  - Launched in Aug, 2015

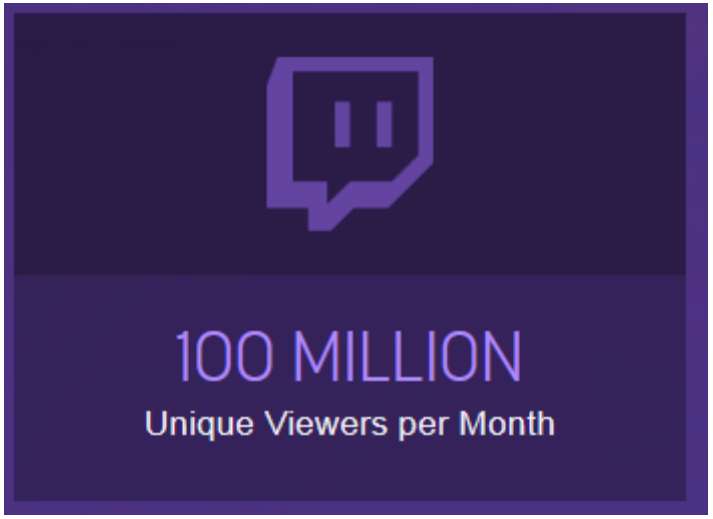
Twitch Is Hot

- 4th largest in peak US Internet traffic



Growing Demands

- Number of viewers doubled in 2014
  - More than twice in 2013



2013 **2014**

Acquired by Amazon.com for $970 million

Everything looks great

WHAT'S THE PROBLEM?

Problem: Lag

- Lag is annoying when watching live streams
  - Rebuffering
  - Other visual artifacts
  - Skipped video segment
- Bad for user experience

Possible Solutions

- Put in more resource
  - Cost money
- Lower the video quality
  - Bad for user experience

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  - Cost money
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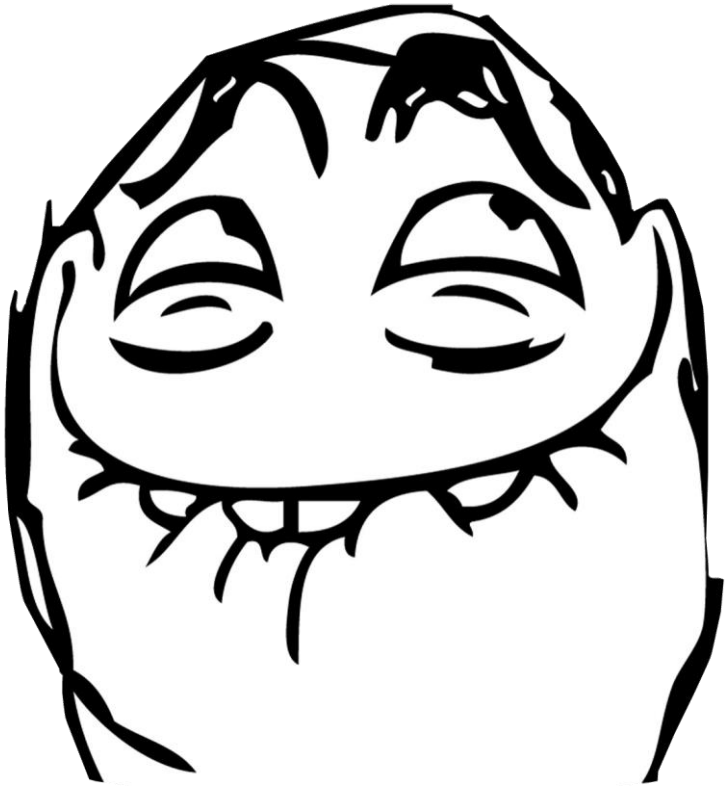
How to do this without degrading the user experience?

LAG AT DIFFERENT TIME CAUSE DIFFERENT LEVEL OF DEGRADATION IN USER EXPERIENCE

At Clutch Time

At Clutch Time



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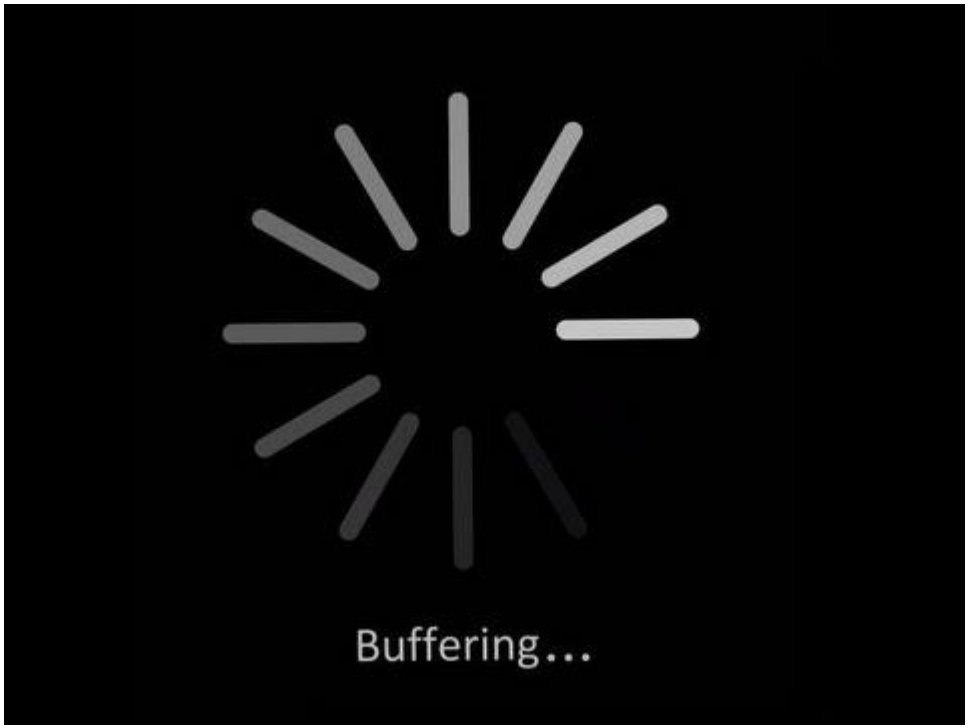

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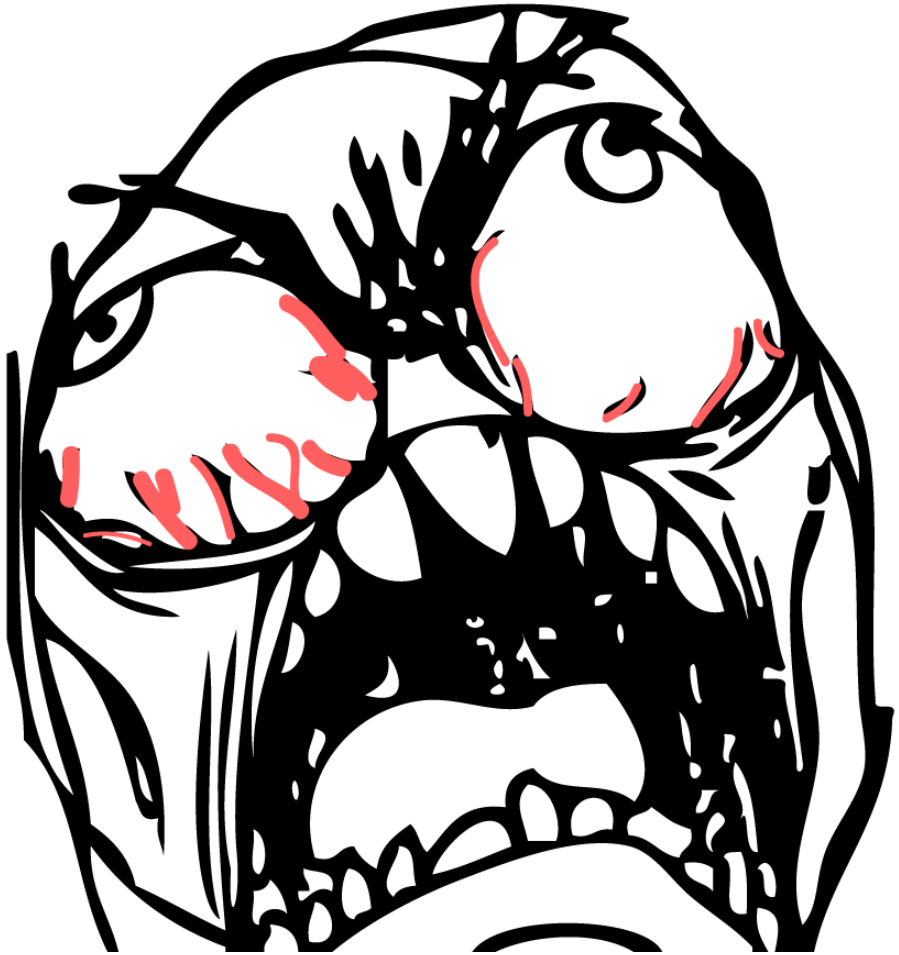

At Normal Time

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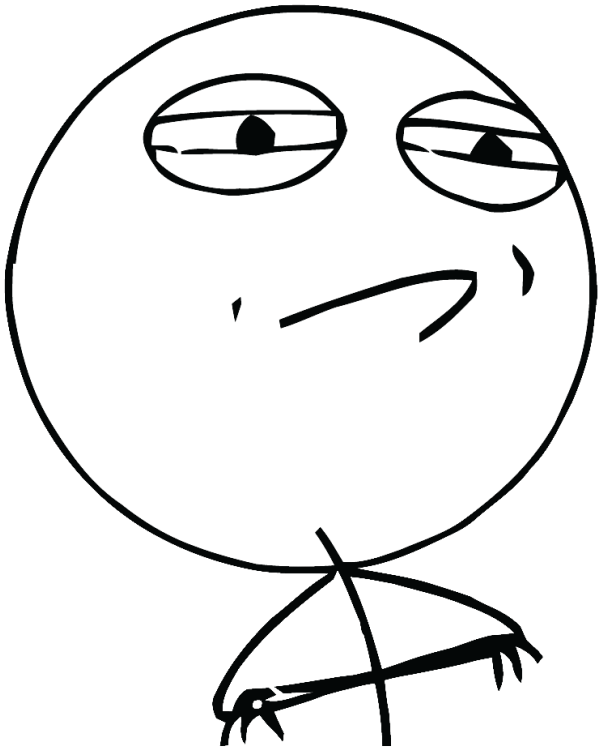

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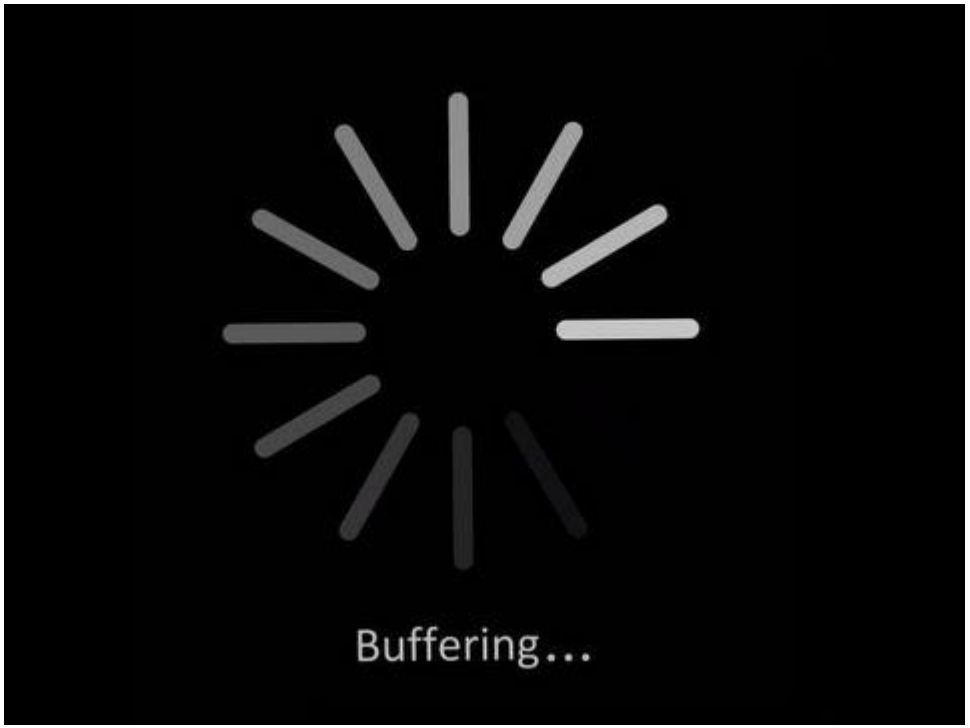

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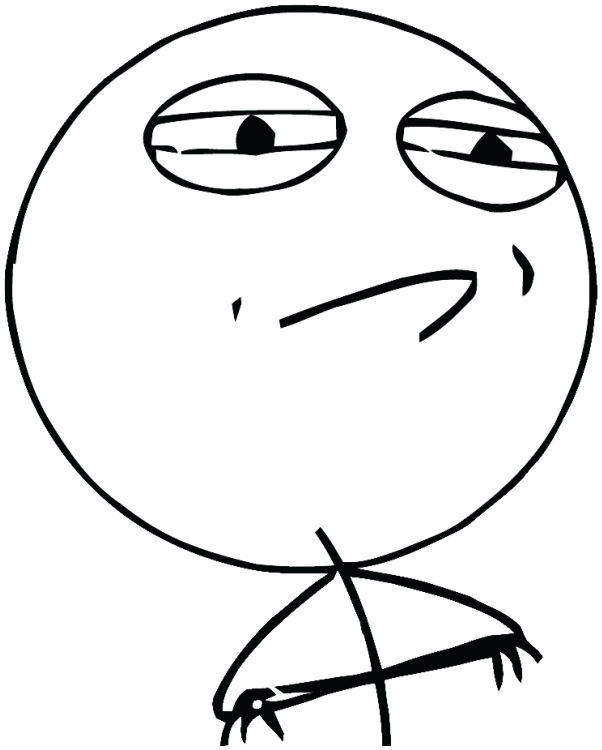

Not that bad

Concept of Segment of Interest (SoI)

- Different segments have different importance
  - We refer to the important one as Segment of Interest (SoI)
- We should put in more resource to deliver SoI
  - Sacrifice non-SoI if we have to

Contributions

- Develop SoI-driven streaming platform
- Answer two questions
  - How to detect SoI efficiently?
  - How to allocate resources among channels?

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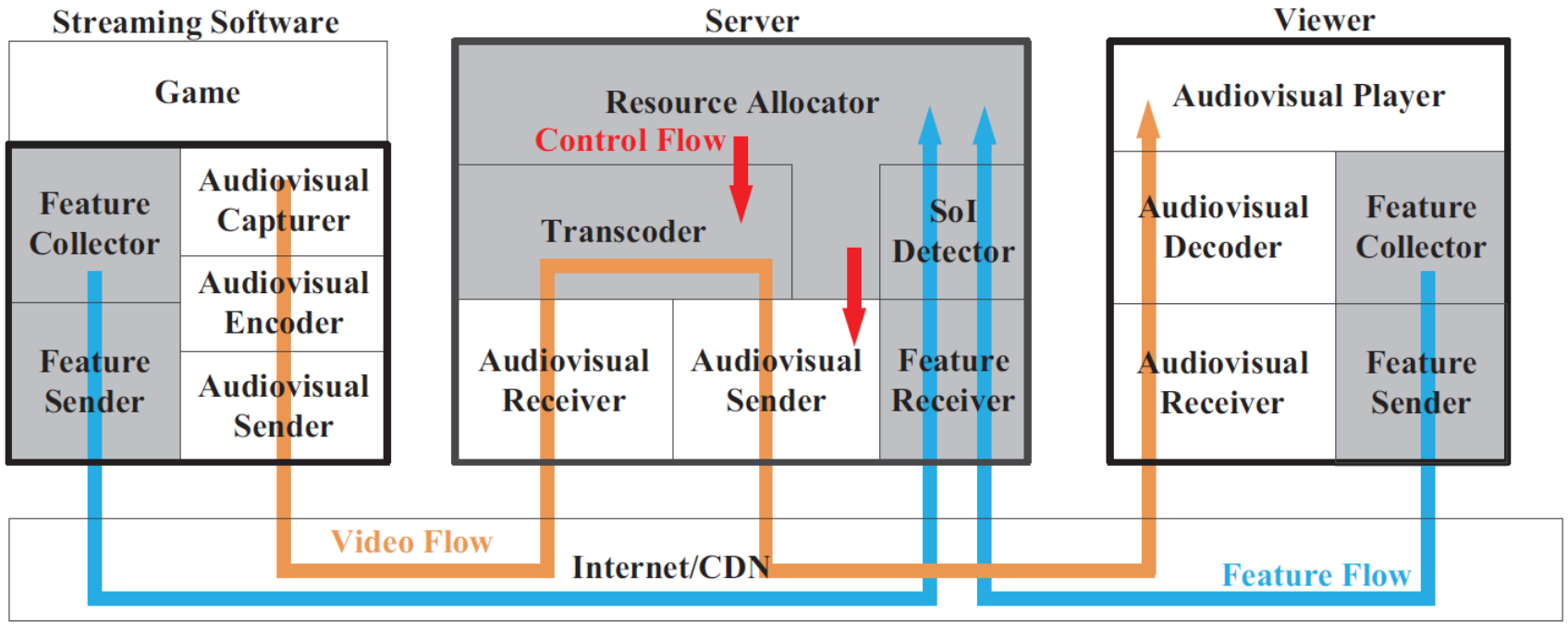
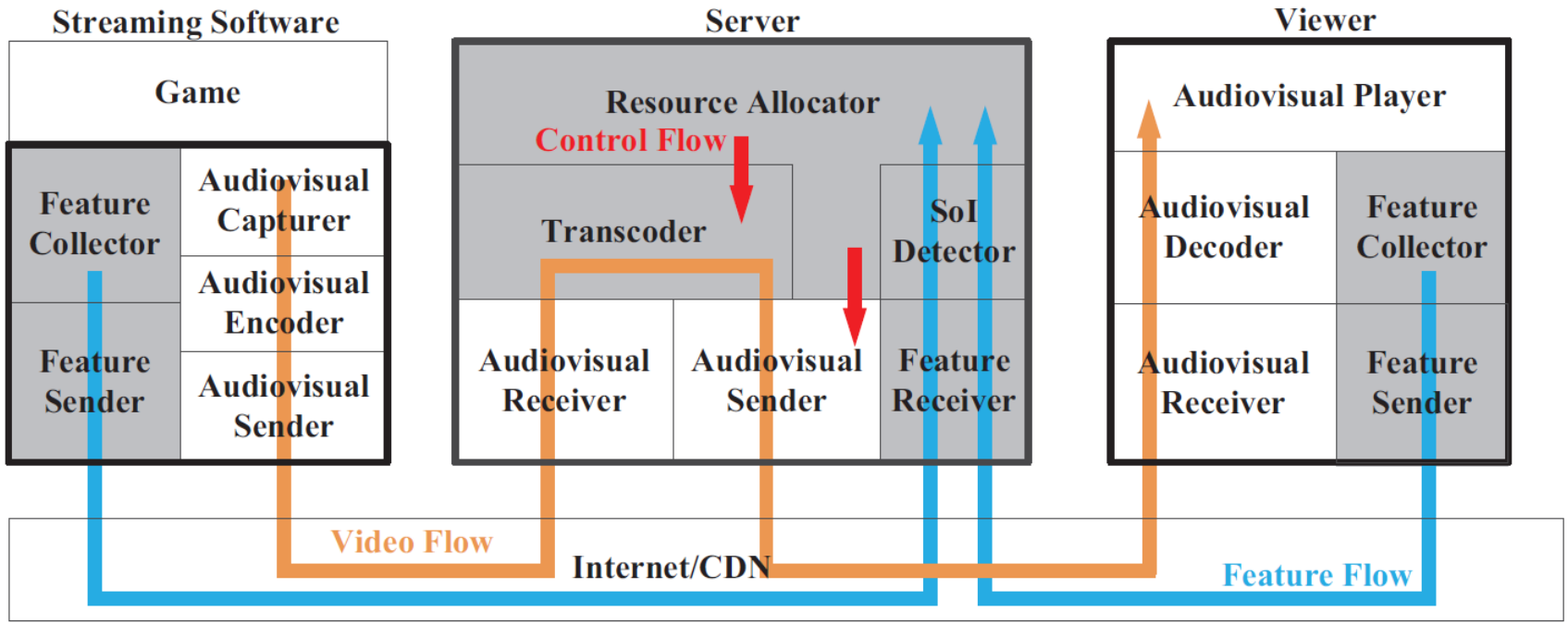
System Architecture



