Department of Computer Science
National Tsing Hua University

CS 5262: Multimedia Networking and Systems

Video Quality Metrics

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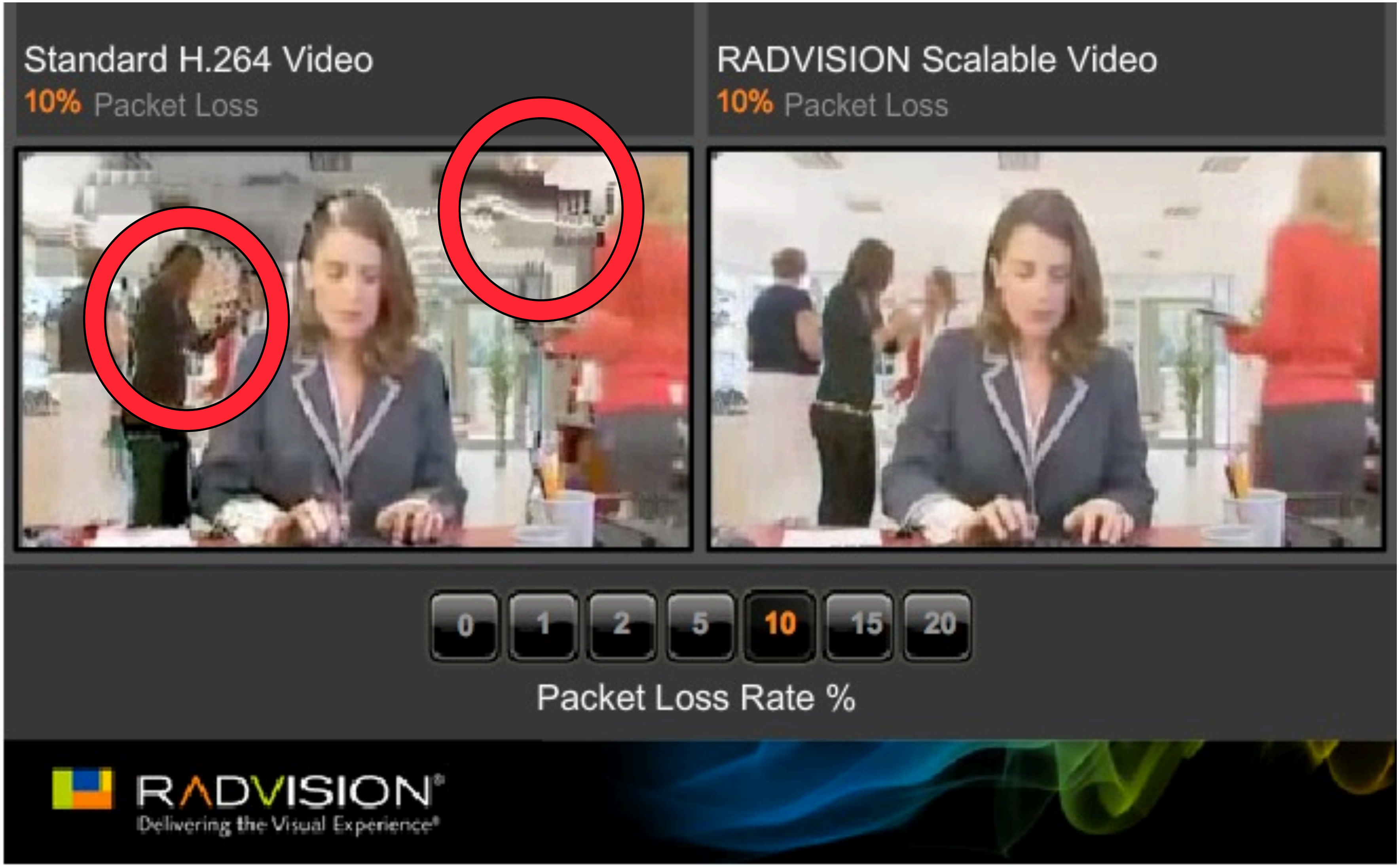
Outline

- Overview on Video Quality Metrics
- A Sample Application
  - Joint Packet Scheduling and Stream Adaptation in Multihomed Video Streaming
- Tools for Calculating Video Quality and Conducting Simulations/Experiments

Overview of Video Quality Metrics

Visual Impairments Caused by Packet Loss



Quality of Experience and Quality of Service

- QoE: Subjective measurements of users' experience
  - What a user (customer) wants? ← about human beings
- QoS: Objective measurements of the delivered service
  - How good is the received content? ← about content
- We refer to them as subjective and objective quality metrics

Quality Metrics

- **Subjective Metrics**
  - Hire people to score individual videos
  - Expensive, cannot be realtime ← E.g., cable TV systems cannot use subjective metrics to recover from network congestion
  - Not reproducible ← rerunning the experiments leads to different results
- **Objective Metrics**
  - Algorithms to analyze content, or infer video quality based on network conditions ← Cheap
  - Can be deployed in live networks for realtime monitoring
  - Reproducible

