

BANDWIDTH CONSUMPTION AND LATENCY TRADE OFF IN VIDEO STREAMING OVER SDN (QOE BASED ANALYSIS)

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Abstract

This paper examines the trade-off between bandwidth usage and latency in video streaming using Software Defined Networking (SDN), which is a limitation of the current literature since it considers the values of these two parameters separately instead of being joint. The research will seek to investigate their joint influence on Quality of Experience (QoE) and give a more comprehensive perspective on streaming performance. The SDN-based controlled SDN-based testbed was used as a quantitative experimental design with the implementation in Mini-net and the Ryu controller. VLC was used in video streaming, and network conditions like bandwidth (1-3 Mbps), latency and network packet loss were varied systematically. The metrics of QoE such as the startup delay and buffering incidents were measured and studied. The findings indicate that high-resolution video (38402160) took up to approximately 3 seconds to start and buffering at 1 Mbps, whereas low-resolution video (640360) took approximately 1 second before starting up and buffering without buffering. At 3 Mbps, high-resolution streams did experience continuous buffering, which validated that bandwidth and latency affect QoE in concert. The empirical evidence of bandwidth/latency interaction in SDN settings presented in the study and the necessity of combined QoE optimization frameworks.

INTRODUCTION

The high growth of video streaming services has greatly boosted the internet traffic across the globe, thus Quality of Experience (QoE) is a very important measure of user satisfaction in multimedia delivery systems. The conventional methods of network performance measurement, including throughput, delay, and packet loss, are

no longer adequate to guarantee optimal user experience, so researchers are focusing on QoE-based strategies that use user perception to shape network optimization policies (Ajeyprasaath & Vetrivelan, 2024; Omar, 2024). Recent developments in 5G and new 6G networks emphasize the role of adaptive streaming and cross-layer optimization where the allocation of

bandwidth and the control of latency should be taken into account jointly, ensuring stable video playback under unstable network conditions (Sidhu et al., 2025; Yan et al., 2025; Woo et al., 2024). Previous literature also shows that combining Software Defined Networking (SDN) with edge computing and adaptive bitrate mechanisms can be used to greatly enhance the quality of experience (QoE) by allowing to dynamically control traffic flow, minimize buffering, and optimize resource usage (Rahman et al., 2023; Nazemi Absardi and Javidan, 2023). Regardless of these developments, the balance between bandwidth usage and latency is one of the key problems as when one of the parameters is improved, the other one is usually harmed, and eventually, the quality of streaming and user satisfaction suffer. Thus, intelligent, SDN-based models that can dynamically implement bandwidth-latency trade-offs in order to improve QoE within the current video streaming context are in demand.

Video streaming is one of the most significant contributors to the overall data flow in the world with the growth of high-speed internet and mobile devices and over-the-top (OTT) platforms which have driven the exponential growth in the video streaming industry over the last few years. According to industry reports, video content constitutes a significant percentage of internet use and media demand of high-definition and ultra-high-definition streaming places a heavy load on the network infrastructure (Raza & Qureshi, 2024). Modern streaming ecosystems in turn are quickly adopting intelligent and adaptive designs, with Software Defined Networking (SDN), edge computing, and real-time analytics to optimize bandwidth utilization and enhance Quality of Experience (QoE) (Liang et al., 2025). Recent research reveals that adaptive bitrate (ABR) streaming, coupled with real-time network-state information, is important in ensuring playback stability in the presence of changing bandwidth and latency scenarios (Woo et al., 2024). Moreover, new 5G and 6G-enabled environments are increasing the pace of switching to edge-assisted streaming, moving computational functions, including, but not limited to, caching,

transcoding, and traffic management, to their end-users to minimize latency and improve service reliability (Sidhu et al., 2025).