Streaming software

- Stream the gameplay to server



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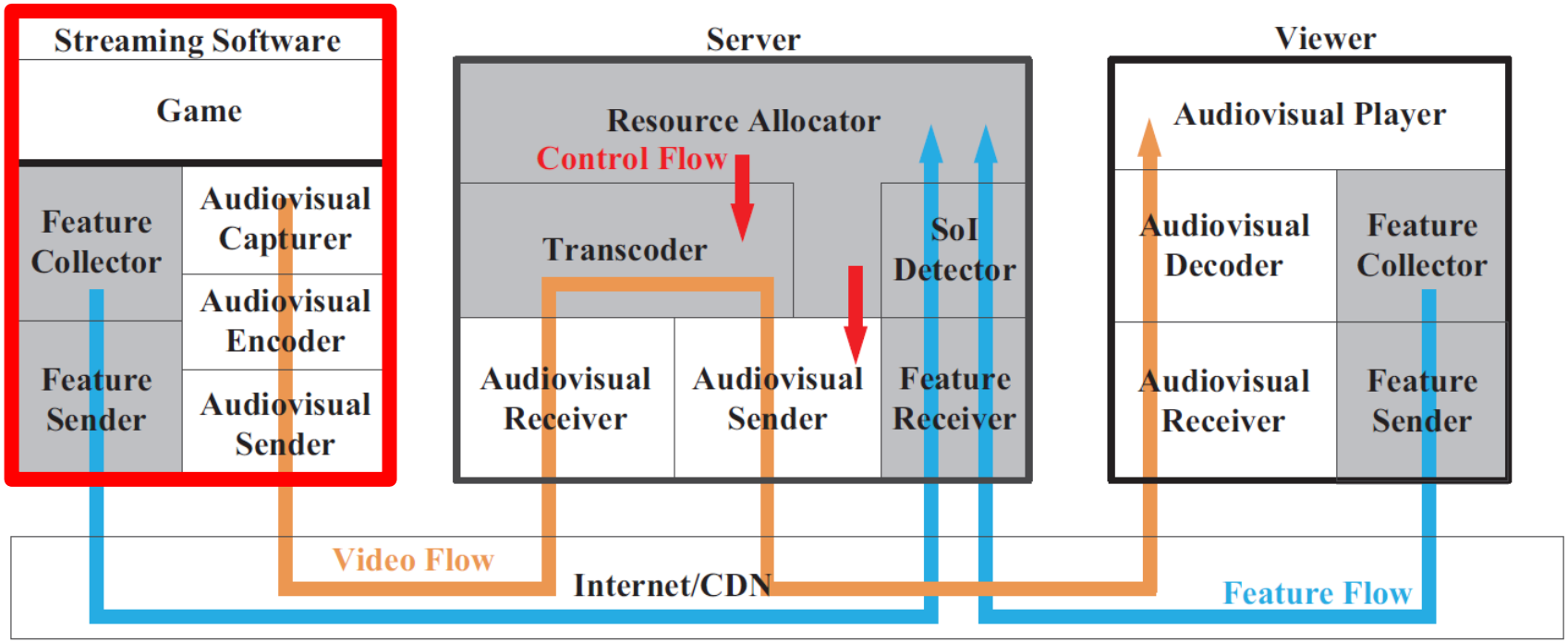

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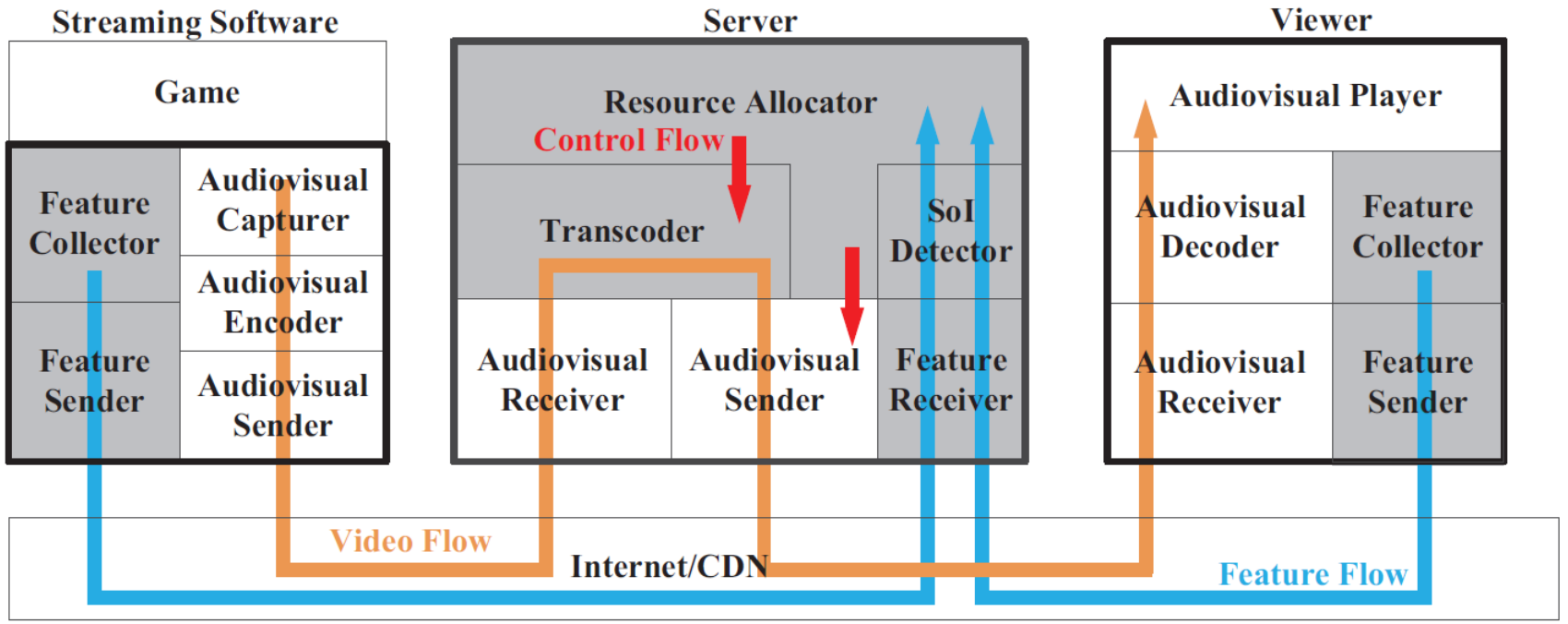

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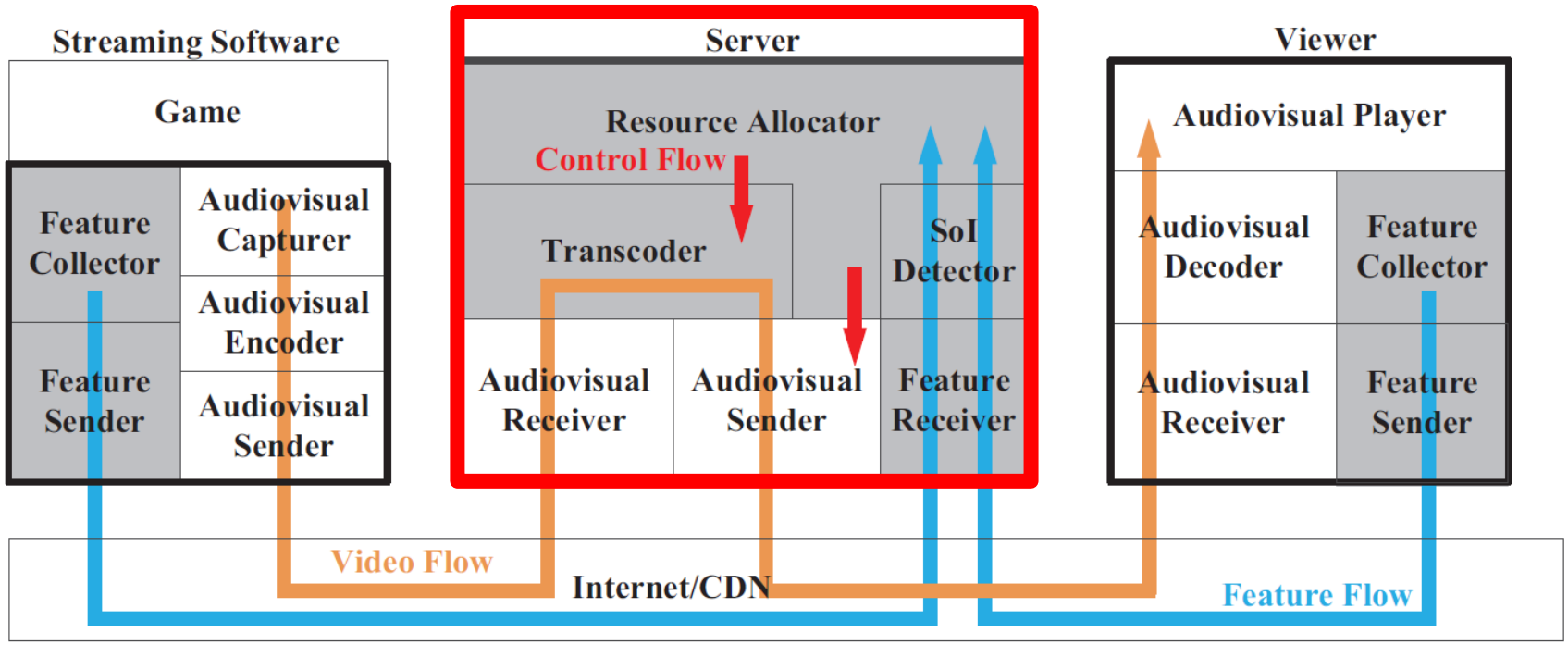
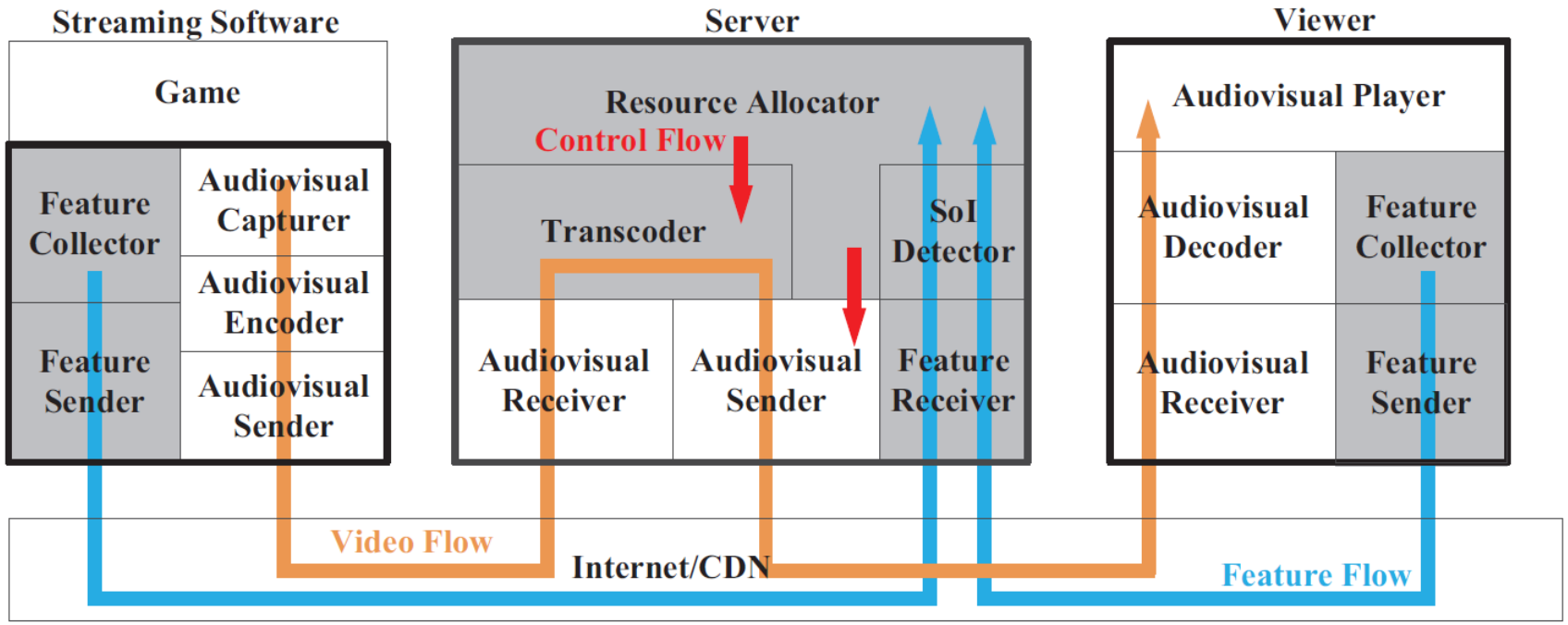


Viewer

- Replay the gameplay stream



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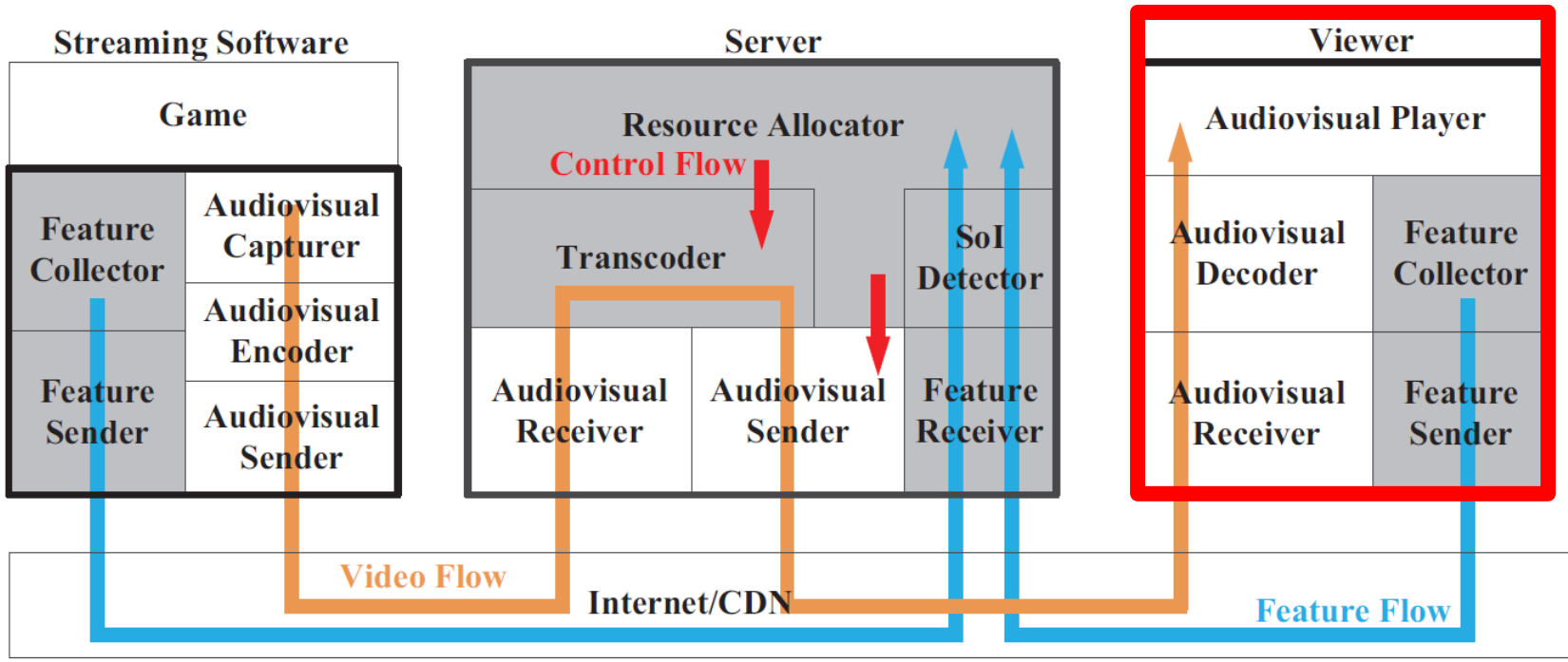
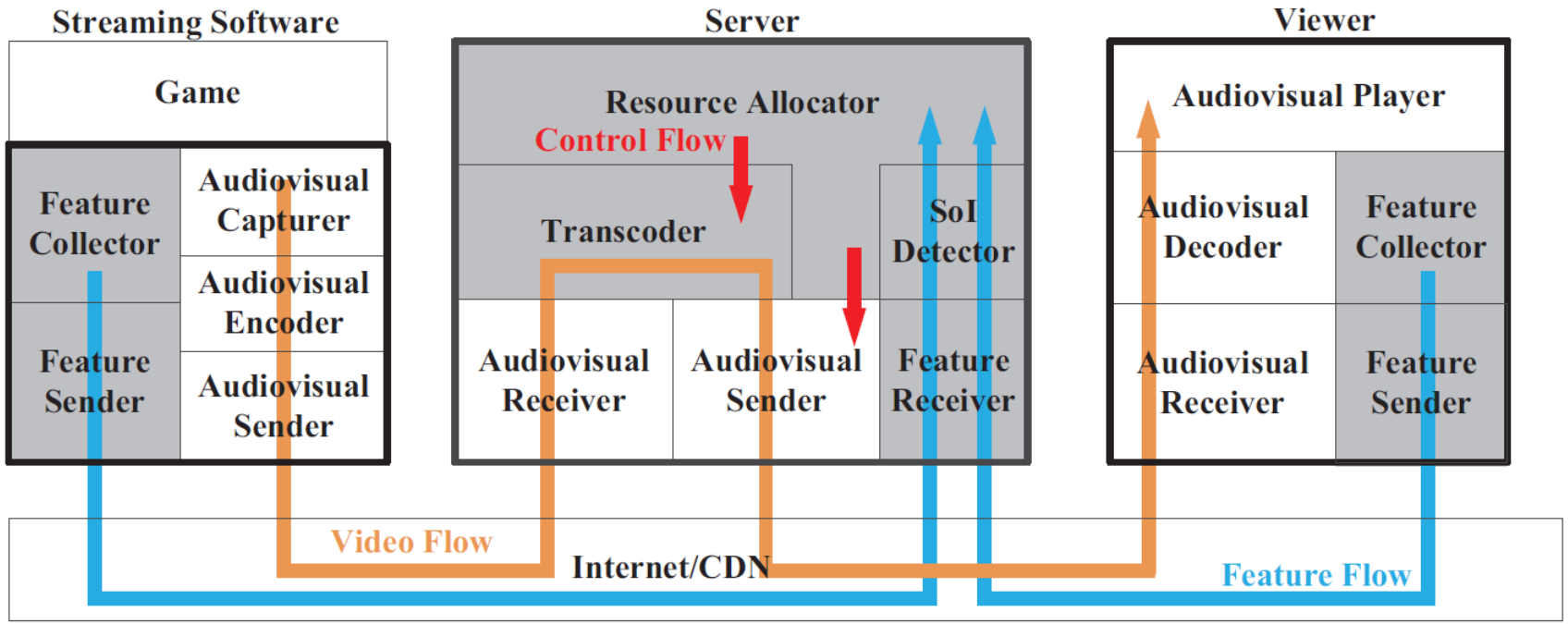


