

# Advances in Video Streaming and Analytics Systems

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## 1 Introduction

This paper summarizes the main contributions of the Wayne State University Computer Systems and Deep Learning Lab in the areas of the design of scalable video streaming systems [31, 28, 25, 25, 6, 37, 45, 30] and the design of video analytics systems [15, 14].

The research lab has other areas of interest that are not covered by this report, including the design of hardware accelerators for AI [21, 17, 20] and epileptic seizure prediction through deep learning [51, 32, 22].

## 2 Design of Scalable Video Streaming Systems

The main work on video streaming systems can be summarized as follows: supporting heterogeneous receivers [31, 28], client-side caching [24], supporting interactive operations [25, 23], supporting advertisements [4, 2, 36, 1], waiting time prediction [6, 8, 37, 9, 36], request scheduling [45, 7, 41, 35], proving time-of-service guarantees [43, 40, 44], resource sharing and server-side cache management [30, 29, 27], streaming media workload characterization [26], storage subsystem support [34, 42, 39, 38], and video coding [48]. The main principles of multimedia streaming are discussed in [33].

We discuss next some of our major work on the design of scalable video streaming systems.

### 2.1 Supporting Heterogeneous Receivers

The number of video streams that can be serviced concurrently is highly constrained by the required real-time and high-rate transfers of multimedia data. Resource sharing techniques, such as Batching, Patching, and Earliest Reachable Merge Target (ERMT), can be used to address this problem by utilizing the multicast facility, which allows multiple requests to share the same set of server and network resources. They assume, however, that all clients have the same available download bandwidth and buffer space. In [31, 28], we study how to efficiently support clients with varying available download bandwidth and buffer space, while delivering data in a client-pull fashion using enhanced resource sharing. In particular, we propose three hybrid solutions to address the variability in the download bandwidth among clients: Simple Hybrid Solution (SHS), Adaptive Hybrid Solution (AHS), and Enhanced Hybrid Solution (EHS). SHS simply combines Batching with either Patching or ERMT, leading to two alternatives: SHS-P and SHS-E, respectively. Batching is used for clients with bandwidth lower than double the video playback rate, and Patching/ERMT is used

for the rest. In contrast, AHS and EHS classify clients into multiple bandwidth classes and service them accordingly. AHS employs a new stream type, called adaptive stream, and EHS employs an enhanced adaptive stream type to serve clients with bandwidth capacities ranging between the video playback rate and double that rate. AHS and EHS employ adaptive streams or enhanced adaptive streams in conjunction with Batching and Patching or ERMT, leading to four possible schemes: AHS-P, AHS-E, EHS-P, and EHS-E. Moreover, we consider the variability of the available buffer space among clients. Furthermore, we study how the waiting playback requests for different videos can be scheduled for service in the heterogeneous environment, capturing the variations in both the client bandwidth and buffer space. We evaluate the effectiveness of the proposed solutions and analyze various scheduling policies through extensive simulation.

## 2.2 Waiting-Time Prediction

Providing video streaming users with expected waiting times enhances their perceived quality-of-service (QoS) and encourages them to wait. In the absence of any waiting-time feedback, users are more likely to defect because of the uncertainty as to when their services will start.

In [6, 37], we analyze waiting-time predictability in scalable video streaming. We propose two prediction schemes and study their effectiveness when applied with various stream merging techniques and scheduling policies. The results demonstrate that the waiting time can be predicted accurately, especially when enhanced cost-based scheduling is applied. The combination of waiting-time prediction and cost-based scheduling leads to outstanding performance benefits

## 2.3 Client-Side Caching

The design of interactive Near Video-on-Demand (NVOD) systems is highly complicated when scalable stream merging is used. We propose an intelligent client-side cache management policy for these systems, allowing and exploiting cache discontinuity. This policy maximizes the percentage of interactive requests serviced from the client's own cache without requiring any resources from the server. The policy caches data from all streams that are being listened to by the client. As the cache becomes full, it purges data according to a purging algorithm. In [24], we present three purging algorithms: purge the oldest data, purge the furthest data from the customer's playback point, and purge adaptively. Moreover, we experiment with another important decision, which is whether pausing users should continue to listen to streams when the cache becomes full. We evaluate the effectiveness of the proposed cache management policy and purging algorithms under realistic and complex workload through extensive simulations. We analyze many metrics, including waiting and blocking metrics, aggregate delay, cache hit rate, and cache fragment