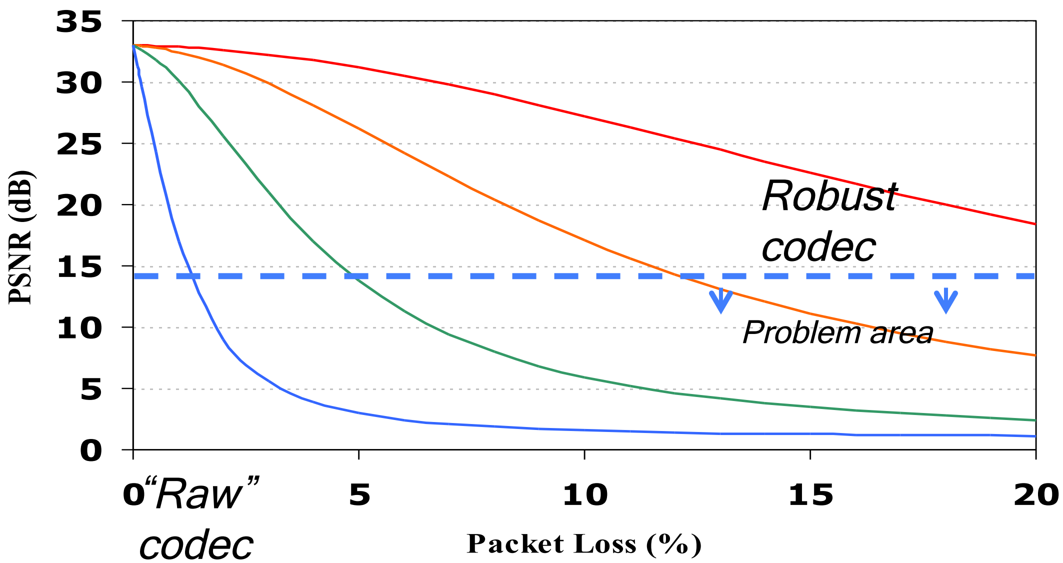
Subjective Metrics

- **Voice – Mean Opinion Score (MOS)**
  - Users grade voice quality from 1 to 5
  - Above 4 is good quality
  - Various variations with difference score ranges

- **Video – ITU-R BT.500**
  - Several modes are defined
  - E.g., Double Stimulus Impairment Scale (DSIS): first show the full-quality video, then show the impaired one. Viewers are informed the order. Viewers are asked to score the impaired video.

Objective Metrics (1/2)

- **Packet Based Metrics**
  - Use network measurements and (optionally) codec properties to infer the degraded video quality
  - Low complexity and work without original videos
- **Example V-Factor**
  - $V = f(QER, PLR, R)$
  - QER: codec quality
  - PLR: packet loss ratio
  - R: video complexity
  - Adopted by Sprint



Source: http://www.dsp-ip.com

Objective Metrics (2/2)

- **Content Based Metrics**
  - Compute the quality level using the video itself
  - Used in research labs for, e.g., comparing video codec performance
- **Classified into three groups**
  - Full reference: assuming both original and impaired videos are available ← less practical, but widely used in research labs
  - Reduced reference: original videos are analyzed and a summary is compared against the impaired video
  - No reference: metrics that do not need original videos ← ideal metrics

Full Reference Metrics

- **Most quality metrics consider Y-component (luminance) only**

- **MSE (mean-square-error) and PSNR (peak signal-to-noise ratio) are pixel based metrics**

$$MSE = \frac{1}{M} \times \sum_{i=1}^{M} (x_i - y_i)^2$$

$$PSNR(dB) = 10log_{10} \sum_{i=1}^{M} \frac{255^2}{(x_i - y_i)^2}$$

Problems with MSE/PSNR

- **MSE/PSNR does not map to user-perceived quality all the time**
- **Still researchers are using them ← Why?**

MSE=0, original picture

MSE=225, MSSIM=0.949

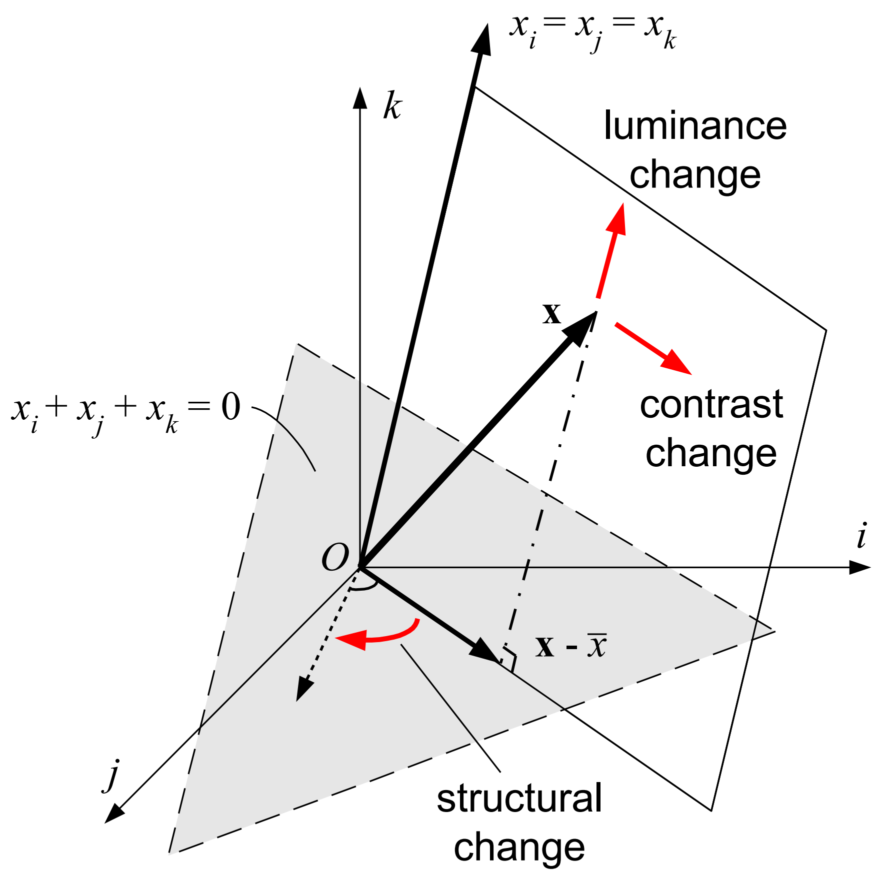
MSE=225, MSSIM=0.688

MSE=225, MSSIM=0.723

Structural Similarity Index (SSIM)