Feature Collector

- Collect the features from streamers
  - Such as CPU usage, foreground window name…
- Also from viewers



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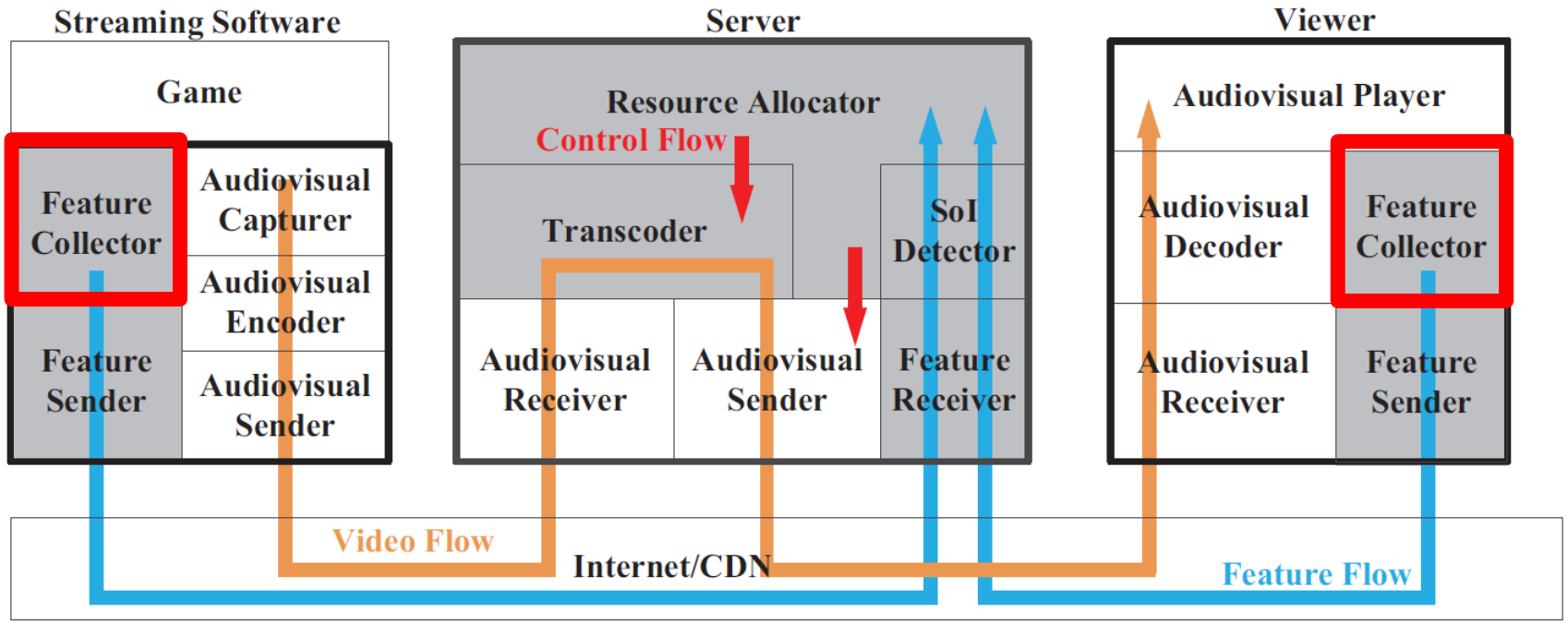
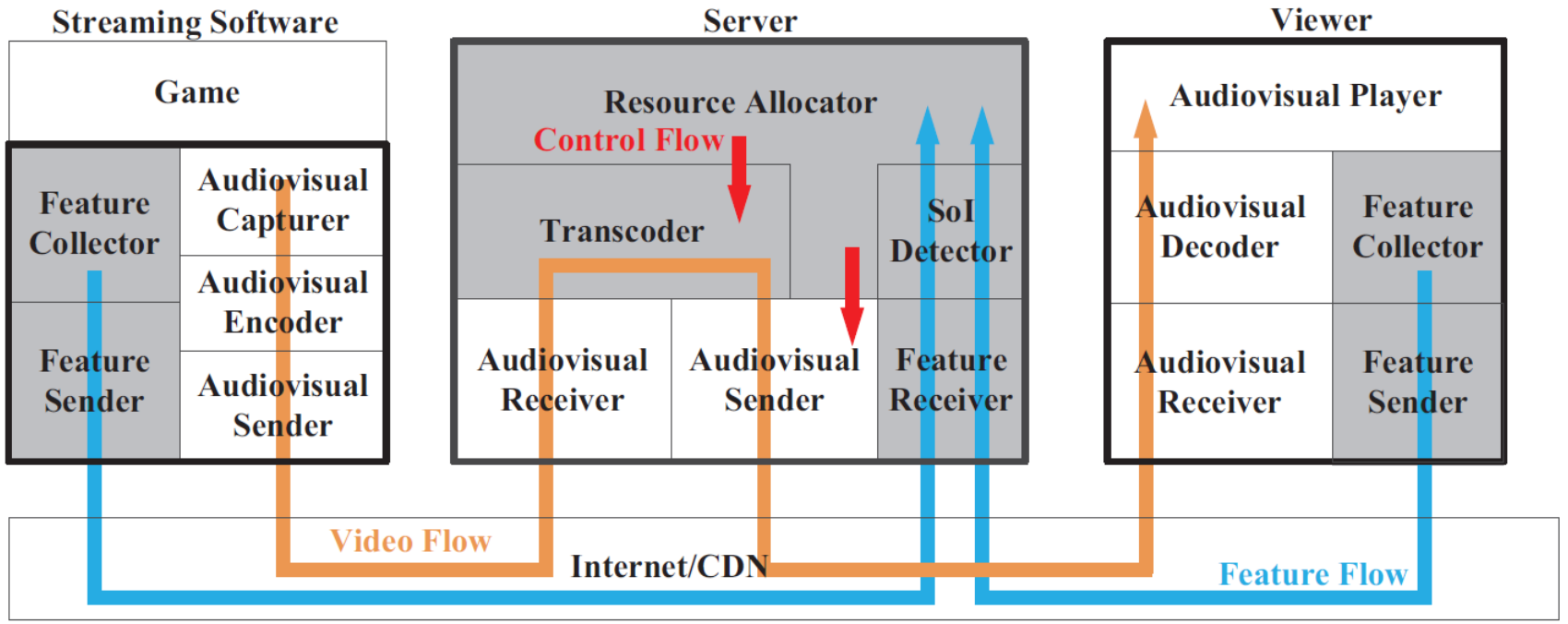


Feature Sender/Receiver

- Send/receive the collected features



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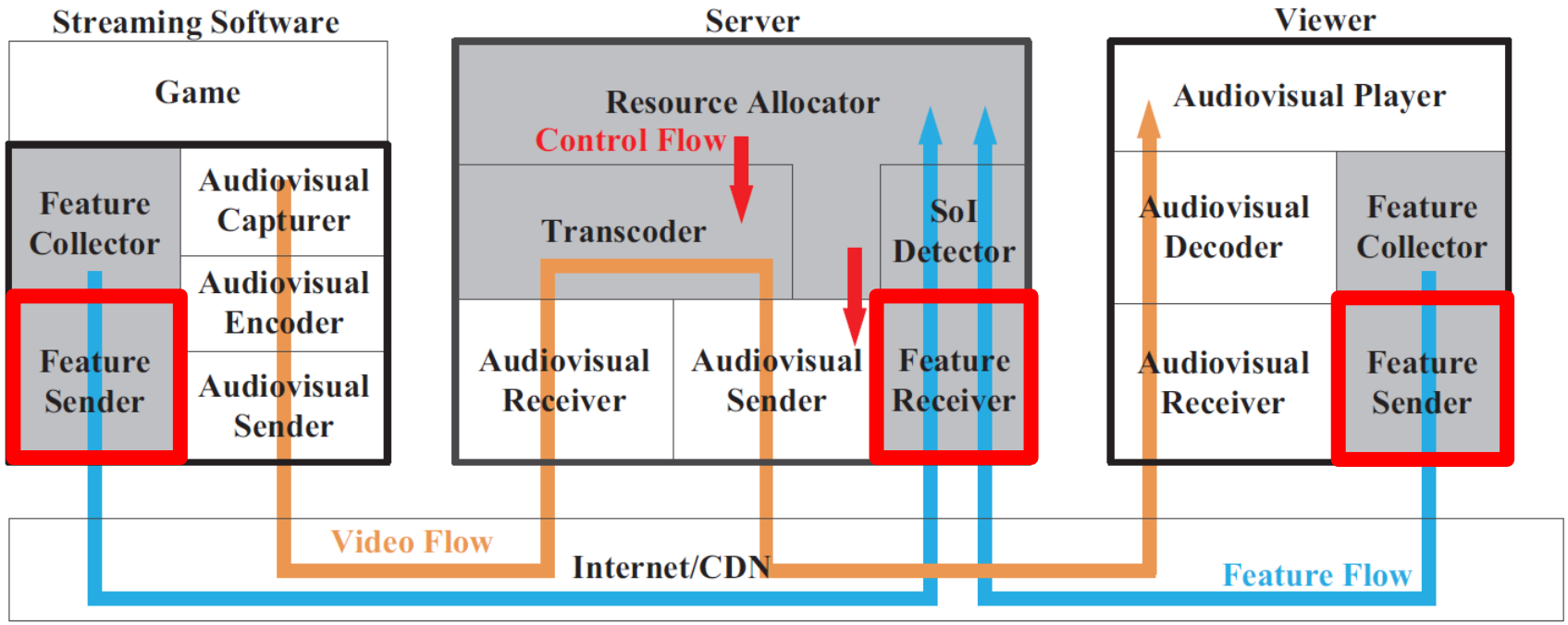
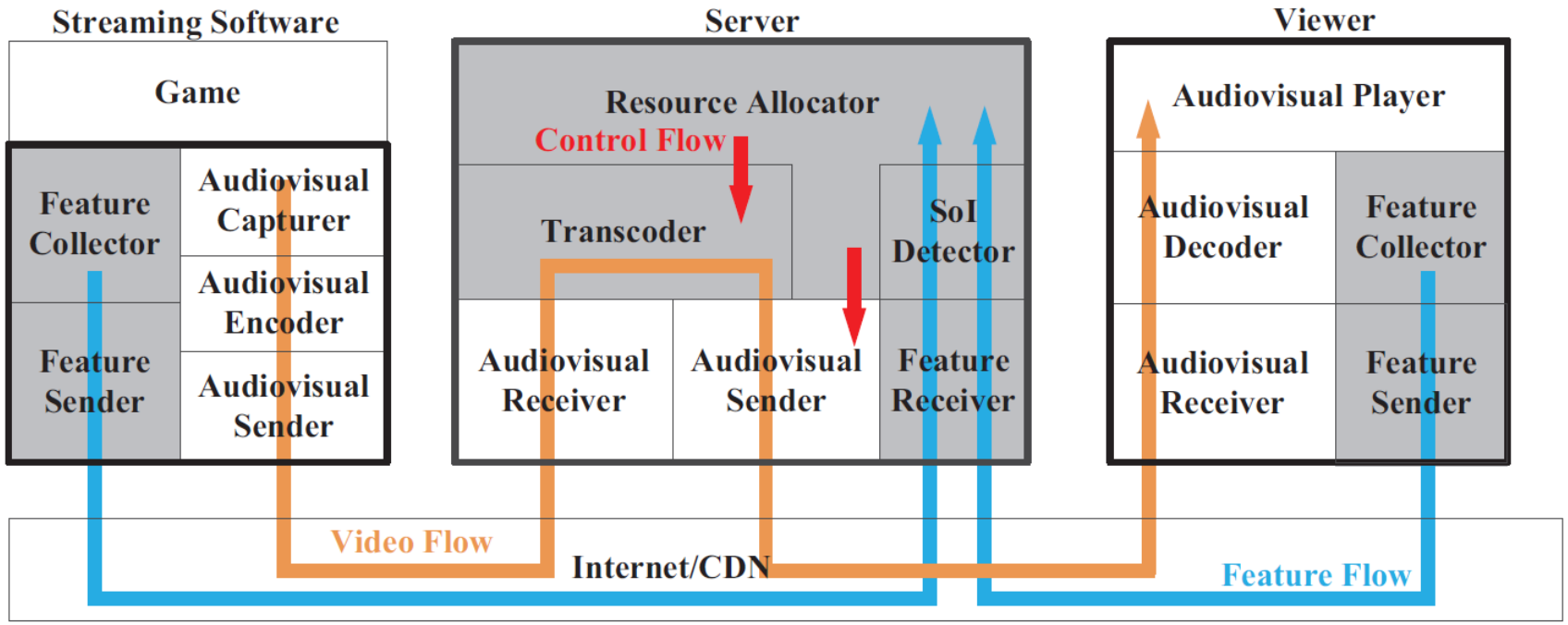


SoI Detector

- Detect SoI from the collected features



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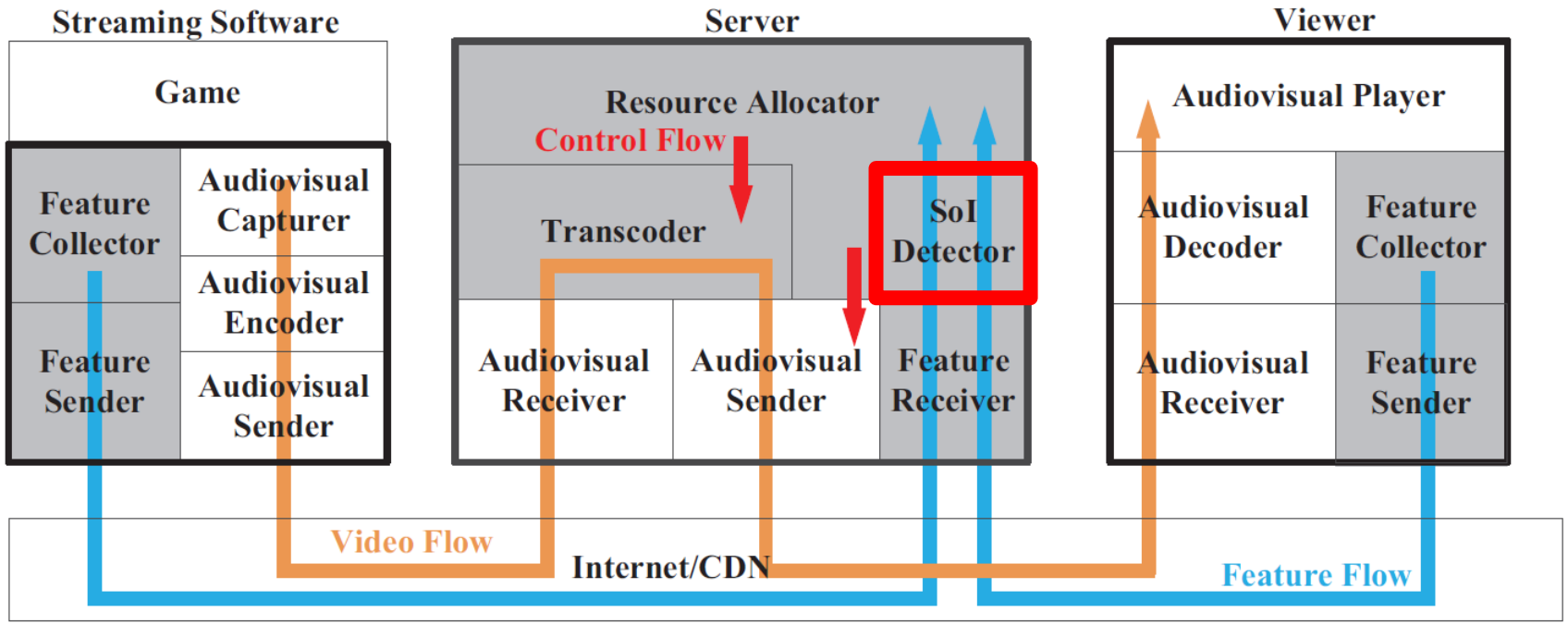
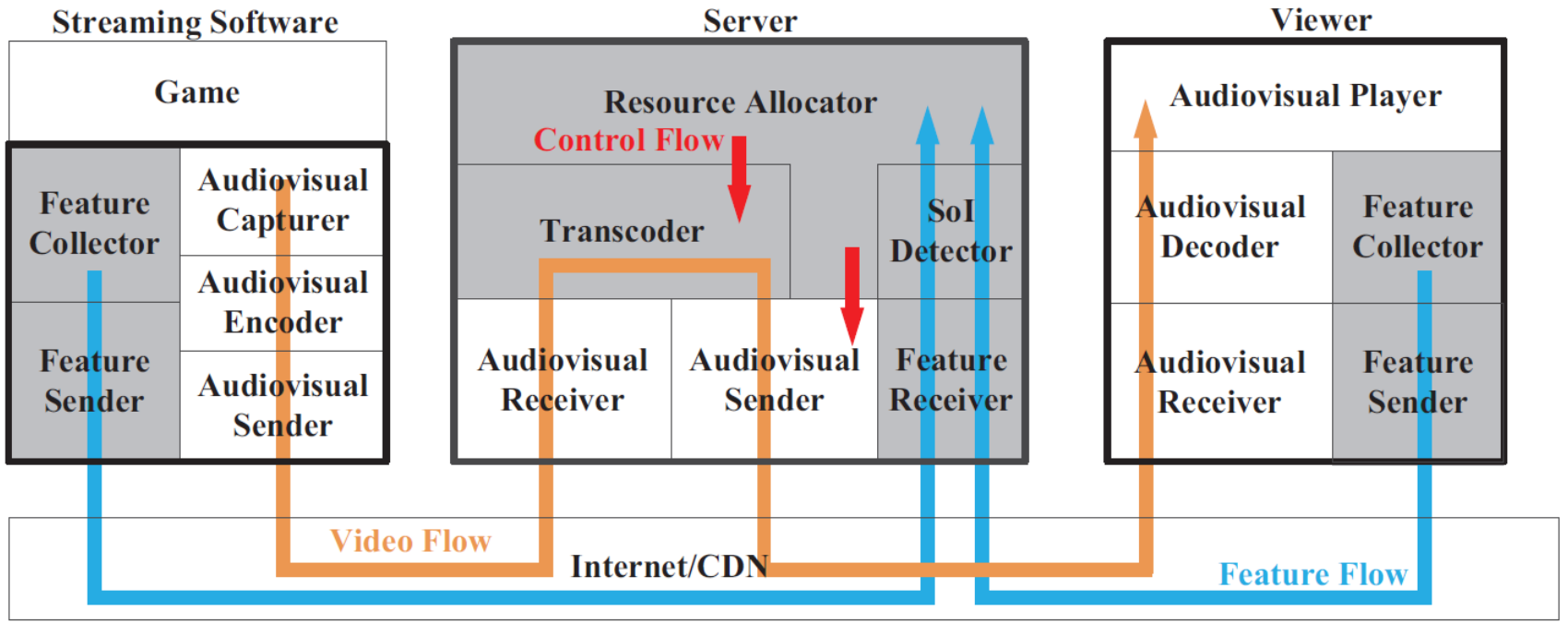