## 2.4 Supporting Interactive Operations

The required real-time and high-rate transfer of multimedia data limits the number of requests that can be concurrently serviced by video-on-demand (VOD) systems. Resource-sharing techniques can be used to address this scalability challenge, but they greatly complicate the efficient support for interactive operations. In [25, 23], we develop an overall solution for interactive near VOD systems that employ resource sharing. The proposed solution supports user interactions with short response times and low rejection probabilities. The solution includes a novel stream provisioning policy, which dynamically determines the best number of I-Streams (unicast streams for supporting interactive requests) and the maximum I-Stream length that can be allocated by the server. Furthermore, we use a sophisticated client-side cache management policy to maximize the

percentage of interactive requests serviced from the client’s own cache. We study the system using a realistic workload through extensive simulation.

## 2.5 Supporting Advertisements

Studies [4, 2, 36, 1] develop a scalable delivery solution for commercial near-on-demand video streaming systems with an associated pricing model. The proposed delivery solution combines the benefits of periodic broadcasting and stream merging, thereby enabling scalable video delivery. Video advertisements are delivered to the clients prior to viewing the requested videos. The revenues generated from the ads are used to subsidize the price of the requested videos. The pricing is determined based on the total ad viewing time. The proposed solution includes an efficient ad allocation scheme and a new constraint-based scheduling approach. In addition, they investigate how targeted advertisements can be efficiently supported. Furthermore, they investigate the effectiveness of the overall solutions and analyze and compare the effectiveness of various scheduling policies and ad allocation alternatives in terms of several metrics, including client defection probability, average number of viewed ads per client, price, channel utilization, revenue, and profit.

## 2.6 Request Scheduling

The number of media streams that can be supported concurrently is highly constrained by the stringent requirements of real-time playback and high transfer rates. To address this problem, media delivery techniques, such as Batching and Stream Merging, utilize the multicast facility to increase resource sharing. The achieved resource sharing depends greatly on how the waiting requests are scheduled for service. Scheduling has been studied extensively when Batching is applied, but up to our knowledge, it has not been investigated in the context of stream merging techniques, which achieve much better resource sharing. In [45], we analyze scheduling when stream merging is employed and propose a simple, yet highly effective scheduling policy, called Minimum Cost First (MCF). MCF exploits the wide variation in stream lengths by favoring the requests that require the least cost. We present two alternative implementations of MCF: MCF-T and MCF-P. We compare various scheduling policies through extensive simulation and show that MCF achieves significant performance benefits in terms of both the number of requests that can be serviced concurrently and the average waiting time for service.

## 2.7 Resource Sharing and Server-Side Cache Management

The required real-time and high-rate transfers for multimedia data severely limit the number of video streams that can be delivered concurrently. Resource-sharing techniques address this problem and can be classified into two main classes: stream merging and periodic broadcasting. In [30], we evaluate major resource-sharing techniques from the two classes, considering different service models and video workloads. We utilize this extensive analysis in developing a workload-aware hybrid solution (WAHS) that combines the advantages of the best performers among resource-sharing techniques. Moreover, we propose a statistical cache management (SCM) approach and derive analytical models for optimal cache allocation to reduce further the demands on the disk I/O when various resource sharing techniques are used.

## 2.8 Providing Time-of-Service Grantees

Recent advances in storage and communication technologies have spurred a strong interest in Video-on-Demand (VOD) services. Providing the customers of VOD servers with time of service

guarantees offers two major advantages. First, it makes VOD services more attractive by improving customer-perceived quality of service (QoS). Second, it improves throughput through the enhanced resource sharing attained by motivating the customers to wait.

In [43, 40, 44], we propose a new class of scheduling policies, called *Next Schedule Time First (NSTF)*, which provides customers with schedule times and performs scheduling based on these schedule times. NSTF guarantees that customers will be serviced no later than scheduled and ensures that the schedule times are very accurate estimates of the actual times of service. We present alternative implementations of NSTF and show through simulation that NSTF works as expected and delivers outstanding performance benefits.