- **New metric proposed in 2004, which measures the similarity between the original and impaired images (extension for videos have also been proposed)**
- **Designed to address the limitations of MSE/PSNR**
- **Between [0, 1], where 1 indicates (iff) two images are identical**

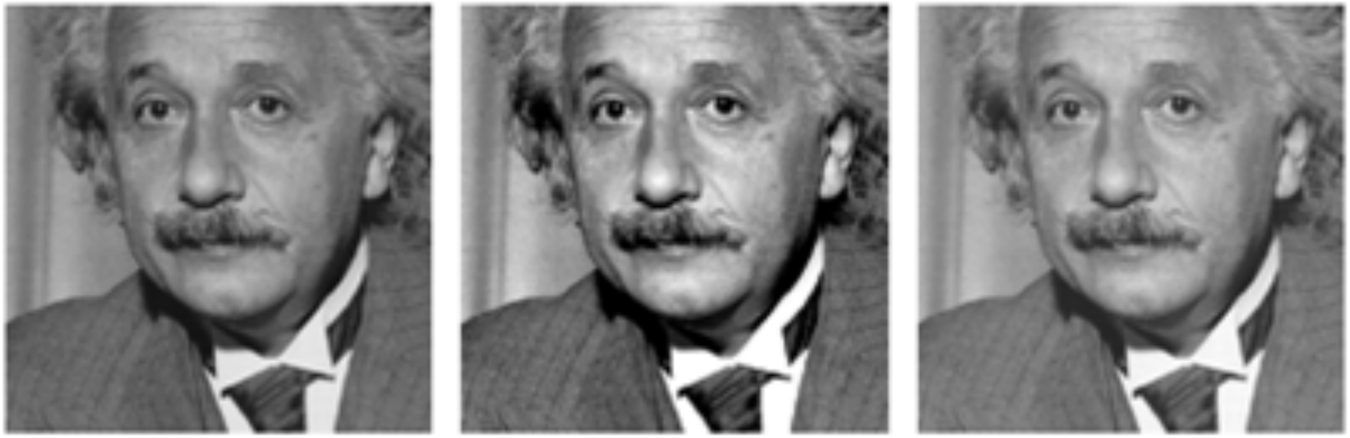
Structural Similarity Index (SSIM)



$$SSIM(\boldsymbol{x}, \boldsymbol{y}) = l(\boldsymbol{x}, \boldsymbol{y}) \cdot c(\boldsymbol{x}, \boldsymbol{y}) \cdot s(\boldsymbol{x}, \boldsymbol{y})$$