Resource Allocator

- Allocate resources between different streams in the system



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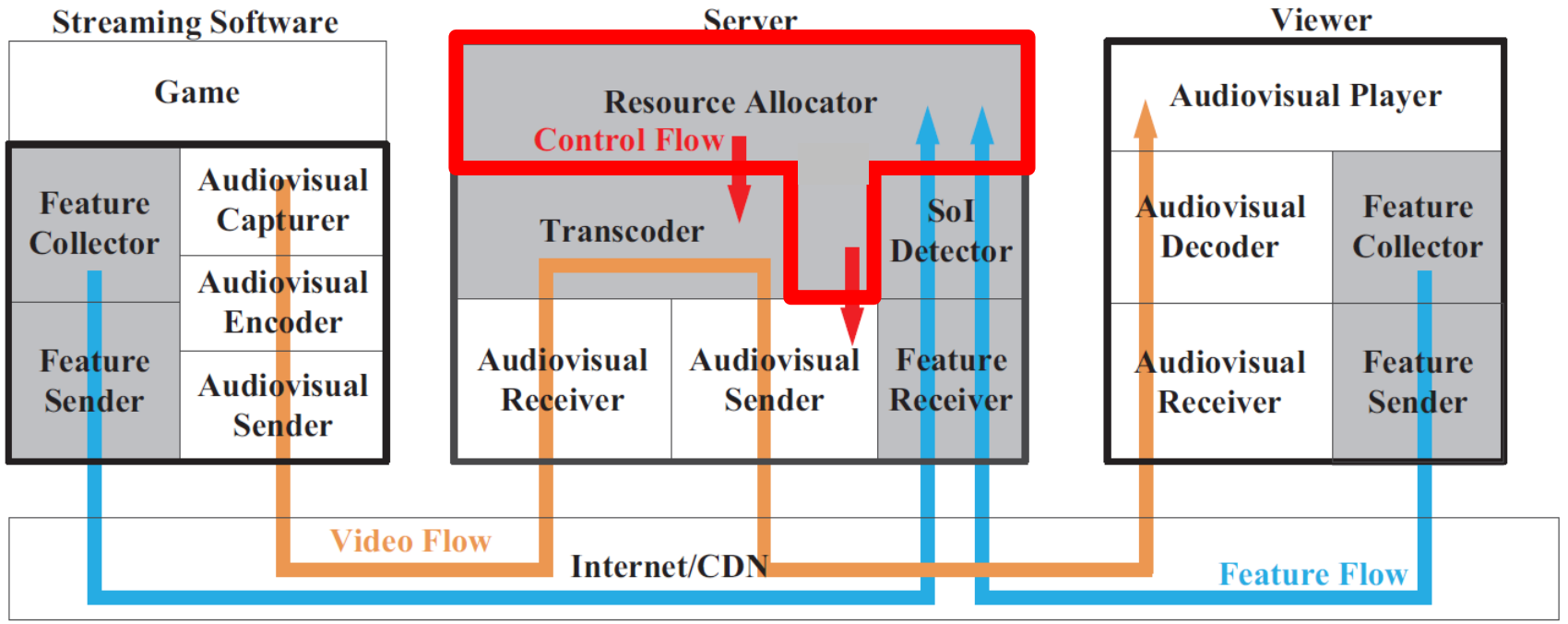
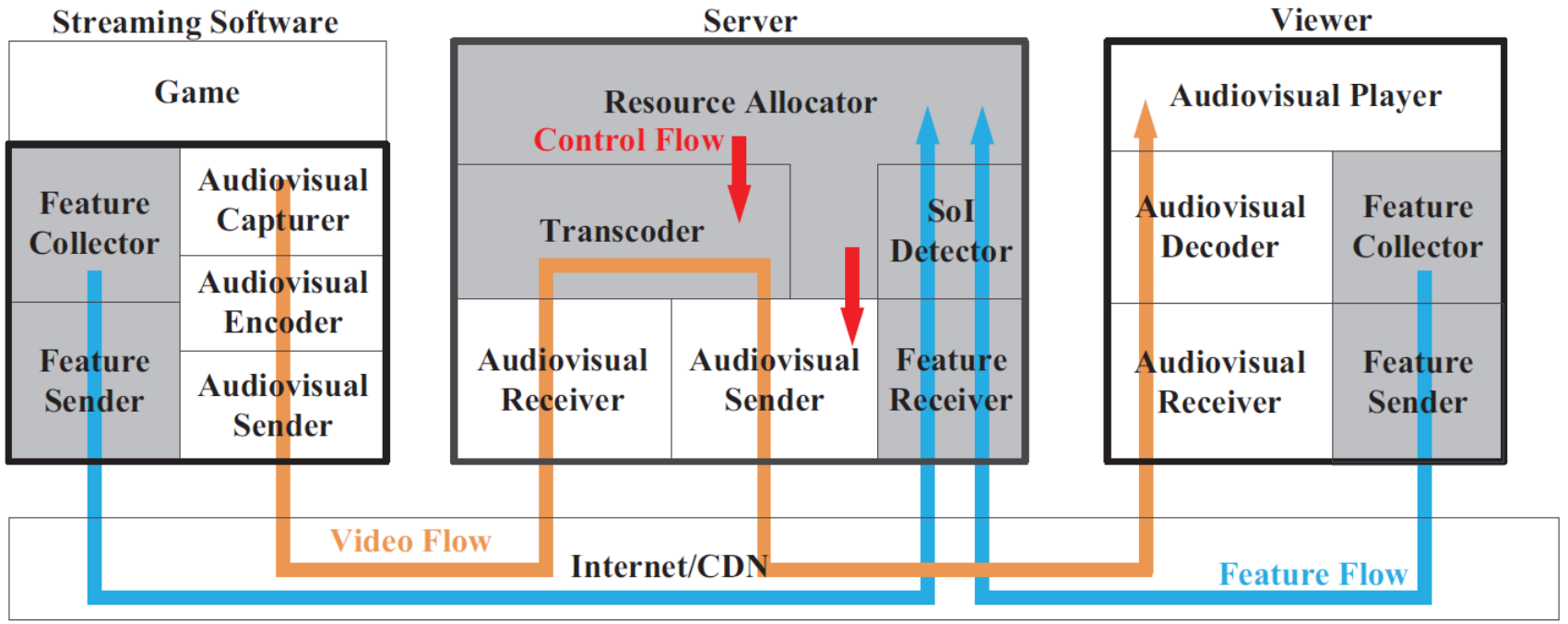


Transcoder

- Transcode the stream



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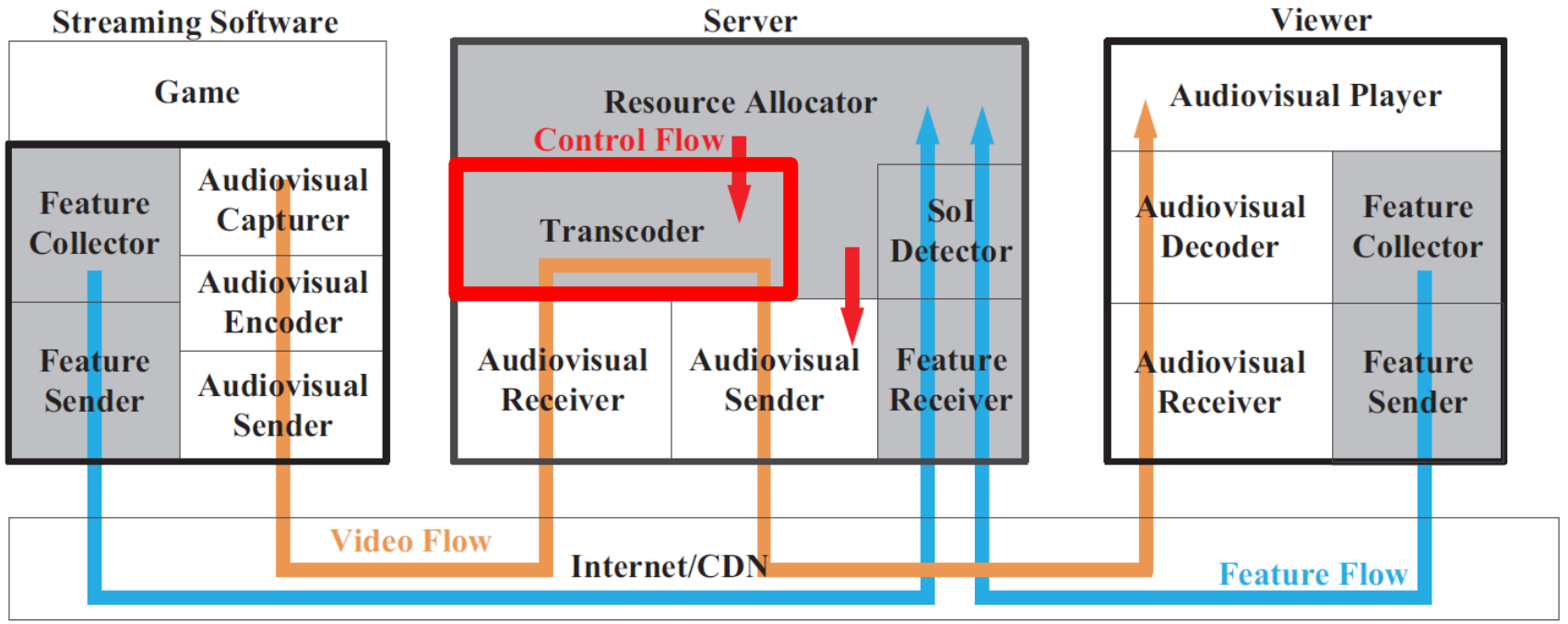
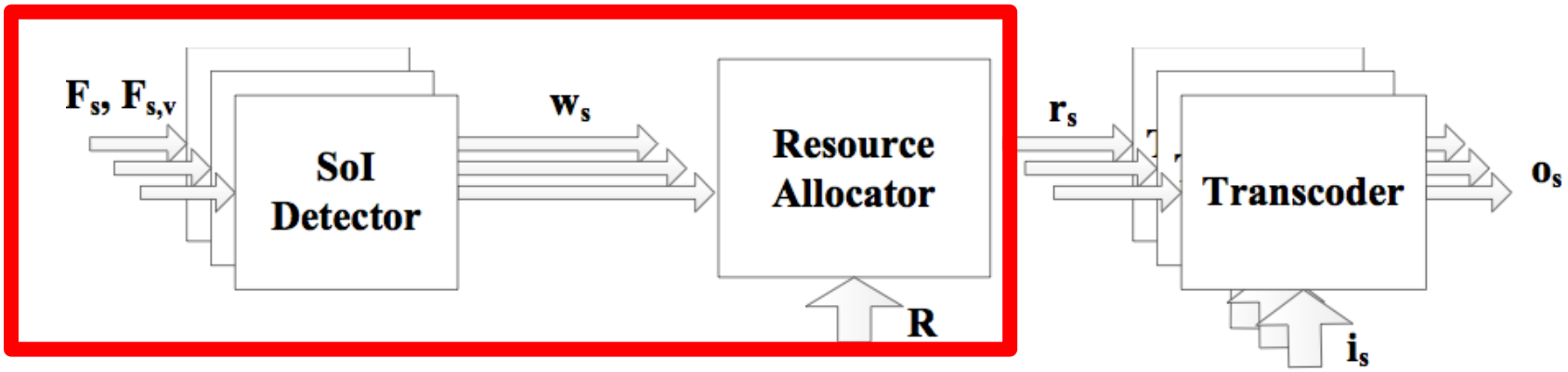


Core Components

- SoI Detector
- Resource Allocator



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SoI Detection

- How to detect SoI?
  - How to detect if viewers are interested?
- From viewers?
  - Ask viewers to manually tell us? Too annoying
  - Automatically? Require mass deploy, privacy issue

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Detect from streamers

How To Detect From Streamer?

- Detect from content (video) [1]?
  - Computationally intensive, not real-time friendly
  - "The segment at 3 hours ago is valuable, to the viewers who've watched it 3 hours ago"
- Detect from other features Our work
  - Features that can be obtained in real-time

[1]. W. Chu and Y. Chou. Event detection and highlight detection of broadcasted game videos. In *Proc. of ACM Workshop on Computational Models of Social Interactions: Human-Computer-Media Communication (HCMC'15)*, Brisbane, Australia, 2015

SoI Detecting Problem

- How to determine SoI weight using features
  - From streamers
  - From viewers (if presented)
- Model the problem as
  - Classification, estimate 0/1
  - Regression, estimate [0, 1]

Features Collected

- CPU usage
- GPU usage
- Context switch
- Streaming bitrate
- Keyboard/mouse input event
- Number of face in webcam
- System sound magnitude
- Microphone sound magnitude
- Name of foreground window

All can be obtained in real-time

But identifying the relations is hard…

Machine Learning

- Use machine learning algorithms
  - Identify the relations between features and SoI
- Which machine learning model to use?[1]
  - Deep Learning?
  - Support Vector Machine?
  - Random Forest?
  - Gradient Boosting Tree?

[1]. Yaser S. Abu-Mostafa, Malik Magdon-Ismail, and Hsuan-Tien Lin. Learning from Data: A Short Course. AMLBook, March 2012

Selected Model

- We choose
  - Random Forest
  - Gradient Boosting Tree
- Both are ensemble models of decision trees
- Efficient in training
  - Unlike SVM and Deep Learning
- Popular
  - Applied in multiple fields

Hyperparameter

- RF-based
  - ***N***, Number of trees
  - ***X***, Maximum number of feature in splitting
  - ***H***, Maximum Depth
- GBT-based
  - ***N***, Number of trees
  - ***E***, Shrinkage (learning rate)
  - ***H***, Maximum Depth
  - ***M***, Subsample

Solution Approach

- Implemented in Python
  - Scikit-learn for Random Forest
  - XGBoost for Gradient Boosting Tree
- Using both regressor and classifier variant of them
  - RFR-based & GBTR-based algorithm
  - RFC-based & GBTC-based algorithm
- We conduct supervised learning
  - Details are given in evaluation

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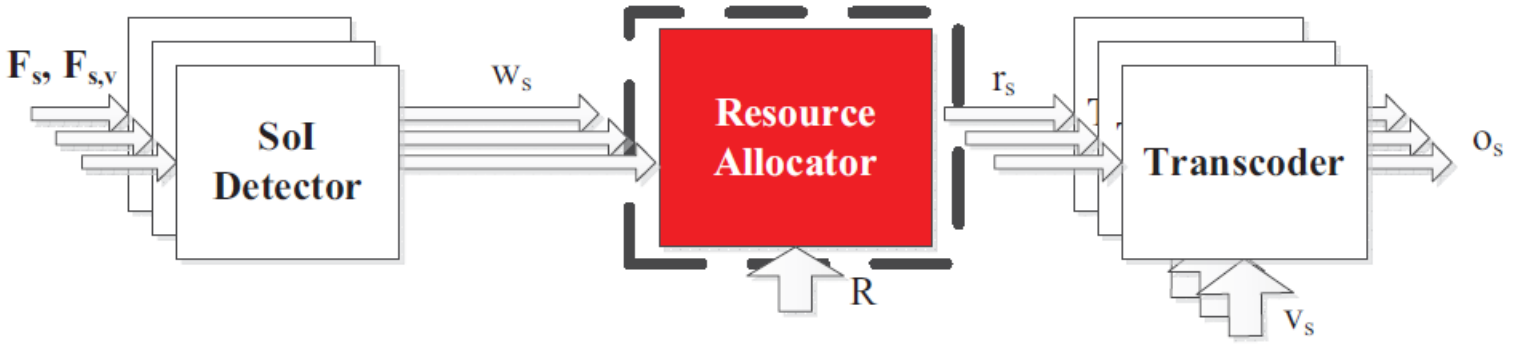
Resource Allocation Problem

- How to allocate resources among streams to maximize viewing quality q_s?
  - Take r_s as the decision variable
- Leverage SoI weight w_s



Connect r_s With q_s

- We adopt a rate-distortion model [1]

$$d_s = D_{0,s} + \frac{\theta_s}{r_s - R_{0,s}}$$

- d_s: distortion in Mean Square Error (MSE)
- $D_{0,s}$, ϑ_s, $R_{0,s}$: model parameters obtained by non-linear regression

[1] X.Zhu, E.Setton, and B.Girod. Congestion-distortion optimized video transmission over ad hoc networks. *Signal Processing: Image Communication*, 20(8):773–783, 2005

Quantifying Viewing Quality

- We use Peak-Signal-to-Noise Ratio (PSNR)
  - $\boldsymbol{q_s = 10 \log_{10} \frac{255^2}{d_s}}$
- The proposed algorithm can utilize other quality metrics with monotonically increasing property

Problem Formulation

$$\text{maximize} \sum_{s=1}^{S} q_s w_s = \sum_{s=1}^{S} 10 \log_{10} \frac{255^2}{D_{0,s} + \frac{\theta_s}{r_s - R_{0,s}}} w_s$$

$$\text{s.t.} \sum_{s=1}^{S} r_s w_s \leq R;$$

$$r_s \in R^+, \forall s = 1, 2, ..., S.$$

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Objective: Maximize the viewing quality of all the viewers in SoI

Problem Formulation

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$$\text{s.t.} \sum_{s=1}^{S} r_s w_s \leq R;$$

$$r_s \in R^+, \forall s = 1, 2, ..., S.$$

Under the constraint that the total bandwidth usage is under R

Derive Closed Form Formula

- Leverage Lagrangian Multiplier method
  - Added $\boldsymbol{\lambda}$
- We get Lagrangian function ***L***

$$\sum_{s=1}^{S}(10\log_{10}\frac{255^2}{D_{0,s}+\frac{\theta_s}{r_s-R_{0,s}}}w_s)+\lambda((\sum_{s=1}^{S}r_sw_s)-R)$$

- Take partial derivative of ***L***

$$\frac{\partial\mathscr{L}}{\partial\lambda}=(\sum_{s=1}^{S}r_sw_s)-R;$$

In order to get the extreme value of L

$$\frac{\partial\mathscr{L}}{\partial r_s}=\lambda+\frac{10\theta s}{\log 10(r_s-R_{0,s})^2(D_{0,s}+\frac{\theta_s}{r_s-R_{0,s}})}$$

S of them

Solving the Formula

- Let $\frac{\partial \mathscr{L}}{\partial r_s} = 0$
- After derivation

$$r_s = R_{0,s} + \frac{-(\lambda \log 10\theta_s) - \sqrt{(\lambda \log 10\theta_s)^2 - 40\lambda \log 10\theta_s^2}}{2(\lambda \log 10 D_{0,s})}$$

- Combine the results above with

$$\frac{\partial \mathscr{L}}{\partial \lambda} = (\sum_{s=1}^{S} r_s w_s) - R = 0$$

The result of the other partial derivative

- We can obtain the optimal $\boldsymbol{\lambda}$
  - Then derive the optimal bitrates for streaming to each viewer ***v*** of streamer ***s***
- **Slow to solve** **There are S + 1 formulas**

A Real-Time Approximation Algorithm

- Solve the problem efficiently
  - With a controllable error of $\boldsymbol{\varepsilon}$
- Called **SoI-based R-D Optimized Algorithm (SoI RDO)**

SoI RDO Algorithm

Algorithm 1 Efficient SoI RDO Algorithm

1: $U \leftarrow 0$, $L \leftarrow -1$ // Upper/lower bounds
2: $\epsilon \leftarrow 10^{-7}$ // Default error
3: **while** $L + \epsilon < U$ **do**
4: $\quad \lambda = (U + L)/2$
5: $\quad$ **for** $\forall s \in S$ **do**
6: $\quad\quad$ Derive all the r_s using λ and Eq. (5)
7: $\quad$ **if** $\exists r_s$, such that $q_s \in \mathbb{C}$ or $r_s < R_L$ or $r_s > R_U$ **then**
8: $\quad\quad$ Adjust U or L accordingly
9: $\quad$ **else if** $\sum_{s \in S} r_s w_s > R$ **then**
10: $\quad\quad U = \lambda$
11: $\quad$ **else**
12: $\quad\quad obj = \sum_{s \in S} q_s w_s$
13: $\quad\quad L = \lambda$
14: if *obj* is undefined, return no answer, o.w. return λ and r_s.

