Online Video Streaming Application: A MERN Stack Implementation with Adaptive Bitrate Streaming and Edge Computing Optimization

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Abstract—

The exponential growth in video content consumption has necessitated the development of robust, scalable streaming platforms capable of delivering high-quality content across diverse network conditions and devices. This paper presents a comprehensive implementation of an online video streaming application utilizing the MERN (MongoDB, Express.js, React.js, Node.js) technology stack, enhanced with adaptive bitrate streaming through HTTP Live Streaming (HLS) protocol and intelligent edge computing optimization. Our system integrates FFmpeg for real-time video transcoding, AI-driven bitrate prediction algorithms, and edge caching mechanisms to address critical challenges in modern video delivery including latency reduction, bandwidth optimization, and scalability. Experimental results demonstrate a 30% reduction in latency compared to baseline implementations, 70% fewer buffering incidents through adaptive quality switching, and stable performance under concurrent loads of up to 10,000 users. The proposed architecture showcases the practical integration of modern JavaScript technologies with advanced streaming protocols, providing a foundation for next-generation content delivery platforms.

I. INTRODUCTION

The digital transformation of media consumption has fundamentally altered user expectations regarding video content delivery. Modern consumers demand seamless, high-quality streaming experiences across multiple devices and varying network conditions, driving the need for sophisticated streaming architectures that can adapt dynamically to changing circumstances [1], [2]. Traditional video delivery methods, characterized by static encoding and limited adaptability, are increasingly inadequate for meeting these evolving requirements.

The proliferation of over-the-top (OTT) streaming services and the exponential growth in video traffic—projected to account for over 82% of all consumer intern& traffic by 2025 [3]—has intensified the focus on developing scalable, efficient streaming solutions. Key challenges in contemporary video streaming include minimizing initial loading times, reducing buffering incidents, optimizing bandwidth utilization across diverse network conditions, and maintaining quality consistency across heterogeneous device ecosystems.

This paper addresses these challenges through the design and implementation of a comprehensive video streaming platform built on the MERN technology stack. Our approach leverages modern web technologies combined with advanced streaming protocols to deliver an optimized user experience. The system incorporates several innovative features:

1) Adaptive Bitrate Streaming: Implementation of HLS protocol with dynamic quality adjustment based on real-time network conditions

2) Intelligent Transcoding: FFmpeg-based real-time video processing with multiple resolution outputs

3) Edge Computing Integration: Strategic content caching and AI-driven bitrate prediction for performance optimization

4) Scalable Architecture: MongoDB-based flexible data management with RESTful API design

The remainder of this paper is organized as follows: Section II reviews related work and existing streaming technologies. Section III presents the comprehensive system architecture. Section IV details the implementation methodology and algorithms. Section V discusses experimental results and performance analysis. Section VI concludes with implications and future research directions.

II. RELATED WORK AND LITERATURE REVIEW *A.*

Evolution of Video Streaming Technologies

The landscape of video streaming has evolved significantly from early progressive download methods to sophisticated adaptive streaming protocols. Kumar et al. [4] provide a comprehensive analysis of cloud-based video streaming services, highlighting trends and challenges in modern content delivery. Their work emphasizes the critical role of cloud computing in enabling scalable video distribution, which aligns with our implementation approach.
Traditional streaming methods relied heavily on pre-encoded video files with fixed bitrates, leading to suboptimal performance across varying network conditions. The introduction of adaptive bitrate streaming (ABR) technologies, particularly HTTP Live Streaming (HLS) and Dynamic Adaptive Streaming over HTTP (DASH), has revolutionized content delivery by enabling real-time quality adjustments [5].

B. Modern Streaming Architectures

Recent research has focused on optimizing streaming architectures through various approaches. Chithra et al. [6] present a full-stack implementation using the MERN stack, demonstrating the effectiveness of JavaScript-based technologies for video streaming applications. Their work provides valuable insights into the integration challenges and benefits of using modern web development frameworks for multimedia applications.

The integration of artificial intelligence in streaming optimization has gained significant attention. DeepStream and similar approaches utilize machine learning algorithms for content-aware per-title encoding, supporting both CPU-only and GPU-available environments [7]. These advances inform our AI-driven bitrate prediction implementation.

C. *Edge Computing and Content Deliver), Networks*

Edge computing has emerged as a critical component in reducing latency and improving streaming performance. By distributing content closer to end users, edge networks significantly enhance the quality of experience (QoE) for streaming applications [8]. Our implementation incorporates edge caching strategies informed by current research in distributed content delivery.

Mobile video streaming presents unique challenges due to network variability and device limitations. Recent studies on mobile video live streaming systems [9] provide insights into optimizing streaming performance for wireless environments, which influences our adaptive streaming algorithm design.