Source: Wang *et al.*, *IEEE Trans. Image Processing*, 2004

Examples of SSIM



(a) MSE=0, SSIM=1 CW-SSIM=1

(b) MSE=306, SSIM=0.928 CW-SSIM=0.938

(c) MSE=309, SSIM=0.987 CW-SSIM=1.000

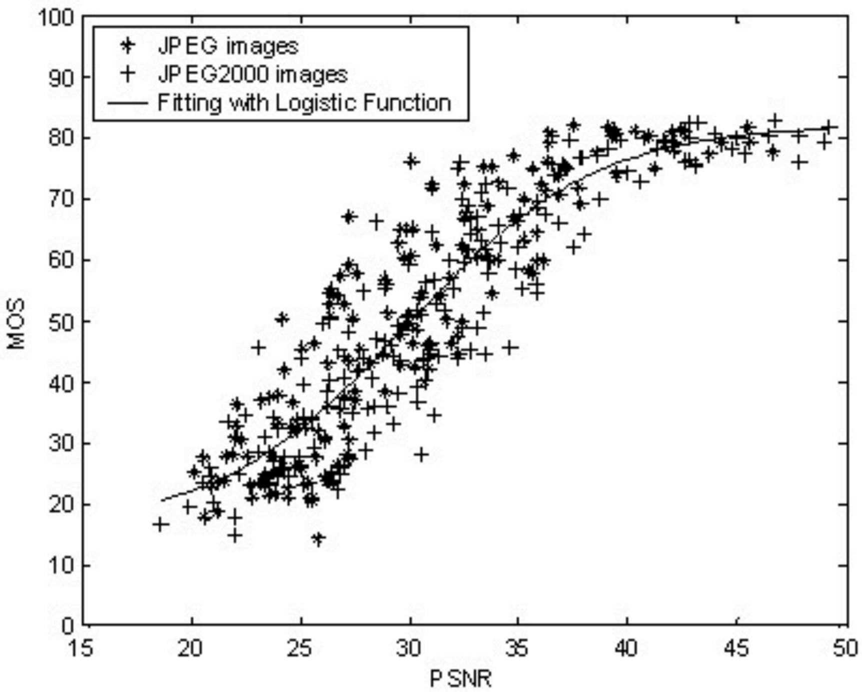
(e) MSE=313, SSIM=0.730 CW-SSIM=0.811

(f) MSE=309, SSIM=0.580 CW-SSIM=0.633

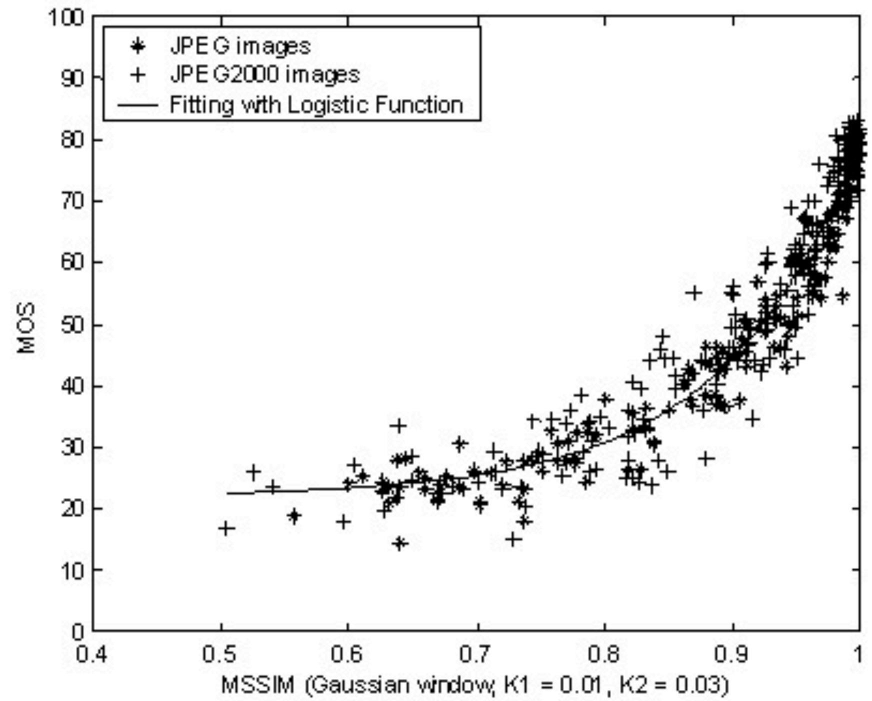
(g) MSE=308, SSIM=0.641 CW-SSIM=0.603

Source: https://ece.uwaterloo.ca/~z70wang/research/ssim/

Performance Comparison



PSNR vs. MOS



MSSIM vs. MOS

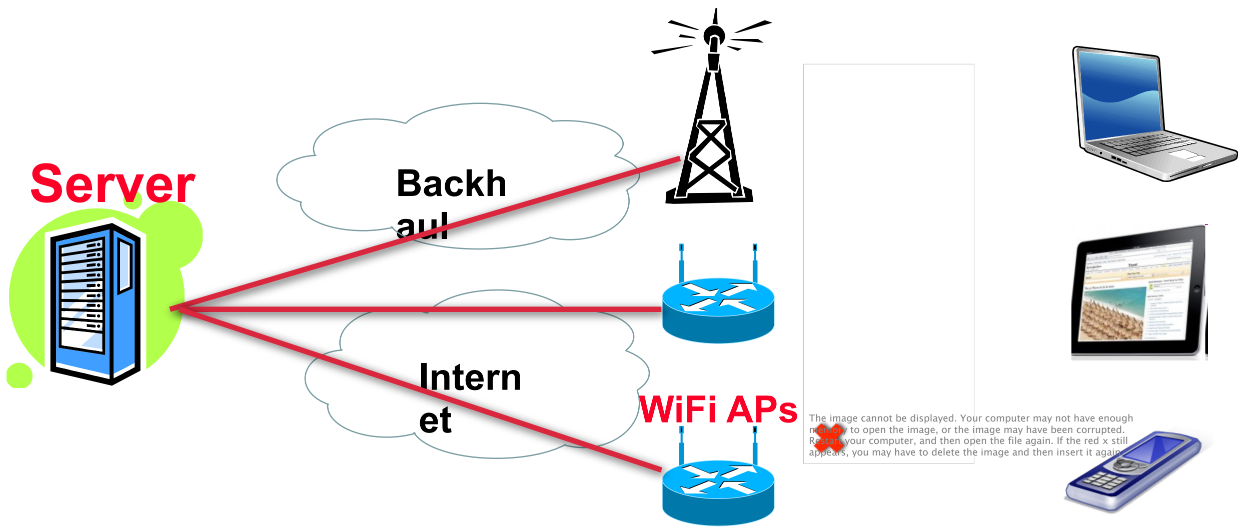
Source: https://ece.uwaterloo.ca/~z70wang/research/ssim/

Multihomed Video Streaming –

A Sample Project using Objective Video Quality as Optimization Criterion

Offloading Traffic from Cellular Networks

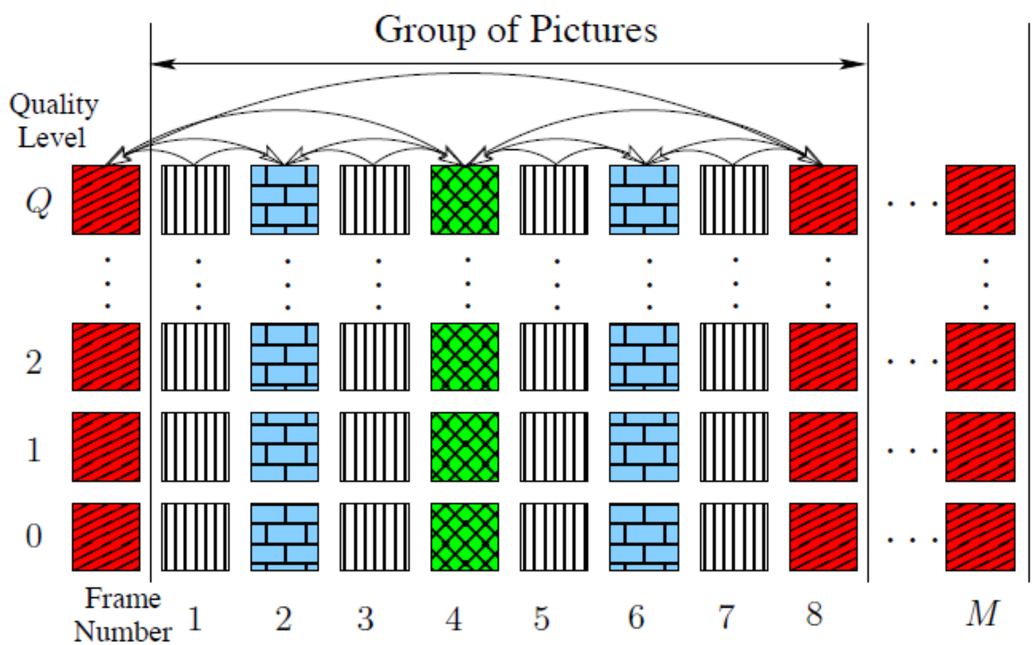
- Video streaming has high bandwidth requirements
- However, T-mobile and AT&T recently reported more than 50 times of data traffic increase [Open Mobile Summit '09]