Binary search on proper λ value

Derive all r_s & q_s using λ this round

Check if all r_s and q_s are valid

Check if use too much bandwidth

Calculate objective function

Lemma 1

Lemma 1 (Approximation Gap)**.** *SoI RDO algorithm always finds* $\boldsymbol{\lambda}$ *within a gap of* $\boldsymbol{\varepsilon}$ *to the optimal* $\boldsymbol{\lambda}^*$ *under the given bandwidth constraint* $\boldsymbol{R}$.

- Reason why the quality metrics need to have monotonically increasing property.

Lemma 2

Lemma 2 (Complexity). *Algorithm 1 runs in* $O(S \log \epsilon^{-1})$

- $\log \boldsymbol{\varepsilon^{-1}}$ round of search in worst case
- Each round need to do
  - Derive $\boldsymbol{r_s}$, $\boldsymbol{q_s}$ for every streamer $\boldsymbol{s}$ $O(\boldsymbol{S})$
  - Check if $\boldsymbol{r_s}$ is valid for every streamer $\boldsymbol{s}$ $O(\boldsymbol{S})$
  - Calculate the total consumed bandwidth $O(\boldsymbol{S})$
  - Calculate the objective value $O(\boldsymbol{S})$
- $O(\log \boldsymbol{\varepsilon^{-1}})$ x $(O(\boldsymbol{S}))$ = $O(\boldsymbol{S} \log \boldsymbol{\varepsilon^{-1}})$

Outline

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Open Source Testbed

- Streaming software: OBS [1]
- Streaming server: NGINX [2] with RTMP plug-in
- Viewer: SMPlayer [3]

[1] https://obsproject.com/
[2] http://nginx.org
[3] http://smplayer.sourceforge.net/

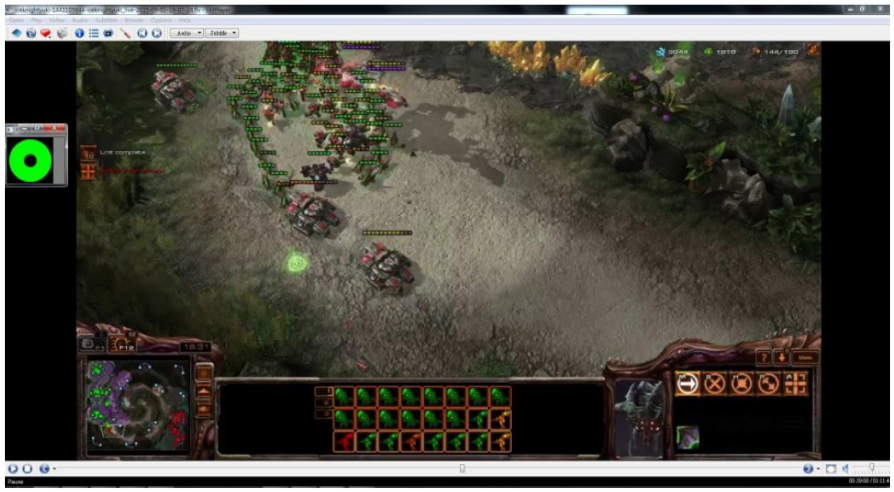
SOI DETECTOR EXPERIMENT SETUP

Collecting the Dataset

- Collected at a League of Legend tournament
- 50 participants, 10 matches
  - 100 video & trace
  - 207004 seconds in total
- 81 valid video & trace
  - 162842 samples

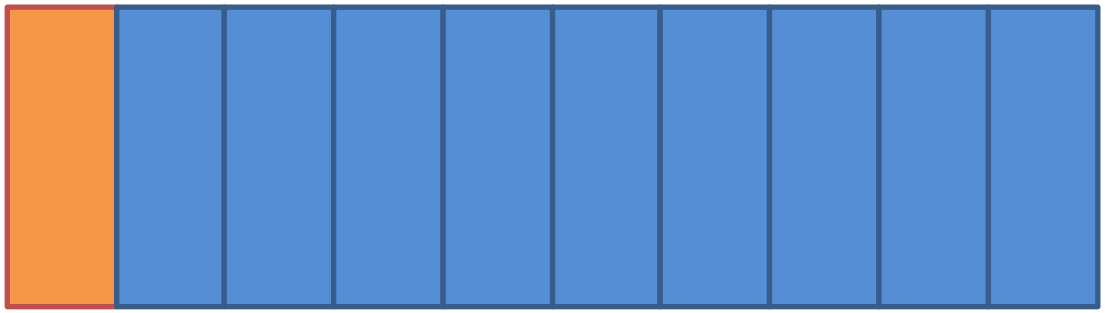
Marking SoI Ground Truth

- We recruited 17 viewers to mark SoI manually
  - 10 videos
  - With a modified video player
- Collected 74 logs
  - Cover 27010 samples



Partition the Dataset

- 90% as training dataset
  - Used in hyperparameter tuning
  - 18677 samples
- The rest 10% as evaluation dataset
  - 2076 samples



Performance Metrics

- Classification
  - F-measure = $2 \cdot \frac{precision \cdot recall}{precision + recall} \in [0, 1]$
  - Training Time
- Regression
  - R-squared score $\in [1, -\infty]$
  - Training Time

Hyperparameter Tuning

- 10-fold cross validation
- Grid search
- RF-based
  - ***N***: [30 ,60, 120, 240, 480]
  - ***X***: [5, 10, 20, 40]
  - ***H***: [10, 20, 40, 80, 160]
- GBT-based
  - ***N***: [5, 10, 20, 40, 80]
  - ***E***: [0.01, 0.05, 0.1, 0.2, 0.4]
  - ***H***: [5, 10, 20, 40, 80]
  - ***M***: [0.5, 0.6, 0.7, 0.8, 0.9]

The Optimal Hyperparameter

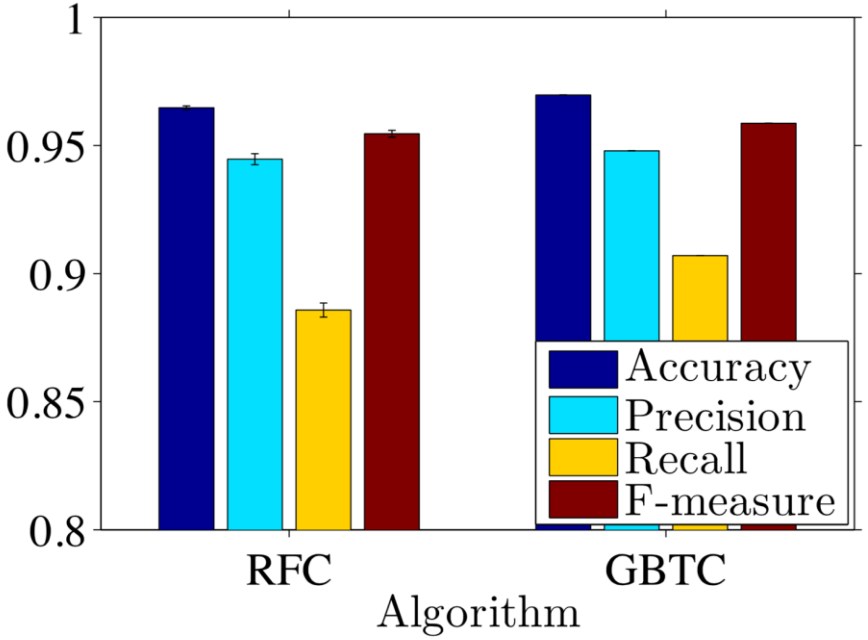
- RFR-based algorithm
  - ***N***: 240, ***X***: 5, ***H***: 40
- GBTR-based algorithm
  - ***N***:80, ***E***: 0.2, ***H***: 10, ***M***: 0.9
- RFC-based algorithm
  - ***N***: 480, ***X***: 5, ***H***: 80
- GBTC-based algorithm
  - ***N***: 80, ***E***: 0.2, ***H***:80, ***M***: 0.7

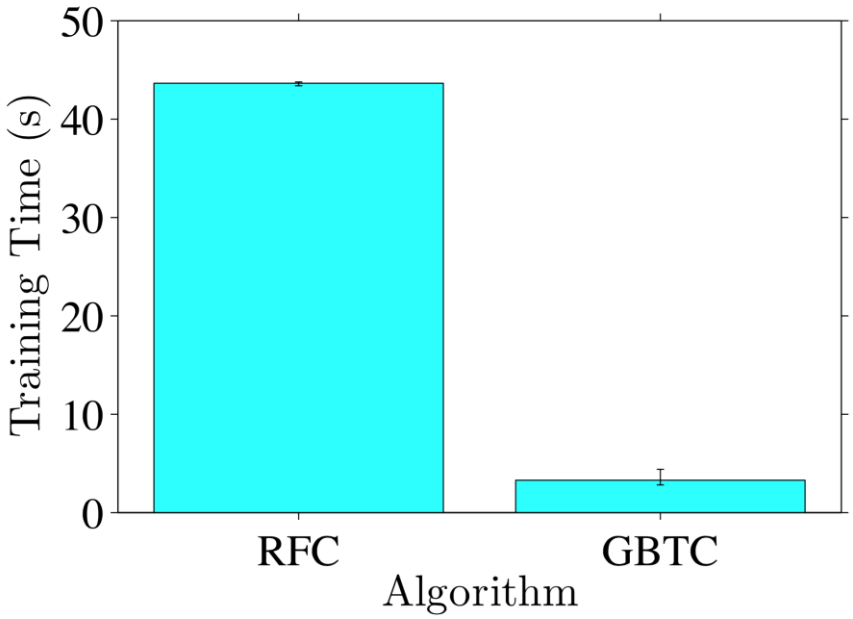
Use them in evaluation

SOI DETECTOR EXPERIMENT RESULT

RFC-based & GBTC-based Algorithm

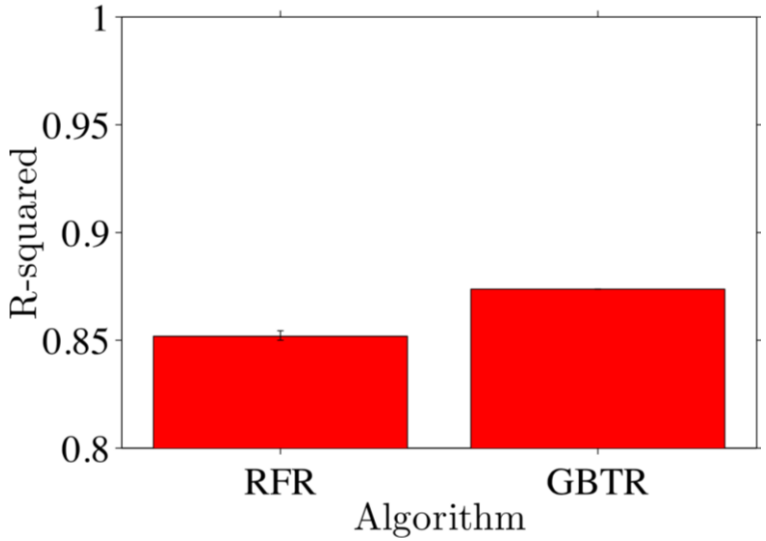
- Over 0.95 F-measure score
- Both terminated under 42 seconds
  - Less than 5 seconds for GBTC

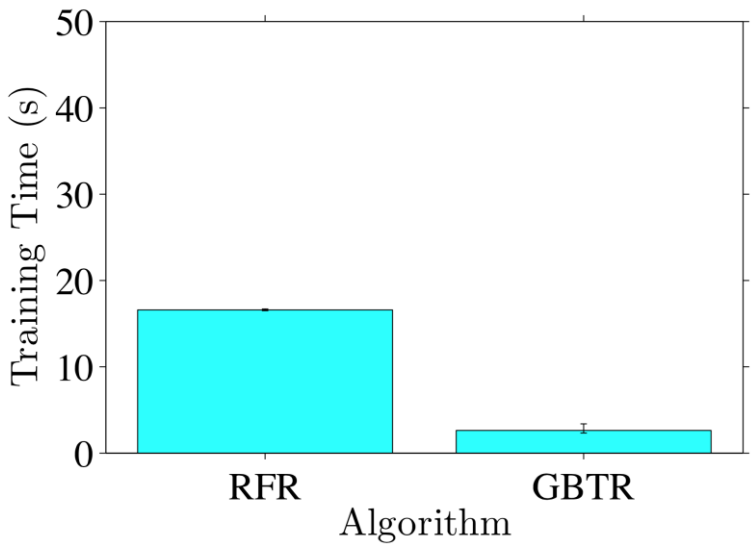




RFR-based & GBTR-based algorithm

- Over 0.85 in R-squared
- Both algorithm terminated under 20 seconds





Observation

- All algorithms provide good result
  - GBT-based algorithm generally gives better result
- GBT-based algorithm have shorter training time
  - Not what we expect
  - XGBoost leverage up to 62 cores in our experiment
  - Scikit-learn's RF implementation only use single core

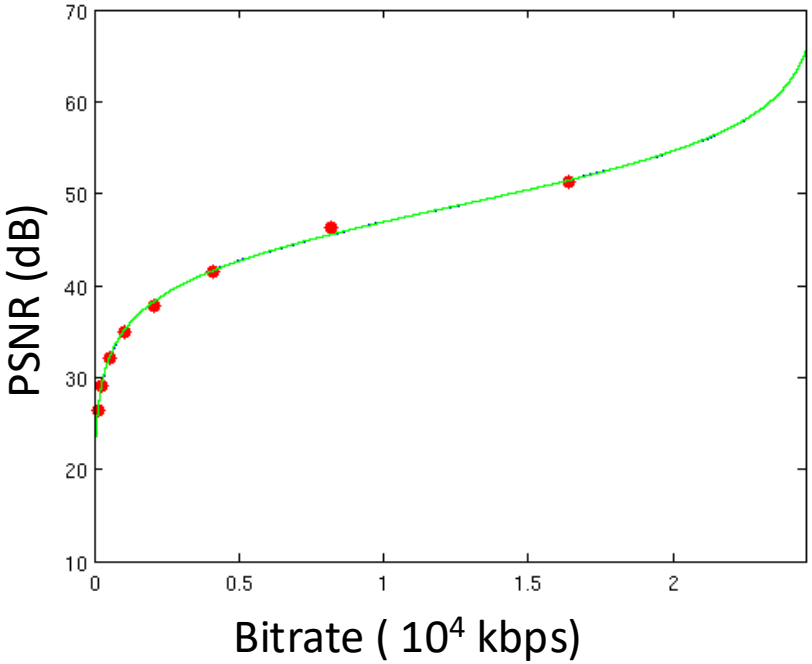
RESOURCE ALLOCATOR EXPERIMENT SETUP

Allocator Simulation Setup

- We captured 8 game streamed on our testbed
  - Age of Empires II
  - Spellweaver
  - Hearthstone: Heros of Warcraft
  - Minecraft
  - Starcraft II
- Resolution between 720p and 1080p

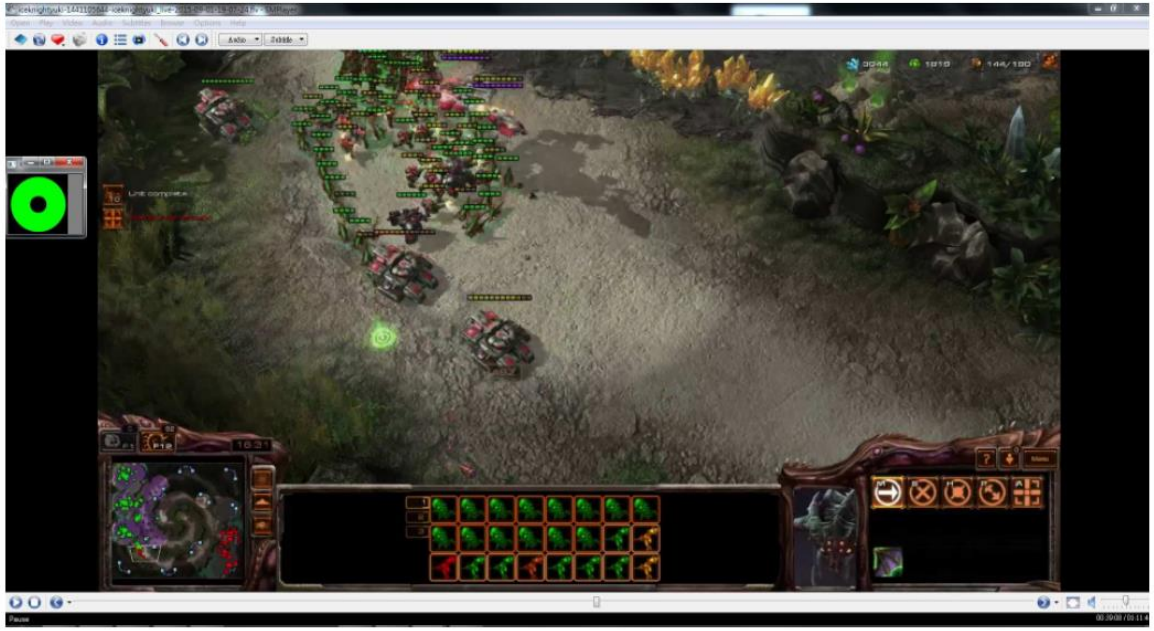
Allocator Simulation Setup (cont.)

- Transcode them into different bitrates
  - Obtain the PSNR value
  - Perform non-linear regression to get the R-D model parameters



Allocator Simulation Setup (cont.)