III. SYSTEM ARCHITECTURE A.

Overall Architecture Design

The proposed streaming application follows a multi-layered architecture designed for scalability, maintainability, and performance optimization. The complete system architecture comprises four primary layers:

Frontend Layer (React.js + Video.js)

Backend Layer (Node.js + Express.js)

Database Layer (MongoDB)

Video Processing & Delivery Layer (FFmpeg

HLS Edge CDN)

Fig. 1. Multi-layered System Architecture

B. Frontend Layer Implementation

The frontend layer, built using React.js framework, provides an intuitive and responsive user interface optimized for various device form factors. Key components include:

1) Video Player Integration: The system utilizes Video.js, a robust HTML5 video player library, to provide advanced playback functionality including HLS stream support with automatic quality switching, custom player controls and overlay management, bandwidth monitoring and quality metrics display, and progressive loading and buffering optimization.

2) Responsive Design: Implementation of responsive design principles ensures optimal viewing experiences across desktop, tablet, and mobile devices. The interface dynamically adjusts layout and control elements based on screen size and orientation.

3) State Management: React hooks and context API manage application state, including user authentication, video metadata, and playback preferences.

C. Backend Infrastructure

The backend layer, implemented using Node.js and Express.js, orchestrates video processing, content delivery, and data management operations:

1) RESTful API Design: The system exposes comprehensive REST endpoints for video management, user authentication, and analytics tracking.

/ Video management endpoints
POST/api/videos/upload // Video file upload GET /api/videos/:id // Video metadata retrieval GET /api/videos/:id/stream // HLS playlist access
POST /api/videos/:id/view // View count tracking
// User management endpoints
POST /api/auth/login // User authentication POST /api/auth/register // User registration GET /api/users/profile // User profile management

2) Video Processing Pipeline: Integration with FFmpeg enables real-time video transcoding with multiple resolution encoding (1080p, 720p, 480p, 360p), HLS segmentation

with 10-second chunks, adaptive bitrate playlist generation, and thumbnail extraction and preview generation.

D. *Database Schema Design*

MongoDB serves as the primary data store, leveraging its document-based structure for flexible metadata management. The video document schema includes comprehensive metadata fields for video properties, resolution variants, analytics data, and user interaction tracking.

E. *Video Processing and Delivery*

The video processing layer handles transcoding, segmentation, and content delivery optimization through FFmpeg integration for format conversion and codec optimization, HLS implementation for adaptive bitrate delivery, and edge caching strategies for performance enhancement.

IV. IMPLEMENTATION METHODOLOGY

A. Video Upload and Transcoding Process

The video processing pipeline begins with secure file upload handling, followed by comprehensive transcoding operations. The transcoding process includes video format validation, metadata extraction, multi-resolution encoding, and HLS segment generation.

Algorithm 1: Video Transcoding Pipeline

```
Input: Original video file (originalVideo)
Output: HLS playlists and segments for multiple resolutions

1. Validate video format and specifications
2. Extract metadata (duration, resolution, codec)
3. For each target resolution in [1080p, 720p, 480p, 360p]:
    a. Calculate optimal bitrate using content analysis
    b. Execute FFmpeg transcoding with parameters
    c. Generate HLS segments and playlist
    d. Store segment files in CDN-accessible location
4. Create master playlist with all quality levels
5. Update database with transcoding results
6. Trigger edge cache population
```

B. Adaptive Bitrate Streaming Algorithm

The adaptive streaming algorithm continuously monitors network conditions and adjusts video quality to optimize user experience. The quality adaptation logic considers current bandwidth, buffer levels, and available quality options to make optimal streaming decisions.

```
Algorithm 2: Quality Adaptation Logic
Input: Current bandwidth (bw), buffer level (buffer), available
qualities (Q)
Output: Selected quality level (selectedQuality)

1. Initialize variables: bufferThreshold = 30 seconds,
stabilityFactor = 0.8
2. If buffer < bufferThreshold: Decrease quality by one level
3. Else if buffer > bufferThreshold AND bw is stable:
Calculate sustainable bitrate = bw x stabilityFactor Select
highest quality where bitrate < sustainable bitrate
4. Apply hysteresis to prevent quality oscillation
5. Return selectedQuality
```

C. Al-Driven Bitrate Prediction

The system incorporates machine learning algorithms to predict optimal bitrates based on historical network performance data. Features used for prediction include historical bandwidth measurements, temporal patterns, geographic characteristics, device specifications, and content complexity metrics.

A gradient boosting regression model trained on historical streaming data predicts the optimal bitrate for the next 30-second window, enabling proactive quality adjustments.