- **This is called multihoming, which is attractive to**
  - **ISPs, such as T-Mobile, for lower transit cost**
  - **Subscribers for better quality-of-service**

Dynamic Network Coditions

- Problem: access networks are heterogeneous and dynamic
- Employ scalable video: frames are coded into multiple layers
  - incremental quality improvement
  - complicated interdependency due to prediction



Challenges and Problem Statement

- Determine streaming rate on each access network is hard [Hsu ISM'10]
  - streaming at a rate close to end-to-end network capacity leads to congestion, and late packets
  - streaming at a low rate wastes available resources
  - need a network model to proactively prevent congestion
- Packets of scalable streams have complex inter-dependency
  - need a video model to predict expected quality
- The problem: determine (i) what video packets to send, (ii) over which network interface, and (iii) at what rate, so that the overall streaming quality is maximized

Notations

- **Scalability**
  - **Client:** $u=1,\ldots,U$
  - **Temporal: Different frames with inter-frame prediction** $m=1,\ldots,M_u$
  - **Spatial: Quality layers** $q=0,\ldots,Q_u$
  - **Multihoming: networks** $n=1,\ldots,N$
  - **Network Abstraction Layer Unit (NALU) :** $g_{u,m,q}$

- **Scheduling**
  - **Deterministic:** $x_{u,m,q,n} \in \{0,1\}$

    If $g_{u,m,q}$ is sent over network n
  - **Randomized:** $x_{u,m,q,n} \in [0,1]$

Video Quality Model

- **Truncation distortion: capturing loss of a NALU $g_{u,m,q}$**
  - **A packet is decodable if all packets in lower quality ($q' < q$) layers are received**

$$e_{u,m} = \hat{\delta}_{u,m} + \sum_{q=0}^{Q_u} \Big(1 - \prod_{q' \leq q} x_{u,m,q'}\Big) \delta_{u,m,q}$$

Distortion if all packets are received

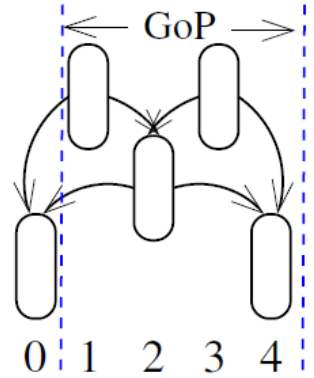
Additional distortion
If $g_{u,m,q}$ is not decoded

- **Drifting distortion: capturing error propagation**
  - **Inter-frame predictions based on imperfectly reconstructed parent packets, $P_{u,m}$**
  - **Convex increasing function**

$$y_{u,m} = \alpha_{u,m} + \sum_{k \in \boldsymbol{P}_{u,m}} \beta_{u,m,k} e_{u,k}$$

Nonnegative

  - **Parameters: Estimated from actual data**



Network Model

- **Packet loss probability (p_n) depends on**
  - Rate: (r_n)
  - Available bandwidth (c_n)
  - Packet decoding deadline (t_0)
- **Model**
  - M/M/1 model $p_n = e^{-\frac{t_0(c_n - r_n)}{\alpha_n}}$
  - Increasing in c_n, decreasing in r_n
  - α_n : linear regression parameter
  - accurate in streaming video applications [Zhu et. al '05]
- **Assumption : statistical independence of different networks**
  - Good approximation using a two-timescale approach [Jiang et al. '10]
  - Network converges to steady-state in between scheduling events

Problem Formulation

- **Cost minimization problem ← a cost function of distortion (MSE)**
  - **Accounts for service differentiation and fairness among users and frames**

$$
\begin{aligned}
\min_{x} \quad & C(\boldsymbol{d}) && \text{Cost function (increasing, convex)} \\
\text{s.t.} \quad r_n = \; & \textstyle\sum_{u=1}^{U} \frac{F_u}{M_u} \sum_{m=1}^{M_u} \sum_{q=0}^{Q_u} s_{u,m,q} x_{u,m,q,n}, && \text{Rate} \\
p_n = \; & e^{-t_0 (c_n - r_n)/\alpha_n}, && \text{Loss probability} \\
x_{u,m,q} = \; & \textstyle\sum_{n=1}^{N} (1 - p_n) x_{u,m,q,n}, && \\
e_{u,m} = \; & \hat{\delta}_{u,m} + \textstyle\sum_{q=0}^{Q_u} (1 - \prod_{q' \le q} x_{u,m,q'}) \delta_{u,m,q}, && \textbf{Not convex} \\
y_{u,m} = \; & \alpha_{u,m} + \textstyle\sum_{k \in \boldsymbol{P}_{u,m}} \beta_{u,m,k} e_{u,k}, && \\
d_{u,m} = \; & e_{u,m} + y_{u,m}, && \\
& \textstyle\sum_{n=1}^{N} x_{u,m,q,n} \le 1, && \\
& x_{u,m,q,n} \in \{0, 1\}. && \text{Randomized scheduling}
\end{aligned}
$$

Heuristic Algorithm 1/2

SRDO

0. INPUT: $P_{\max}$ is the maximum packet loss rate
1. **let** $\boldsymbol{x} = \{x_{u,m,q,n} = 0 \mid \ \forall u, m, q, n\}$
2. **sort** $g_{u,m,q}$ on $\frac{\delta_{u,m,q}}{s_{u,m,q}}$
3. **for** $\hat{n} = \mathrm{argmin}_{n=1}^{N} p_n$
4. **let** $g_{\hat{u},\hat{m},\hat{q}}$ be the next unsent NALU
5. **if** sending $g_{\hat{u},\hat{m},\hat{q}}$ on $\hat{n}$ causes $p_{\hat{n}} > P_{\max}$ **return** $\boldsymbol{x}$
6. **else update** $\boldsymbol{x}$ with $x_{\hat{u},\hat{m},\hat{q},\hat{n}} = 1$
7. **if** no more unsent NALU **return** $\boldsymbol{x}$