## 2.9 Streaming Media Workload Characterization

The popularity of social media has grown dramatically over the World Wide Web. In [26], we analyze the video popularity distribution of well-known social video websites and characterize their workload. We identify trends in the categories, lengths, and formats of those videos, as well as characterize the evolution of those videos over time. We further provide an extensive analysis and comparison of video content amongst the main regions of the world.

## 2.10 Storage Subsystem Support

Video streaming servers waste precious resources in performing store-and-forward copying. This excessive overhead increases cost and severely limits the scalability of these servers. In [42, 39], we propose using the Network-Attached Disk (NAD) architecture to design highly scalable and cost-effective video streaming servers. To ensure enhanced performance, we propose a scheme, called Distributed Interval Caching (DIC), which utilizes the on-disk buffers for caching intervals between successive streams. We also propose another scheme, called Multi-Objective Scheduling (MOS), which increases the degrees of resource sharing by scheduling the waiting requests for service intelligently. We then integrate the two schemes and study the overall performance benefits through extensive simulation. The results demonstrate that the integrated policy works very well in increasing the number of customers that can be serviced concurrently while decreasing their waiting times for service. The performance benefits vary with several architectural, system workload, and scheduling parameters. We conclude this study by developing an analytical model for ideal DIC to estimate the performance limits which may be achieved through various optimizations.

In [38], we exploit video access patterns and propose an adaptive rearrangement of the blocks on each disk within the server. With this approach, the blocks of the videos with comparable access frequencies are kept closer to each other. We analyze two rearrangement schemes: centered-layout and sequential layout. In the centered layout, blocks are placed according to their access patterns starting with the most popular movie at the center. The sequential layout places movies in the order of their popularity starting at the edge of the disk.

## 2.11 Video Coding

Study [48] describes the major differences between VP8 and H.264 and provides detailed comparative evaluations through extensive experiments. We use 29 raw video sequences, offering a wide spectrum of resolutions and content characteristics, with the resolution ranging from 176x144 (QCIF) to 3840x2160 (2160p). To ensure a fair study, we use 3 coding presets in H.264, each with three types of tuning, and 7 presets in VP8. The presets cover a variety of achieved quality or complexity levels. The performance metrics include accuracy of bitrate handling, encoding speed, decoding speed, and perceptual video quality.

### 3 Design of Video Analytics Systems

The main work on video analytics systems, such as automated video surveillance systems, includes the following: video rate adaptation [47, 46, 19], cross-layer optimization [11, 10, 16, 12, 13, 15], autonomous control of PTZ cameras for optimal threat detection accuracy [3, 5, 14], characterization of deep learning accuracy [19, 18], and power consumption modeling [49, 50],

We discuss next some of our major work on the design of video analytics systems.

#### 3.1 Video Rate Adaptation

Video rate adaptation is analyzed in [47, 46, 19]. These papers analyze and compare the rate-accuracy and rate-energy characteristics of various video rate adaptation techniques in computer vision applications. The analyzed rate adaptation techniques include spatial, spatial with upscaling, temporal, and Signal-to-Noise Ratio (SNR). We experiment with standard video sequences as well as security, surveillance, news, and speech videos. These videos total 19.15 hours of recording time. We consider both MPEG-4 and H.264 compression standards.

#### 3.2 Cross-layer Optimization

Studies [10, 12] develop a cross-layer optimization framework for video streaming from multiple sources to a central proxy station over a wireless network. The proposed framework manages the application rates and transmission opportunities of various video sources based on the dynamic network conditions in such a way that minimizes the overall distortion. The framework utilizes a novel online approach for estimating the effective airtime of the network. We demonstrate the effectiveness of the proposed framework and effective airtime estimation approach through extensive experiments.

Studies [11, 13] develop an accuracy-based cross-layer optimization solution for wireless automated video surveillance systems, in which multiple sources stream videos to a central proxy station. The proposed solution manages the application rates and transmission opportunities of various video sources based on the dynamic network conditions in such a way that maximizes the overall detection accuracy of the computer vision algorithm(s). We demonstrate the effectiveness of the proposed solution through extensive simulations.