D. Edge Caching Strategy

The edge caching implementation optimizes content delivery through intelligent segment distribution using popularity-based caching, geographic distribution, and time-based cache invalidation strategies.

V. EXPERIMENTAL RESULTS ANDPERFORMANCE ANALYSIS

A. Experimental Setup

Performance evaluation was conducted using a controlled testing environment with Intel Xeon E5-2680 v4 processors, 64GB DDR4 RAM, 2TB NVMe SSD storage, and 10Gbps Ethernet connectivity. Test parameters included simulated network conditions from 1Mbps to 100Mbps bandwidth, concurrent user simulation from 100 to 10,000 users, and geographic distribution across 5 edge locations.

B. Performance Metrics

TABLE I
LATENCY PERFORMANCE COMPARISON

Metric	**Baseline**	Our **Implementation**	**Improvement**
Initial Load Time	4.2s	2.8s	33.3%
Seek Time	2.1s	1.4s	33.3%
Quality Switch Time	3.5s	1.2s	65.7%
Average Latency	850ms	595ms	30.0%

The adaptive streaming algorithm demonstrated significant improvements in user experience metrics with 70% reduction in rebuffering events, 45% reduction in quality oscillations, 23% improvement in average video quality, and 15% more efficient bandwidth utilization.

C. ScalabiliO, Analysis

Load testing results demonstrate system scalability under varying concurrent user loads, with response times remaining acceptable even under high concurrent loads of 10,000 users.

TABLE II
SCALABILITY PERFORMANCE UNDER LOAD

Concurrent Users	**Avg Response Time**	**95th Percentile**
100	45ms	89ms
500	52ms	103ms
1,000	61ms	127ms
5,000	89ms	201ms
10,000	134ms	298ms

D. Edge Computing Impact

Edge caching implementation showed substantial performance improvements with 78% cache hit rate for popular content, 40-60% geographic latency reduction, 65% decrease in origin server load, and 35% reduction in bandwidth costs.

E. AI-Driven Bitrate Prediction Accuracy

The machine learning model for bitrate prediction achieved 84% prediction accuracy for 30-second window predictions, 12% false positive rate, 8% false negative rate, and 2.3 hours model training time on historical dataset with 1M data points.

VI. DISCUSSION

A. Technical Contributions

The implemented system demonstrates several key technical contributions including integrated MERN stack approach, hybrid optimization strategy combining traditional ABR with AI-driven prediction, and strategic edge computing integration.

B. Comparison with Existing Solutions

Compared to commercial streaming platforms, our implementation offers open-source flexibility, cost-effective scaling capabilities, and full compatibility with modern web standards and progressive web application capabilities.

C. Limitations and Challenges

Several limitations were identified including transcoding overhead requiring careful resource management, edge cache consistency challenges, and network heterogeneity requiring additional algorithm refinement.

D. Industry Implications

The research has significant implications including democratization of streaming technology, establishment of performance benchmarking standards, and provision of comprehensive educational resources.

VII. FUTURE WORK AND RESEARCH DIRECTIONS

A. Short-term Enhancements

Future work includes integration of advanced codecs (AV1, VVC), enhanced AI models incorporating computer vision techniques, and specialized mobile optimizations for battery usage and cellular network adaptation.

B. *Long-term Research Opportunities*

Long-term opportunities include extension to immersive media support for 360-degree video, blockchain integration for content distribution, and edge AI computing for real-time content analysis.

C. *Emerging Technology Integration*

Emerging technology integration includes 5G network optimization, WebRTC integration for interactive streaming, and quantum-safe security implementation for future-proof content protection.

VIII. CONCLUSION

This paper presents a comprehensive implementation of a scalable online video streaming application utilizing modern web technologies and advanced streaming protocols. The MERN stack-based architecture, enhanced with adaptive bitrate streaming, AI-driven optimization, and edge computing integration, demonstrates significant performance improvements over traditional streaming approaches.
techniques and architectures presented in this work provide a solid foundation for addressing current and future challenges in video content delivery.

Key achievements include a 30% reduction in average latency, 70% fewer buffering incidents, and stable performance under high concurrent loads. The system's modular design facilitates rapid development and deployment while maintaining high standards of user experience and technical performance.

The integration of FFmpeg for real-time transcoding, HLS for adaptive streaming, and machine learning algorithms for predictive optimization represents a forward-thinking approach to content delivery challenges. The comprehensive performance evaluation validates the effectiveness of the proposed architecture and algorithms.

The research contributes to the broader understanding of modern streaming system design and provides a practical framework for developing next-generation video streaming platforms. The open-source approach and detailed implementation methodology enable widespread adoption and further research in the field.

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