Heuristic Algorithm 2/2

PRDO

let $\boldsymbol{x} = \{x_{u,m,q,n} = 0 \mid \forall u, m, q, n\}$
forever
    if $\boldsymbol{g}_d$ is empty **return** $\boldsymbol{x}$
    let $\boldsymbol{g}_d$ be all immediately decodable NALGs
    for $g_{u,m,q} \in \boldsymbol{g}_d$
        for $n = 1$ to N
            compute $b_{u,m,q,n}$ based on $\boldsymbol{x}$
            let $\frac{b_{\hat{u},\hat{m},\hat{q},\hat{n}}}{s_{\hat{u},\hat{m},\hat{q}}} \geq \frac{b_{u,m,q,n}}{s_{u,m,q}} \quad \forall u, m, q, n$
            if $b_{\hat{u},\hat{m},\hat{q},\hat{n}} \leq 0$ **return** $\boldsymbol{x}$
            update $\boldsymbol{x}$ with $x_{\hat{u},\hat{m},\hat{q},\hat{n}} = 1$, **update** $\boldsymbol{g}_d$.

Term-by-Term Convex Approximation

Goal: Obtain a convex superset of the constraint set

1. Term-by-term convex approximation (TTC)

$$
\begin{aligned}
x_{u,m,q} &\leq \sum_{n=1}^{N} \min(1-p_n, x_{u,m,q,n}),\\
e_{u,m} &\geq \hat{\delta}_{u,m} + \sum_{q=0}^{Q} (1 - \min_{q' \leq q} x_{u,m,q'})\delta_{u,m,q},
\end{aligned}
$$

- **Polynomial number of constraints in U,M,Q,N**
- **Weak approximation of the probability of successful packet delivery $x_{u,m,q}$**

Multilinear Convex Approximation

Goal: Obtain a convex superset of the constraint set

2. Multilinear convex approximation (MC)

- Convex envelope of multilinear functions [Sherali '97]
  - Minimum of affine functions
- Tightest convex approximation
- Exponential number of constraints in Q,N
- Constraint on $x_{u,m,q}$ depends exclusively on N, NOT on problem parameters

Hybrid Convex Approximation

Goal: Obtain a convex superset of the constraint set

3. Hybrid Convex Approximation (HC)

- **Term-by-term approximation for truncation distortion $e_{u,m}$**
- **Multilinear approximation for probability of successful packet delivery $x_{u,m,q}$**

$$
\begin{aligned}
x_{u,m,q} \leq &\quad \textstyle\sum_{n=1}^{N} \min(1-p_n, x_{u,m,q,n}),\\
e_m \geq &\quad \hat{\delta}_m + \textstyle\sum_{q=0}^{Q} \delta_{m,q} - \min \{ L_m^2(\xi, \bar{\mathbf{x}}) := \sum_{q=0}^{Q} (\sum_{q'=0}^{q-1} \prod_{i \leq q'} \xi(i)\delta_{m,q'} + \\
&\quad \textstyle\sum_{q'=q}^{Q} \prod_{i \leq q', i \neq q} \xi(i) x_{m,q} \delta_{m,q'}) - Q \sum_{q=0}^{Q} \prod_{i \leq q} \xi(i) \delta_{m,q} \\
&\quad \text{s.t.} \quad \xi \in \{0,1\}^{Q+1}, L_m^2(\xi, \bar{\mathbf{x}}) \leq \textstyle\sum_{q=0}^{Q} \bar{x}_{m,q} \delta_{m,q} \quad \forall \bar{\mathbf{x}} \in \{0,1\}^{Q+1} \},
\end{aligned}
$$

- **Polynomial complexity in U,M,Q, exponential in N**
- **Good trade-off of approximation accuracy vs. complexity for low N**