- We recruited several viewers to watch the recorded live stream session
  - Mark SoI
  - 14 logs in total



Simulator & Baseline

- Simulator is implemented in Python
- SoI RDO algorithm is implemented in C
- Two baseline solution
  - **Equal Share (ES)**: equally divides bandwidth between all viewers **State-Of-The Art live game streaming solution**
  - **R-D Optimized (RDO)**: optimized in R-D sense, but does not take SoI into consideration

Quantify the benefit of SoI driven allocation

- Also an implementation of optimal algorithm
  - In Matlab, as a benchmark of SoI RDO

Performance Metrics

- Expected quality
  - The objective value reported by algorithm
- Actual quality
  - The objective value reported by simulator
- Running time
  - Runtime of solving the resource allocation problem
- Expected consumed bandwidth
  - Reported by algorithm
- Actual consumed bandwidth
  - Reported by simulator
- Network overhead
  - Network traffic generated by feature senders

Experiment Parameters

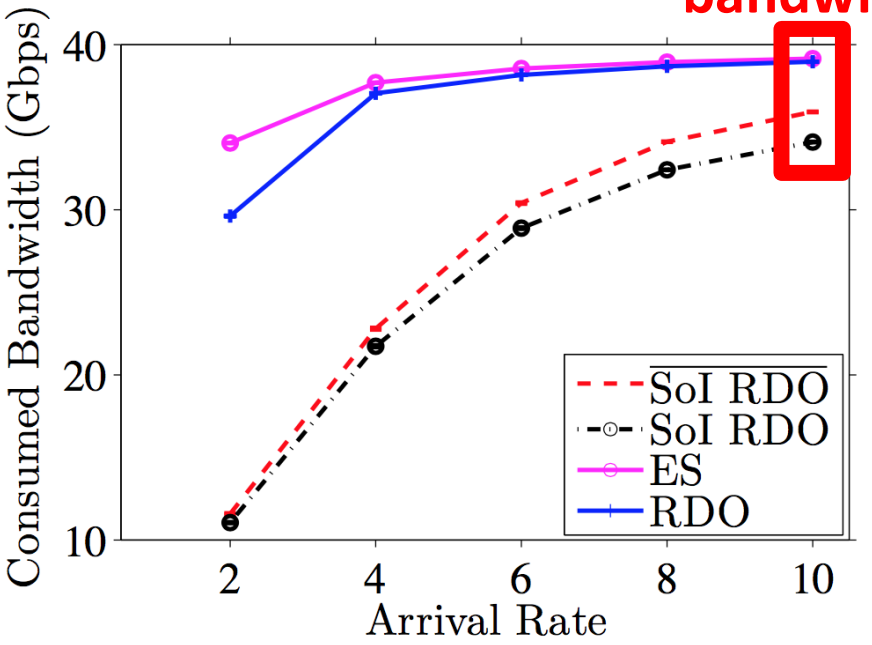
- 6 hour long simulations
- Poisson arrival rate of viewers in each stream
  - {2, 4, 6, 8, 10} per minutes
- Number of stream
  - {16, 32, 64, 128, 256}
- Total outbound bandwidth
  - {10, 20, 40, 80, 160} Gbps
- Interval of invoking resource allocator
  - {1, 2, 5, 10, 60} seconds

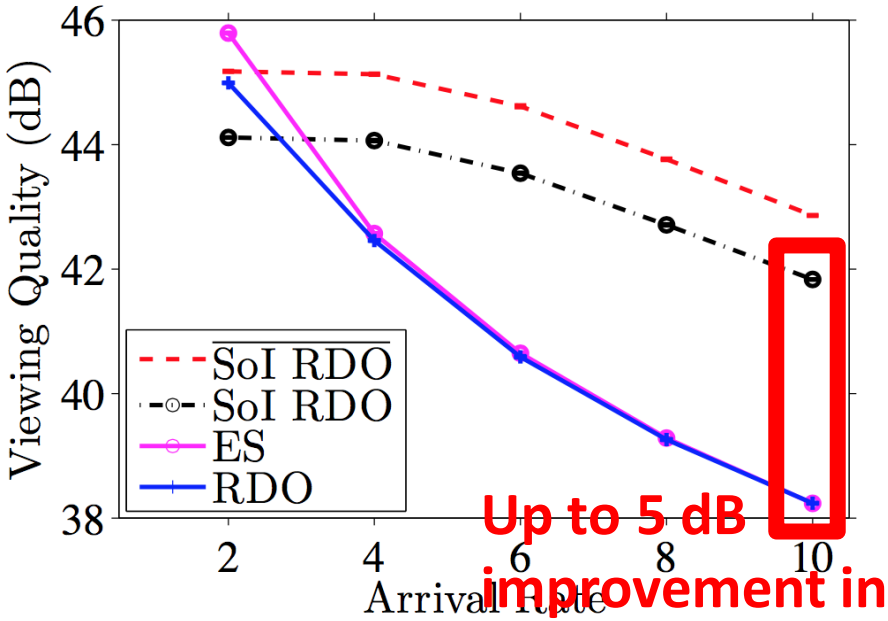
RESOURCE ALLOCATOR RESULTS

Our Algorithm Outperforms RDO and ES

- Different viewer arrival rate

With less consumed bandwidth



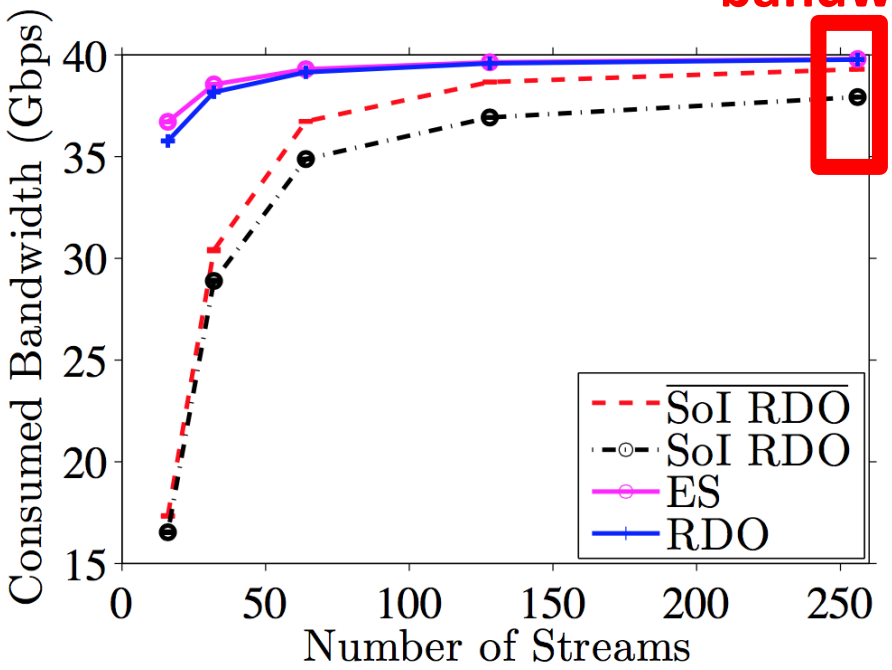


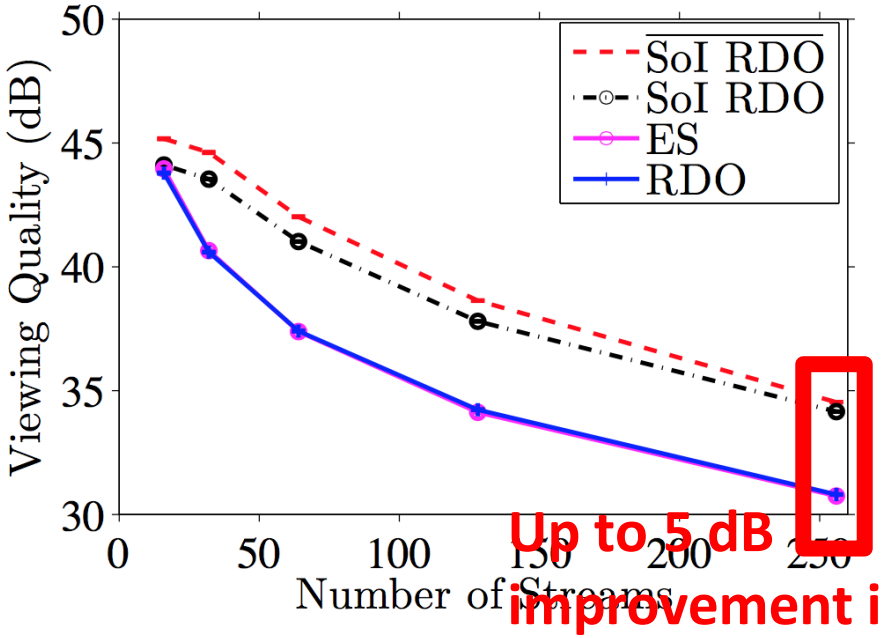
Up to 5 dB improvement in viewing quality

Our Algorithm Outperforms RDO and ES

- Different number of stream

With less consumed bandwidth

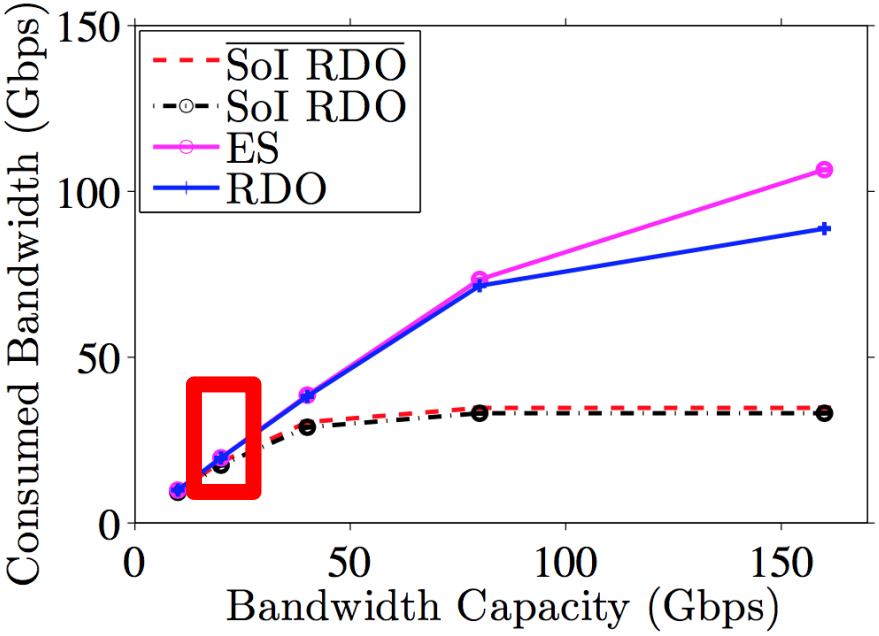


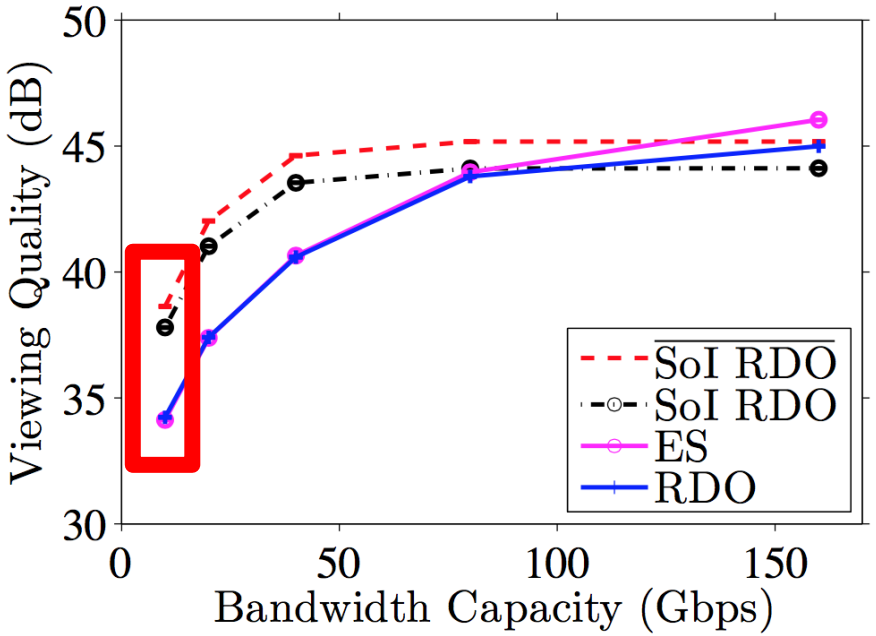


Up to 5 dB improvement in viewing quality

Our Algorithm Outperforms RDO and ES

- Different bandwidth capacity

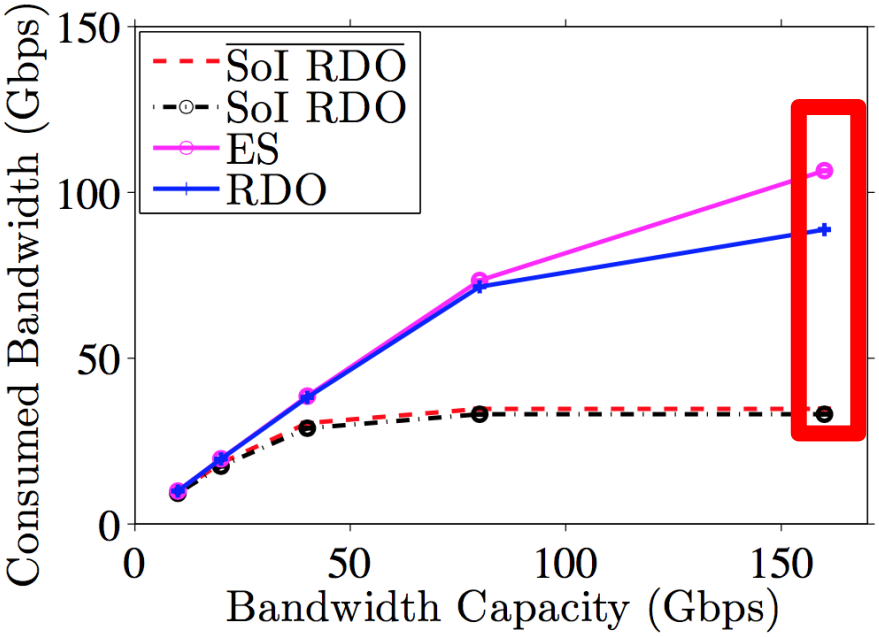


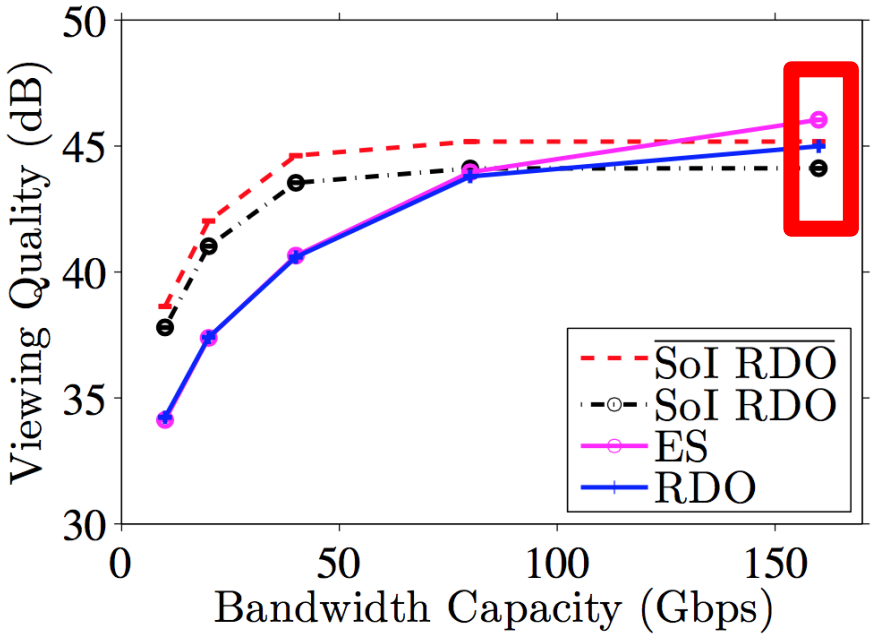


Better quality under the same bandwidth usage

Our Algorithm Outperforms RDO and ES

- Different bandwidth capacity

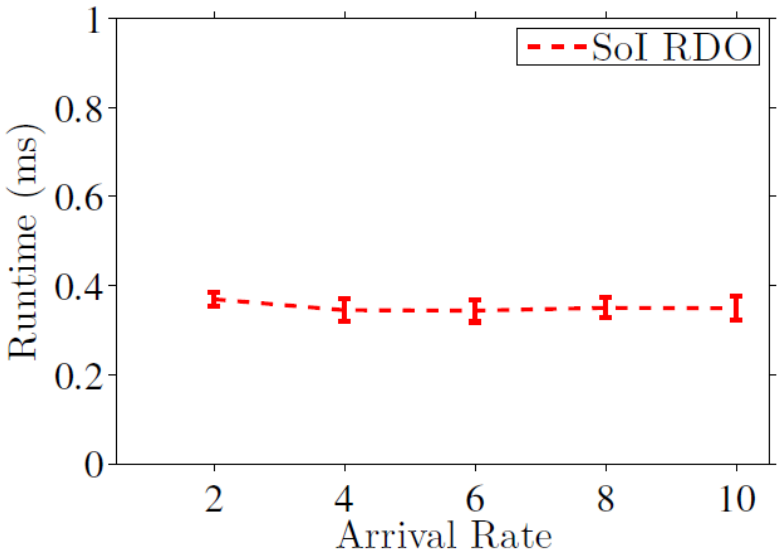


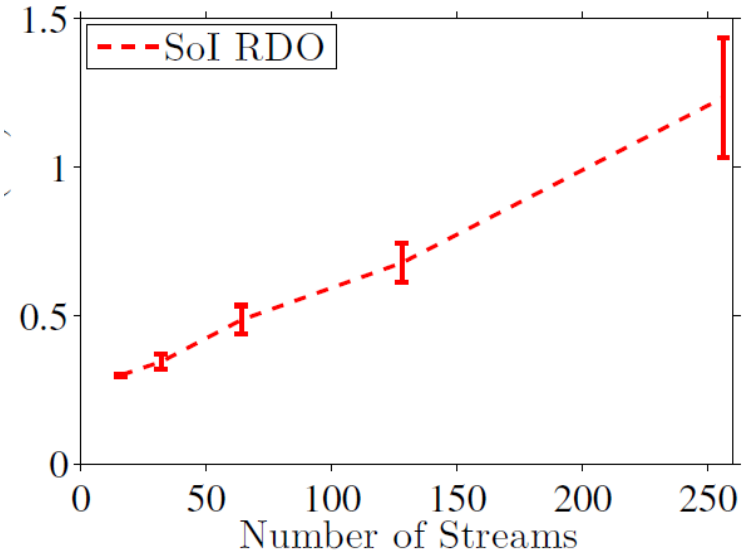


Slightly outperformed by ES and RDO, but that was with significantly larger bandwidth consumption

Our Algorithm Scales Well

- Always below 1.5 ms
  - 100+ thousand viewers
- Matlab solution may take over 6 minutes
  - With 58% chance of feasible solution





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Conclusion

- We proposed the concept of **Segment of Interest (SoI)**
  - New possibility for optimization
- We build an open source testbed
  - Collect real world traces
- We develop accurate SoI detector for MOBA game
  - Up to 0.95 F-measure and 0.87 R-squared score
- Efficient SoI driven resource allocation algorithm
  - Outperforms the current solution up to 5 dB

A SHORT LIVE DEMO OF OUR SYSTEM

Future Work

- Consider device capability in SoI detector
  - Only homogeneous device in evaluation
- Leverage features collected from viewers
  - More fine-grained optimizations
- Resource allocator with finer transcoder control
  - Not only bandwidth, e.g., with FPS, resolution options
- Integrate with a real transcoder
- Provide API for deep integration with game engines

Research Highlight

- **T. Fan-Chiang**, H. Hong and C. Hsu, "Segment-of-Interest Driven Live Game Streaming: Saving Bandwidth Without Degrading Experience", in **Proc. of ACM Annual Workshop on Network and Systems Support for Games (NetGames '15)**
- Y. Huang, M. Lee, **T. Fan-Chiang** and C. Hsu, "Minimizing Flow Initialization Latency in Software Define Networks", in **Prof. of Asia-Pacific Network Operations and Management Symposium (APNOMS'15)**
- H. Hong, **T. Fan-Chiang**, C. Lee, K. Chen, C. Huang and C. Hsu, "GPU Consolidation for Cloud Games: Are we There Yet?", in **Proc. of ACM Annual Workshop on Network and Systems Support for Games (NetGames '14)**
- C. Mao, **T. Fan-Chiang**, M. Lee and C. Hsu, "Taming Flow Initialization Delay in Multi-Site Software Defined Enterprise Networks", in preparation for **IEEE/ACM Transaction on Networking (TNET)**
- TMM submission (based from this thesis)