Studies [16, 15] consider video analytics systems in which a central monitoring station receives and analyzes the video streams captured and delivered wirelessly by multiple cameras. They address how the bandwidth can be allocated to various cameras by presenting a cross-layer solution that optimizes the overall detection or recognition accuracy. In further contrast with prior work, they present and develop a real CV system and subsequently provide a detailed experimental analysis of cross-layer optimization. Other unique features of the developed solution include employing the popular HTTP streaming approach, utilizing homogeneous cameras as well as heterogeneous ones with varying capabilities and limitations, and including a new algorithm for estimating the effective medium airtime. The results show that the proposed solution significantly improves the CV accuracy.

#### 3.3 Autonomous Control of PTZ Cameras for Optimal Threat Detection

Studies [3, 14] address the research problem of how to autonomously control Pan/Tilt/Zoom (PTZ) cameras in a manner that seeks to optimize the face recognition accuracy or the overall threat detection and proposes an overall system. The papers present two alternative schemes for camera scheduling: Grid-Based Grouping (GBG) and Elevator-Based Planning (EBP). The camera control

works with realistic 3D environments and considers many factors, including the direction of the subject’s movement and its location, distances from the cameras, occlusion, overall recognition probability so far, and the expected time to leave the site, as well as the movements of cameras and their capabilities and limitations.

Study [14] utilizes clustering to group subjects, thereby enabling the system to focus on the areas that are more densely populated. The clustering approach is detailed in [5]. Moreover, it proposes a dynamic mechanism for controlling the pre-recording time spent on running the solution. Furthermore, it develops a parallel algorithm, allowing the most time-consuming phases to be parallelized and thus run efficiently by the centralized parallel processing subsystem. We analyze through simulation the effectiveness of the overall solution, including the clustering approach, scheduling alternatives, dynamic mechanism, and parallel implementation in terms of overall recognition probability and the running time of the solution, considering the impacts of numerous parameters.

### 3.4 Analytical Modeling of Deep Learning Accuracy in Adaptive video Streams

To fit the tight resource constraints, including network bandwidth, the video streams in Computer Vision systems are adapted dynamically by changing the video capturing and encoding parameters. In [19, 18], we propose two novel analytical models that characterize the face recognition accuracy in terms of these parameters, specifically resolution, quantization, and actual bitrate. We find that the accuracy is a logistic function of the video quantization parameter, with the value of the Sigmoid’s midpoint being a function of the resolution. Alternatively, we find that the accuracy is equal to the sum of two exponentials of the actual video bitrate, with the resolution as a multiplicative factor with one exponential. We develop an evaluation framework to validate the models using two distinct video datasets with 99 videos and the widely used Labeled Faces in the Wild (LFW) dataset with 13,233 images. We conduct 1,668 experiments that involve varying combinations of encoding parameters. We show that both models hold true for the deep-learning and statistical-based face recognition. The developed models achieve an average coefficient of determination ( $R^2$ ) of 98.7% to 99.8%.

### 3.5 Power Consumption Modeling

Study [49] analyzes and compares the rate-accuracy and rate-energy characteristics of various video rate adaptation techniques in computer vision applications. The analyzed rate adaptation techniques include spatial, spatial with upscaling, temporal, and Signal-to-Noise Ratio (SNR). We experiment with standard video sequences as well as 300 security, surveillance, news, and speech videos. These videos total 19.15 hours of recording time. We consider both MPEG-4 and H.264 compression standards.

Study [50] develops an aggregate power consumption model for live video streaming systems, including many-to-many systems. In many-to-one streaming systems, multiple video sources (i.e., cameras and/or sensors) stream videos to a monitoring station. We model the power consumed by the video sources in the capturing, encoding, and transmission phases and then provide an overall model in terms of the main capturing and encoding parameters, including resolution, frame rate, number of reference frames, motion estimation range, and quantization. We also analyze the power consumed by the monitoring station due to receiving, decoding, and upscaling the received video streams. In addition to modeling the power consumption, we model the achieved bitrate of video encoding. We validate the developed models through extensive experiments using two types of systems and different video contents. Furthermore, we analyze many-to-one systems in terms of bitrate, video quality, and the power consumed by the sources, as well as that by the monitoring

station, considering the impacts of multiple parameters simultaneously.

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