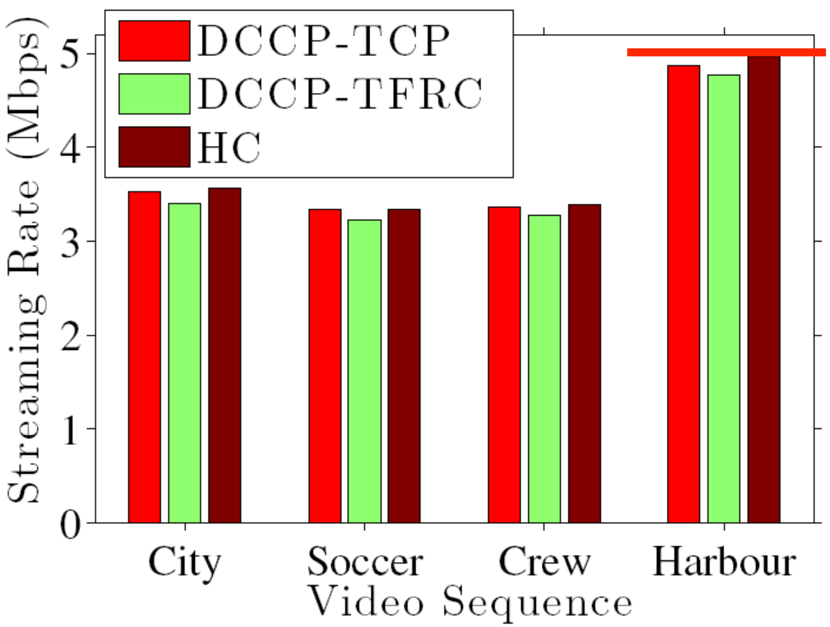
Solving the Convex Approximations

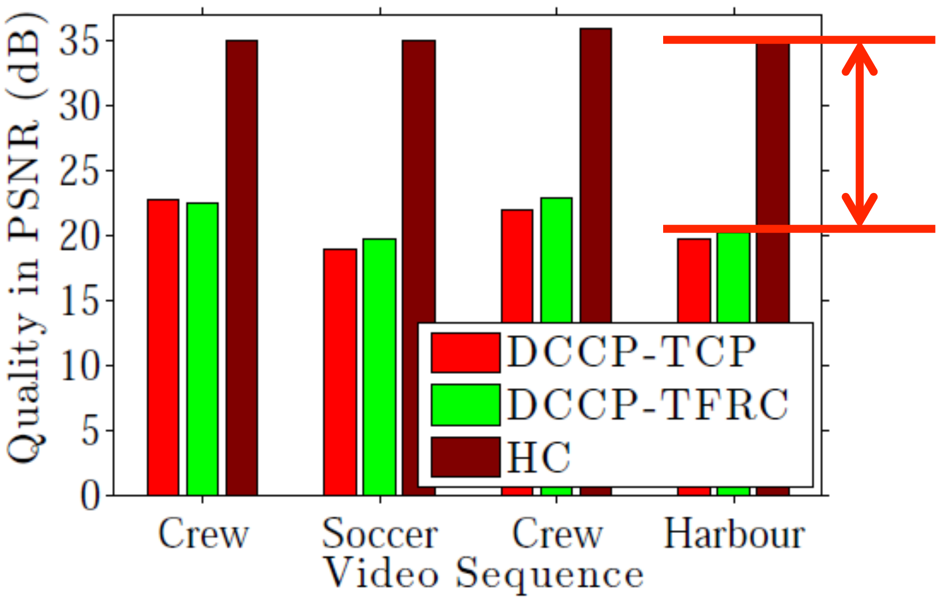
- **Properties of our convex approximations**
  - Non-empty compact set of solutions
  - Strong duality
  - Non-empty set of dual optimal solutions
- **These properties are important for the performance of numerical methods** [Boyd et al. 04']
- **We use CVX to solve our convex programs**
  - a convex program solvers based on Matlab
  - developed at Stanford

Simulation Setup

- Scheduling period : $M = 32$
- Number of quality enhancement layers : Q=7
- Number of access networks : N=3
- Decoding deadline : $t_0 = 1$ sec
- SVC video streams: Crew, Harbour, City, and Soccer
- Trace-driven simulations (NS-2)
  - Data from subnets at Stanford University and DT Labs Berlin
  - Used Abing to measure end-to-end available bandwidth and round-trip time
  - Run 300 simulations for each setup

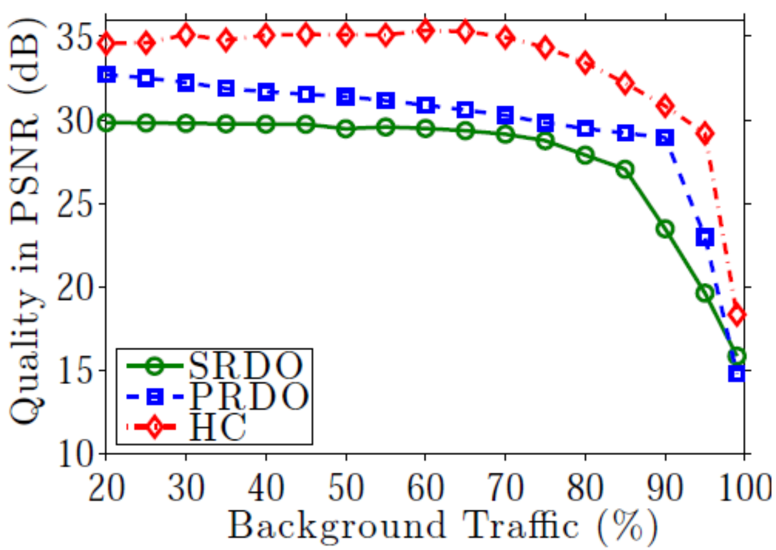
Comparison against Current Solutions

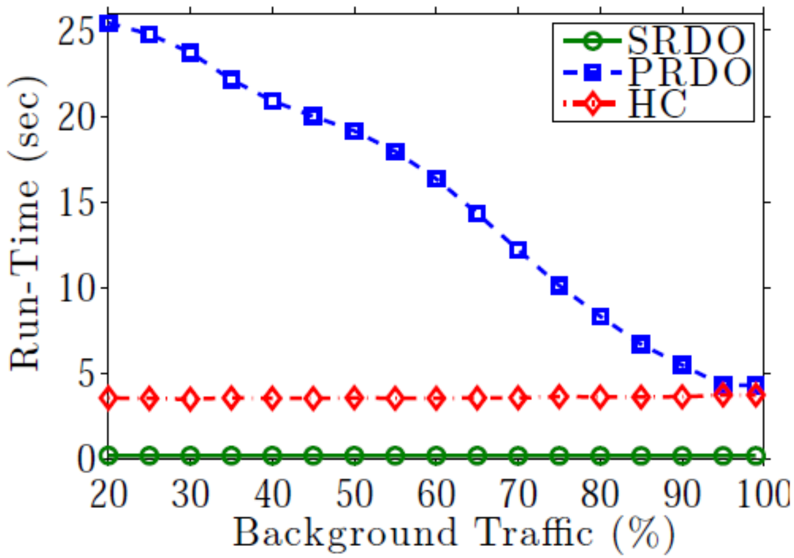




- **Proposed algorithms are TCP-Friendly**
- **Proposed algorithms constantly outperform current ones by more than 10 dB**