THANK YOU

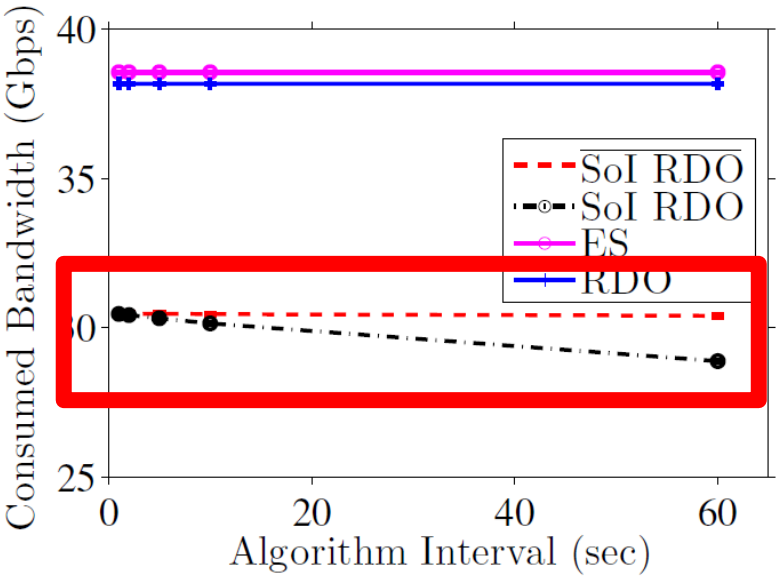
Q & A

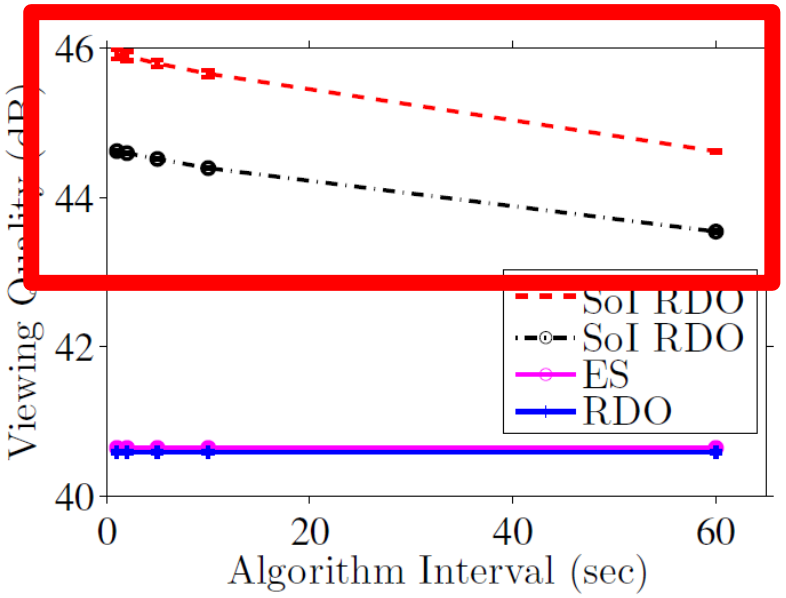
tyfanchiang92@gmail.com

BACKUP SLIDES

Implication Of Calling Interval

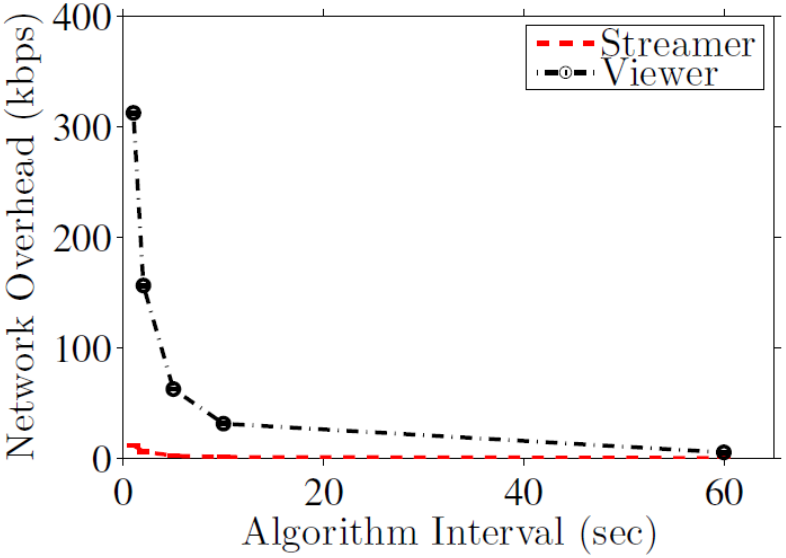
- Slightly better quality and more bandwidth consumption

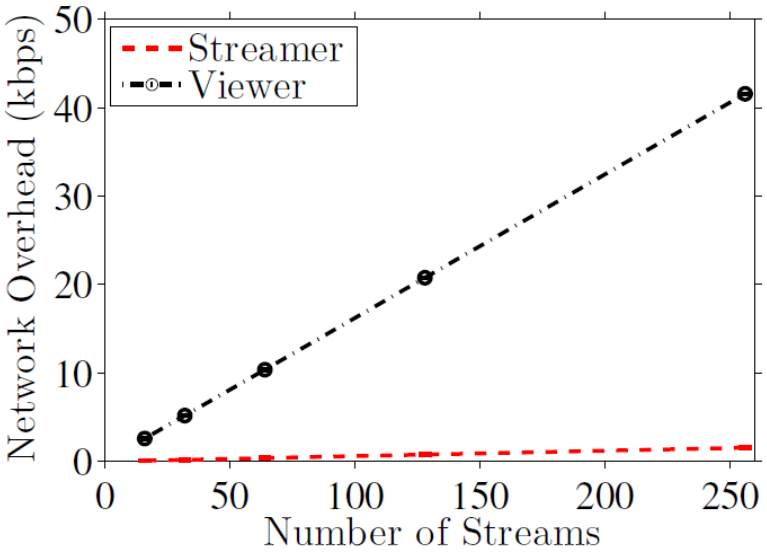




Negligible Network Overhead

- Just around 300 kbps with 12000+ viewers



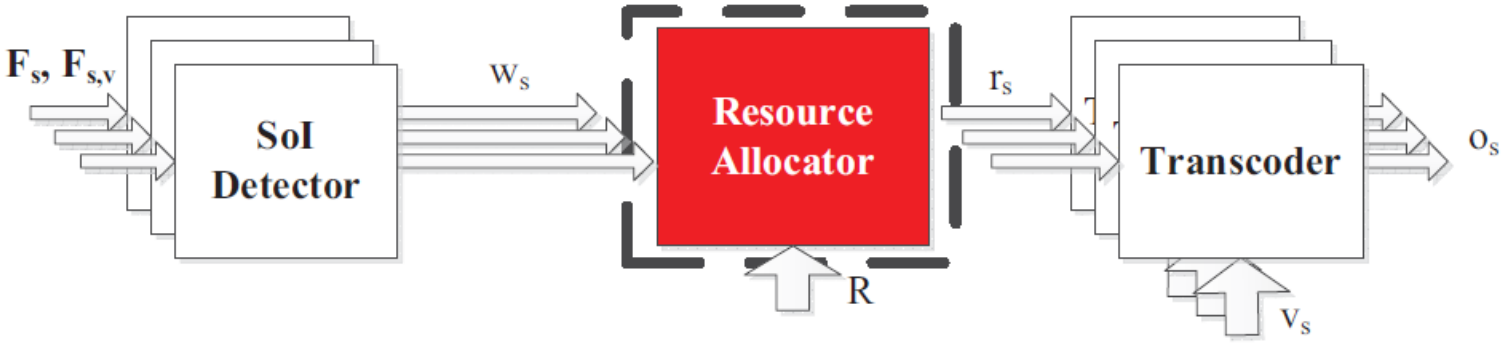


SoI-Driven Streaming Platform

- Develop SoI-driven streaming platform
- Answer three question
  - How to detect SoI efficiently?
  - How to allocation resources among channels?
  - How to perform transcode on the streaming videos?

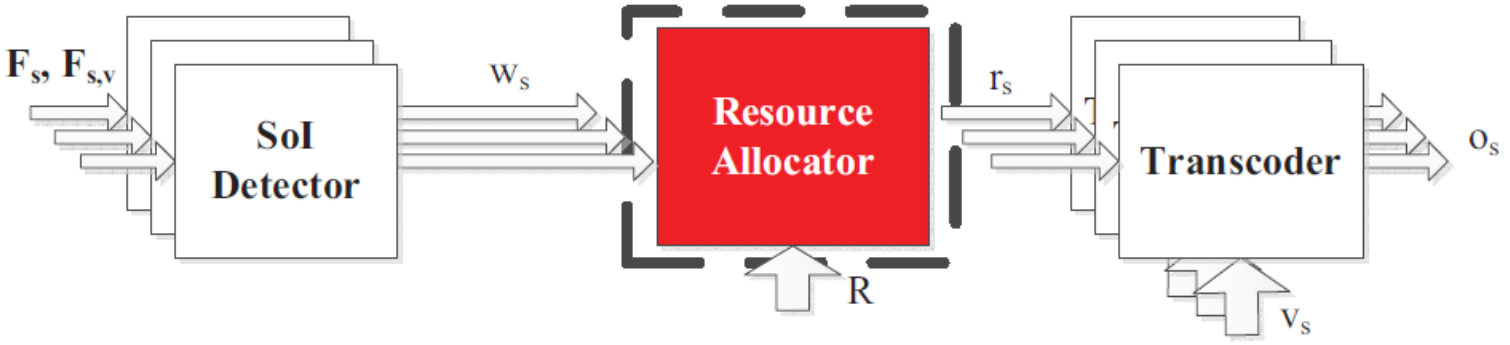
Notations

- The system collects
  - A set of features F_s from streamer s
  - A set of features $F_{s,v}$ from viewer v of streamer s
- SoI detector take F_s and $F_{s,v}$ as input
  - Output SoI weight w_s for current segment

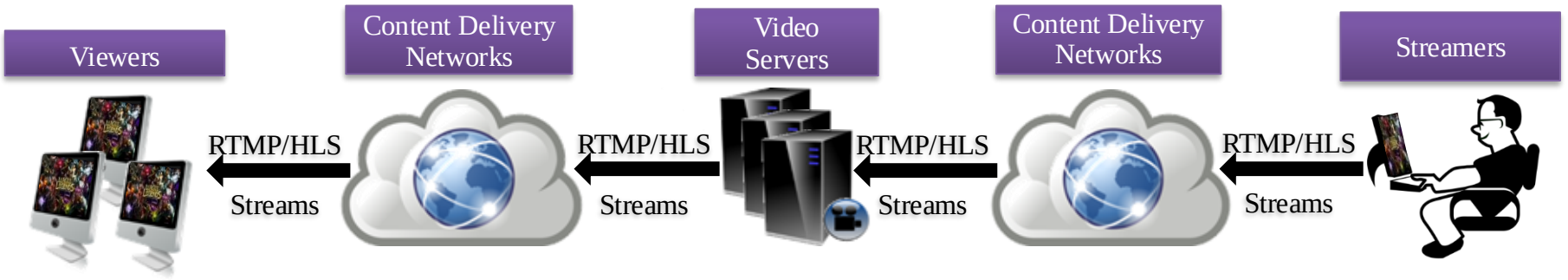


Notations

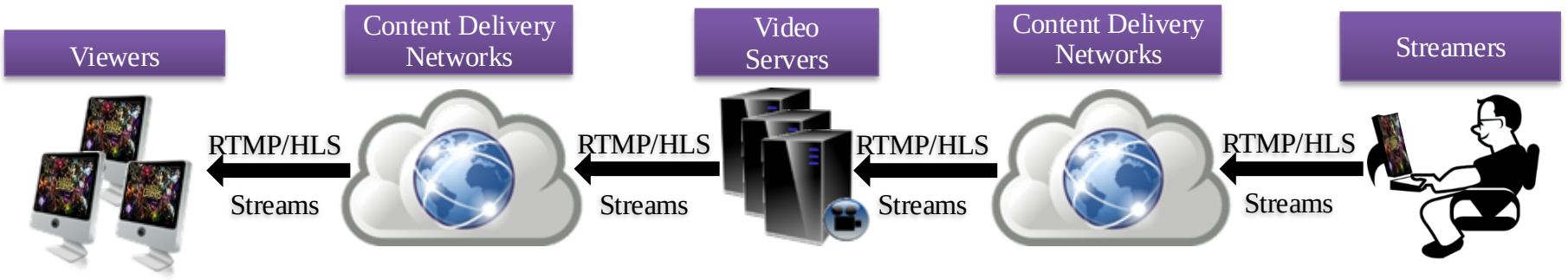
- Resource allocator take all the w_s and bandwidth capacity R as input
  - Output r_s as the bitrate for video segment v_s from s
- Transcoder use r_s as parameter to transcode v_s
  - Output o_s stream to viewers



WHY DO LAG HAPPENS?

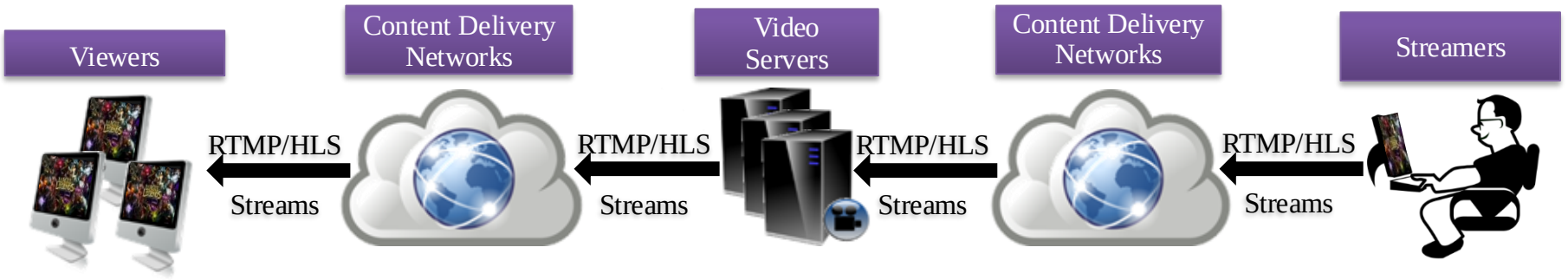


Reason 1: Server Too Busy



Reason 1: Server Too Busy

- Too many viewers



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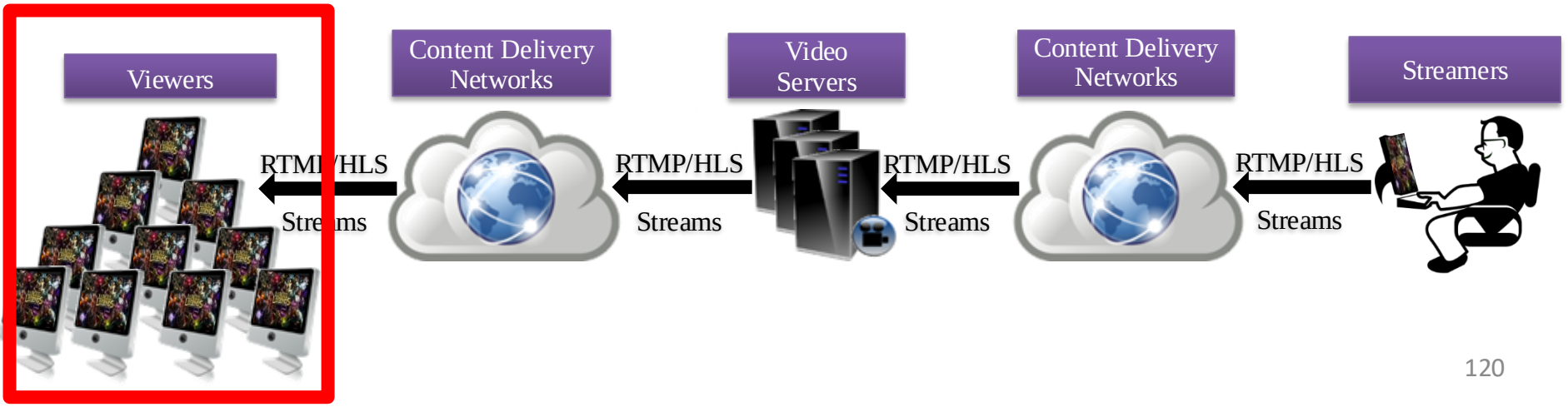
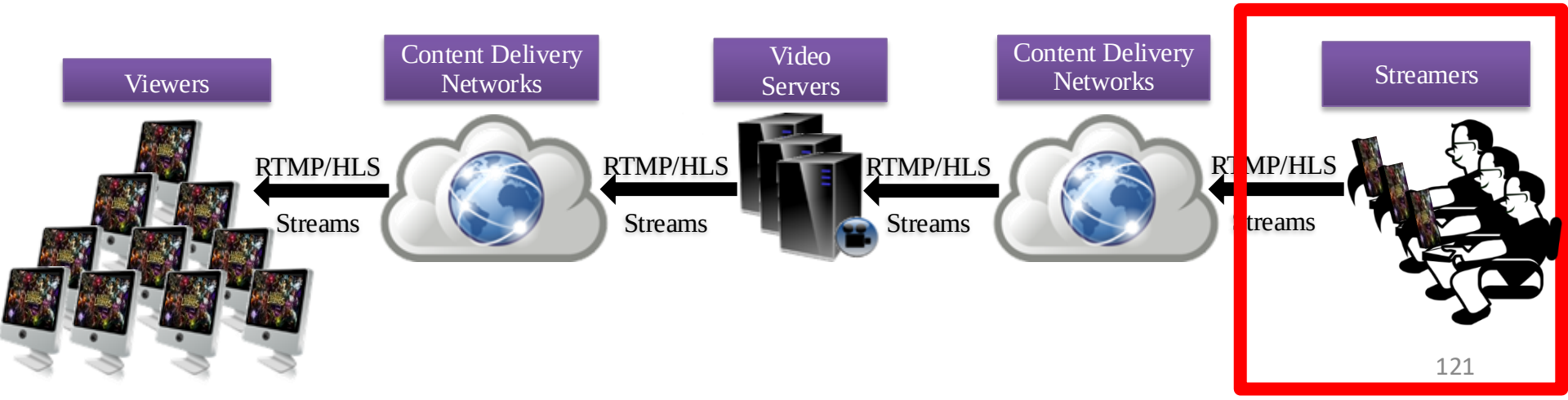


Reason 1: Server Too Busy

- Too many viewers
- Too many streamers
  - Too many transcode workload



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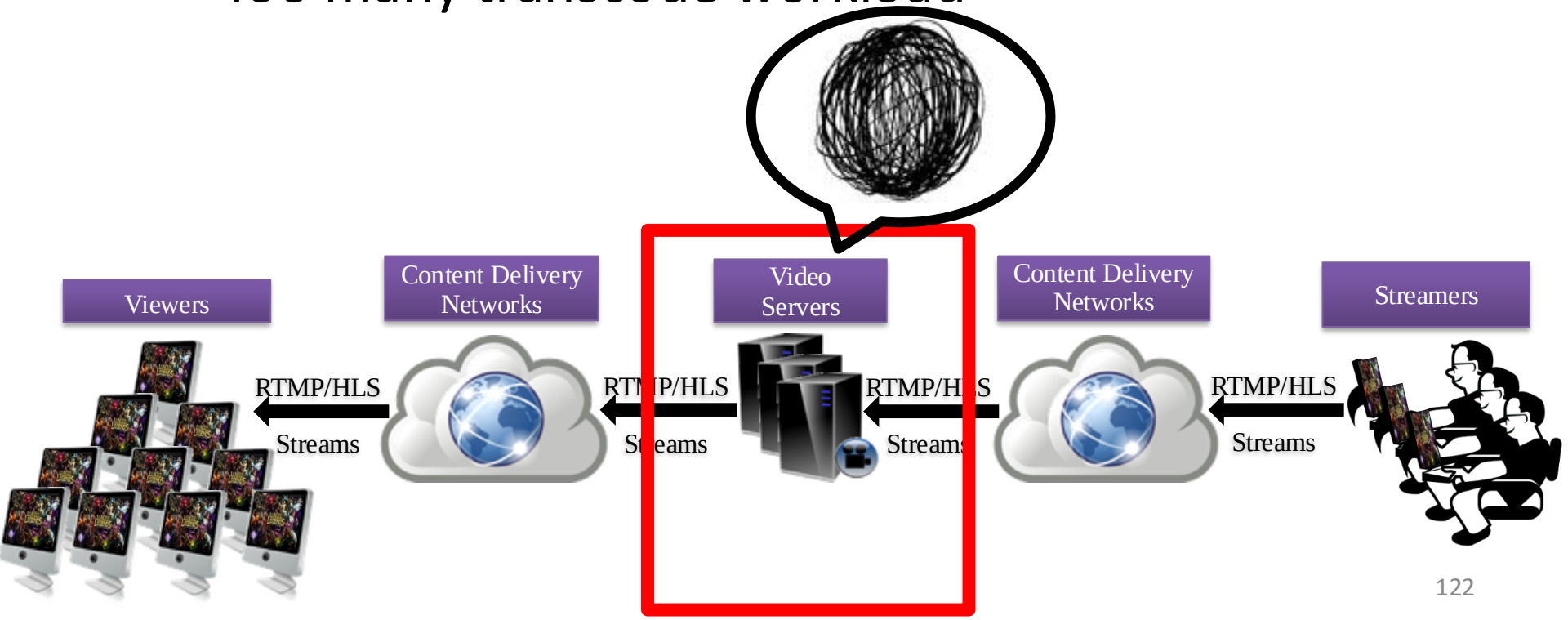
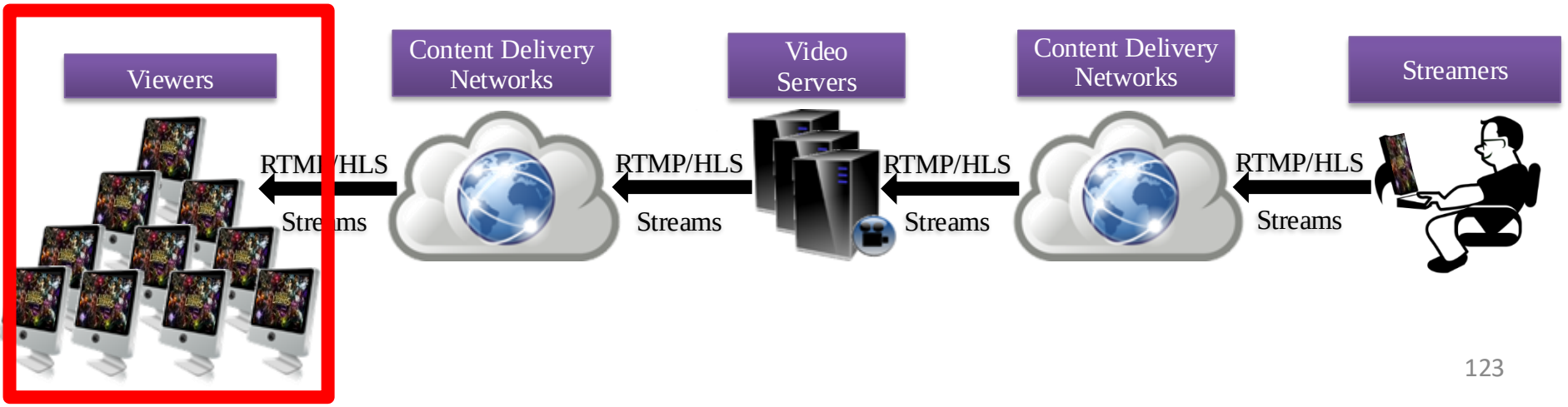


Reason 2: Outbound Bandwidth

- Too many viewers



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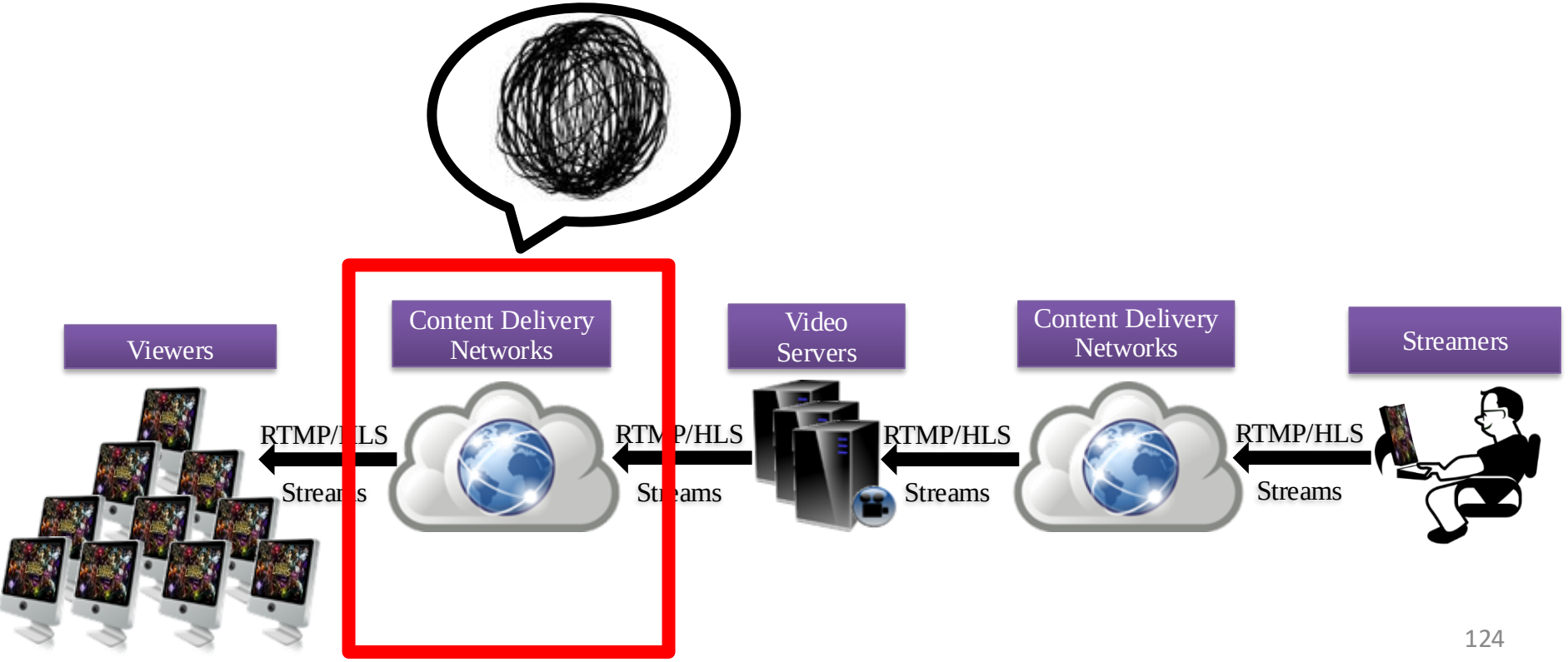


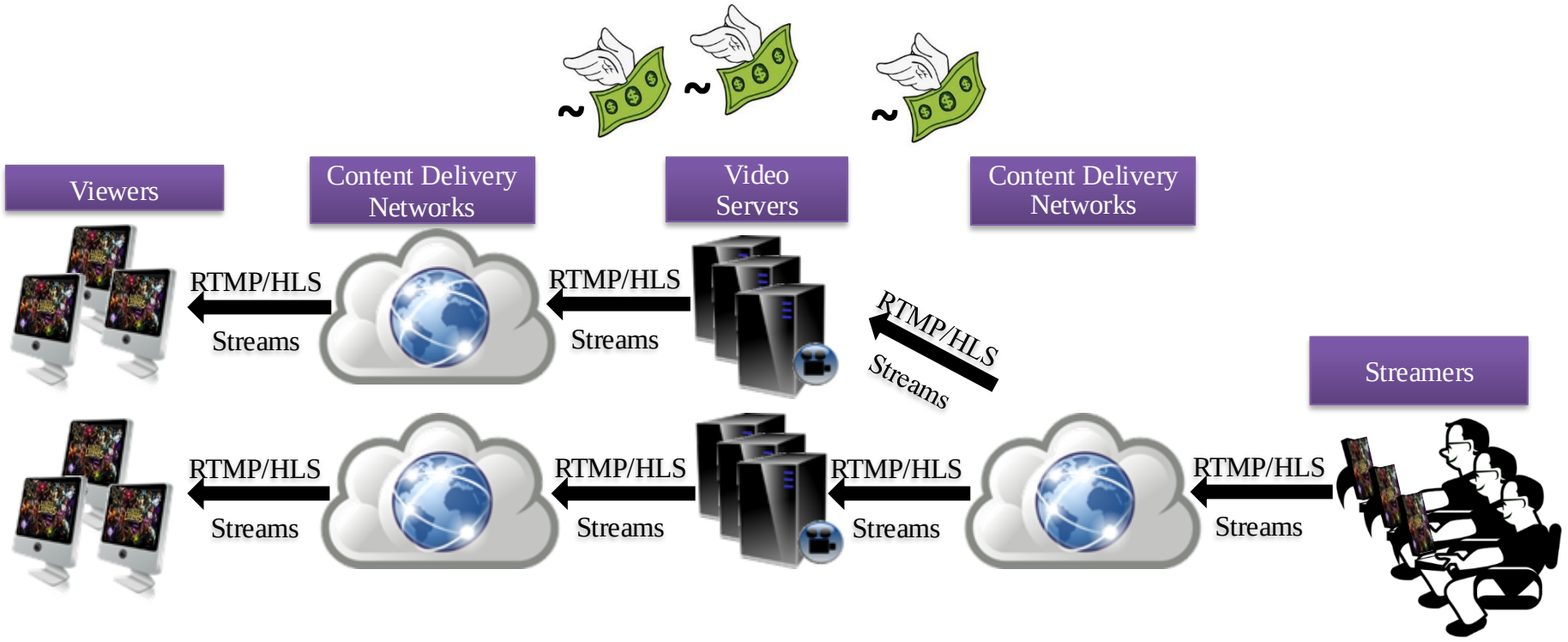
POSSIBLE SOLUTION

Add more resource

Reduce the video quality

Add More Resource

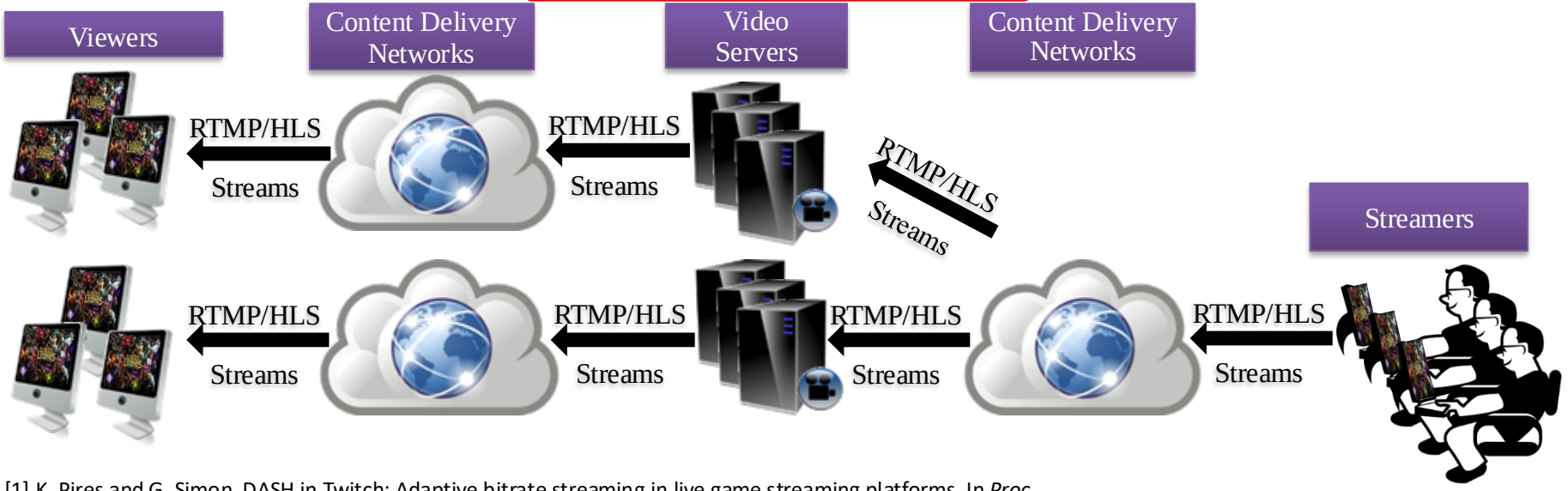
- Twitch upgraded it's transcoding server in 2014
  - Also doubled it's CDN bandwidth in Europe region



Add More Resource

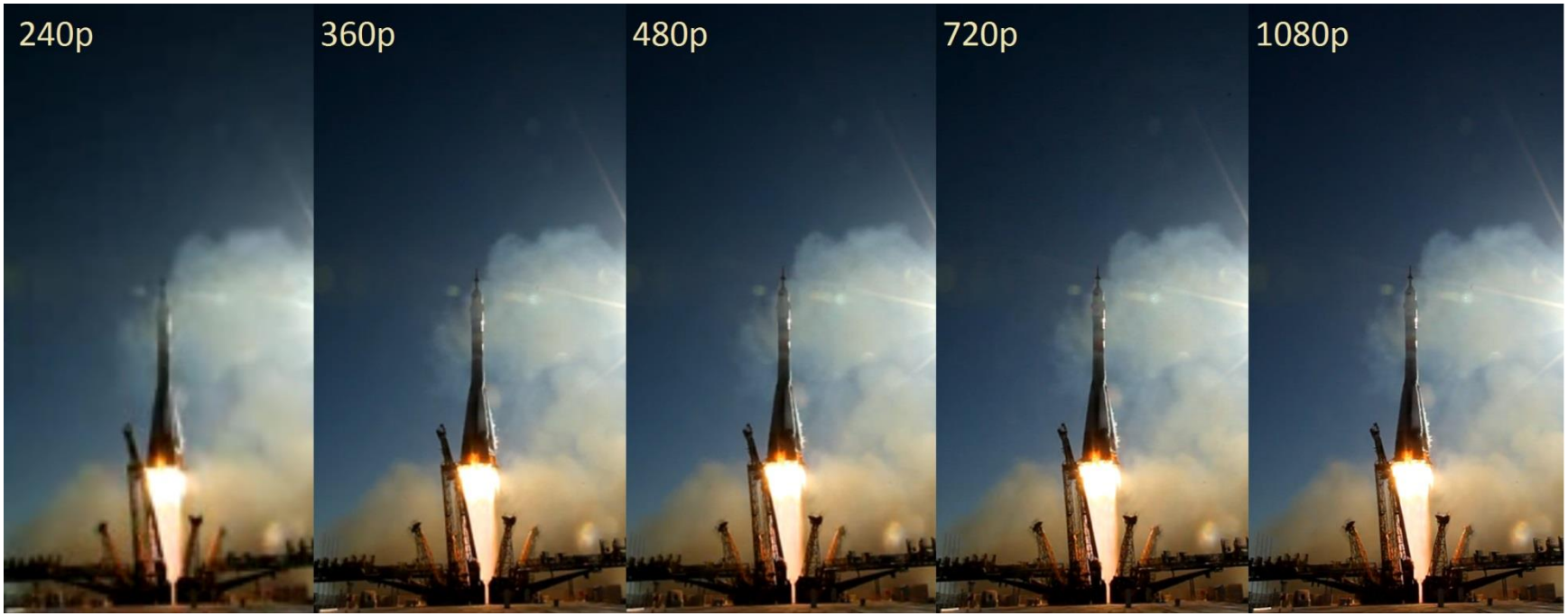
- Twitch have avg 1Tbps bandwidth usage in 2014 [1]
  - May cost as much as $ 11.34 million per month

Bad for business

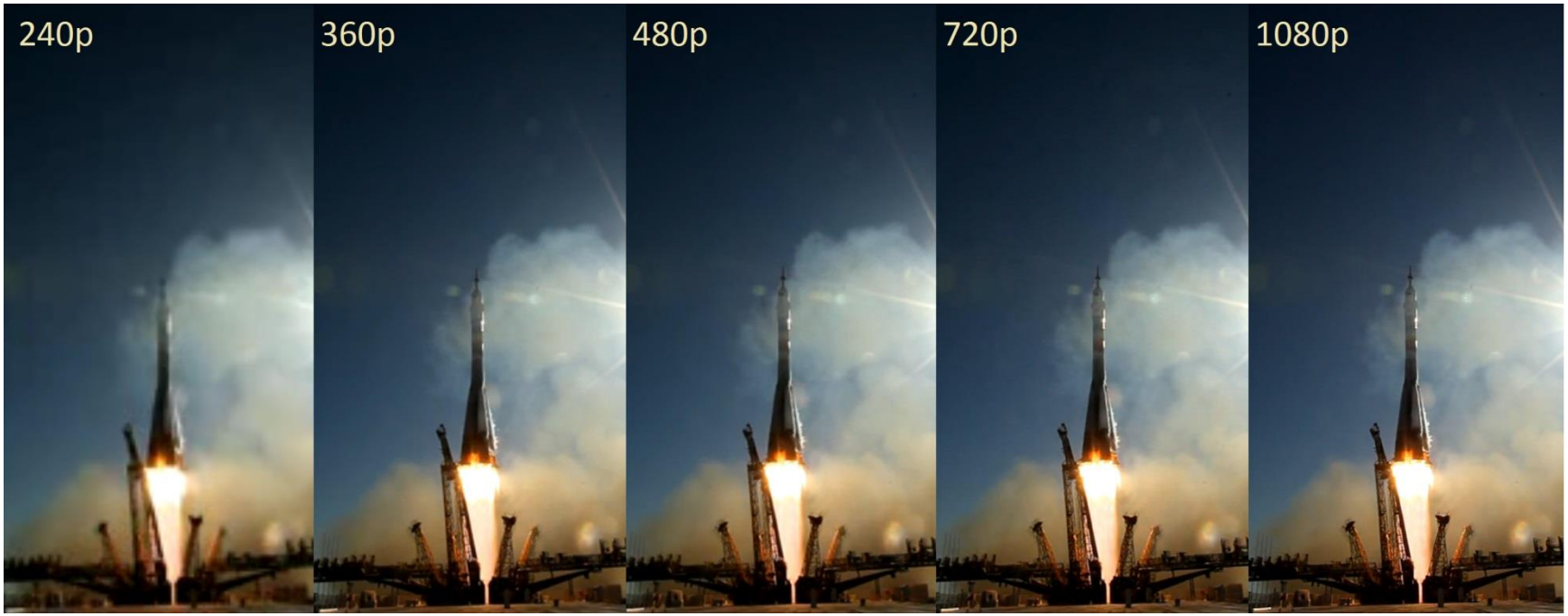


[1] K. Pires and G. Simon. DASH in Twitch: Adaptive bitrate streaming in live game streaming platforms. In *Proc. of ACM Workshop on Design, Quality and Deployment of Adaptive Video Streaming (VideoNext'14)*

Lower Video Quality



Lower Video Quality



How to do this without degrading user experience?

How To Leverage SoI

- Devote more resource into streaming SoI
  - Lower the quality of non-SoI if necessary
- Higher user experience
- Lower bandwidth consumption

How To Leverage SoI

- Devote more resource into streaming SoI
  - Lower the quality of non-SoI if necessary
- Higher user experience
- Lower bandwidth consumption

Wait, how to determine SoI?

Detecting SoI

- The game is running on the machine of streamer
  - Unlike other kind of live streaming
- Collect features in the system
  - CPU/GPU usage, keyboard input event…e.t.c.
  - Use these features to help us determine