Complexity versus Performance



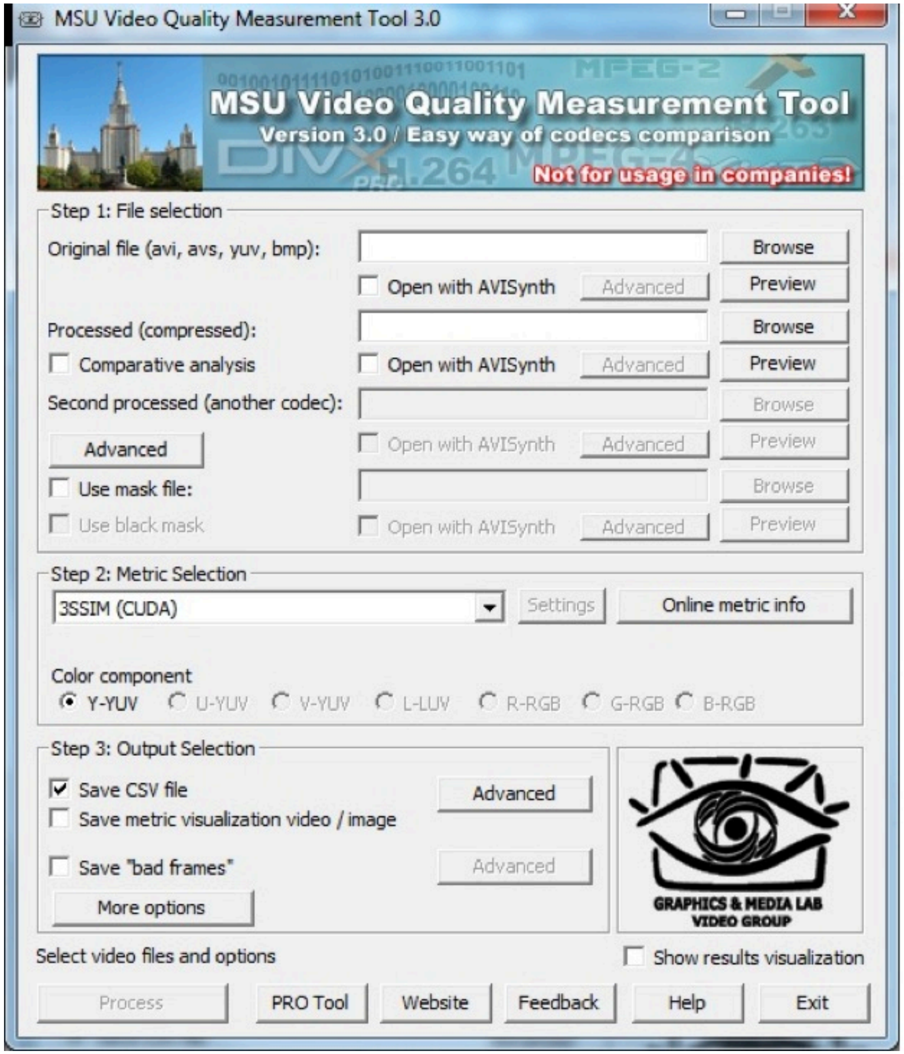


Convex solution outperforms heuristics in performance

Convex solution has a reasonable time complexity

Useful Tools

Tools to Compute Video Quality (1/2)



- **MSU Video Quality Measurement Tool**
  - MSU Graphics and Media Lab, Moscow State University
  - Supports 20 quality metrics: including variations of PSNR, SSIM, and VQM (another popular metric we didn't discuss)
  - Supports 20 video file formats
  - Comes with academic/ commercial versions
  - http://graphics.cs.msu.ru/

Tools to Compute Video Quality (2/2)

- **VQM (Video Quality Metric)**
  - A U.S. national standard (ANSI T1.801.03-2003), and an international ITU Recommendations (ITU-T J.144, and ITU-R BT.1683, in 2004)
  - Public tool available
  - http://www.its.bldrdoc.gov/vqm/
- **SSIM**
  - Matlab implementation at Prof. Wang's utility page
  - https://ece.uwaterloo.ca/~z70wang/research/ssim/
- **MSE/PSNR**
  - PSNRStatic comes with JSVM software
  - Write your own

Other Resources for Evaluation

- **Video Traces**
  - Arizona State: http://trace.eas.asu.edu/, long video sequences coded in SVC, AVC, MPEG-4, MPEG-2, and MDC coders
  - TU Berlin http://www.tkn.tu-berlin.de/research/trace/ltvt.html, long video sequences coded in MPEG-4 and H.263
- **Video Sequences**
  - Xiph Open-source Video Production http://media.xiph.org/, pointing to many other links for Raw video sequences
- **Codecs**
  - AVC Reference Coder http://iphome.hhi.de/suehring/tml/
  - SVC Reference Coder http://ip.hhi.de/imagecom_G1/savce/downloads/SVC-Reference-Software.htm
  - X264 Coder http://www.videolan.org/developers/x264.htm
  - Nokia's 3D Coder/Decoder http://research.nokia.com/research/mobile3D

Other Resources for Evaluation

- **Streaming Tools**
  - Darwin Open-source Version of QuickTime Server http://dss.macosforge.org/
  - VLS VideoLAN's Streaming Server http://www.videolan.org/vlc/streaming.html
  - VLC VideoLAN's Player http://www.videolan.org/vlc/
  - Live555 Streaming Library http://www.live555.com/liveMedia/
- **Misc**
  - Matlab Central's File Exchange http://www.mathworks.com/matlabcentral/

Summary

- **Quality metrics are means to quantify the performance of multimedia systems, and can be classified into**
  - **Subject (tester) versus objective (program)**
  - **Full reference, no reference, and reduced reference**

- **Quality metrics play central roles on optimizing multimedia system**
  - **Simple metrics are preferred for good properties, e.g., convex/concave of MSE/PSNR, for efficient algorithms**