Statement of Problem

Although the video streaming technologies have made tremendous progress, a consistent Quality of Experience (QoE) in dynamic network conditions has been a very crucial issue to both researchers and industry practitioners. Current streaming systems are typically designed to optimize either bandwidth usage or latency decrease alone and do not take into account the intricate interplay of these parameters, which can result in unstable playback, continuous buffering, and low user experience (Lyko et al., 2024; Uddin et al., 2025). Recent research points to the fact that low-latency streaming methods, although efficient in minimizing delay, can adversely affect bitrate stability and the quality change frequency, which eventually affects the overall quality of experience (Sidhu et al., 2025; Woo et al., 2024). Additionally, most modern solutions are heavily dependent on either client-side adaptive bitrate (ABR) algorithms or machine-learning-based prediction models without including real-time network control mechanisms, which makes them incapable of effectively responding to the rapid changes in network conditions (Ajeypasaath & Vetrivelan, 2024). Previous studies also suggest that conventional Quality of Service (QoS)-based strategies cannot represent user-perceived experience as they do not consider the trade-offs between bandwidth usage, latency, and playback performance (Rahman et al., 2023). This results in an apparent research gap in creating unified frameworks capable of cooperatively controlling bandwidth and latency within a programmable network platform like Software Defined Networking (SDN), which allows real-time management of QoE and stable video streaming performance under different network conditions.

Research questions of the Study

- To create an SDN-based video streaming tested with tools like Mininet and Ryu controller to experiment network conditions under control.

- To determine how the changes in bandwidth would affect the Quality of Experience (QoE) measures such as the startup delay, buffering events, and the stability of playback.
- To study how latency and network impairments (e.g., delay and packet loss) impact video streaming performance in an SDN-controlled setting.
- To explore trade-off between bandwidth usage and latency and identify the best conditions to improve QoE in video streaming systems.

Research Questions

- RQ1. What is the relationship between the Quality of Experience (QoE) and the network bandwidth when video streaming is done over a Software Defined Networking (SDN) infrastructure?
- RQ2. How do latency and network impairments (delay, and packet loss) affect video streaming performance and perceived user QoE?
- RQ3. What is the best way to have SDN-based dynamic traffic control to manage the trade-off between bandwidth usage and latency to improve the overall quality of video streaming?

Review of Literature

Table 1 Related Works

Research Authors	Title	GIST	Challenges
Sushi Anna George & Vinay Joseph, 2025	Adaptive Bandwidth Sharing for Optimizing QoE of Real-Time Video	The study proposes an adaptive semi-static bandwidth sharing policy for wireless networks to improve Quality of Experience (QoE) for real-time video traffic. The method balances static and dynamic bandwidth sharing to allocate resources efficiently while	The approach requires coordination among multiple operators and depends on accurate monitoring of traffic conditions and packet arrivals to adjust bandwidth allocation effectively.
Mohammad Tarik & Qutaiba Ibrahim, 2025	Adaptive Video Streaming with AI-Based Optimization for Dynamic Network Conditions	The paper presents an adaptive video streaming framework that uses artificial intelligence to adjust video resolution and buffer size based on real-time network parameters such as data rate and latency. The system integrates VLC streaming, Python-based monitoring, and AI analysis to reduce buffering and improve video quality.	Streaming performance still depends on fluctuating network conditions and requires accurate real-time data collection and AI processing for effective decision making

Awan Mahmood et al 2025	Nahel Challenges and Solutions for Video Streaming Services QoE Prediction Toward 6G Wireless Networks	This research reviews challenges in predicting Quality of Experience for video streaming in future 5G and 6G networks. It highlights the use of deep learning models such as LSTM, CNN, SVM, and GNN for QoE prediction and discusses adaptive bitrate streaming techniques to improve user experience	QoE prediction is complex due to heterogeneous networks, dynamic wireless conditions, user behavior variability, and the need for real-time scalable prediction models
Ali M. Alhatim & Jalal K. Jalal, 2026	Investigation of Software-Defined Networking (SDN) to Enhance Wi-Fi Networks in University Campus	The study analyzes the use of Software-Defined Networking to improve the performance of campus Wi-Fi networks. Simulation results show improvements in throughput, latency, packet loss, and fairness by using centralized SDN control and dynamic network resource allocation	The framework is evaluated mainly through simulations and requires real-world deployment to fully validate its performance in practical network environments
Parsa H. S. Panahi 2024 et al.	Machine Learning-Driven Open-Source Framework for Assessing QoE in Multimedia Networks	The research proposes an open-source machine learning framework for evaluating QoE in multimedia networks using network parameters such as delay, jitter, packet loss, throughput, and bitrate. A random forest model predicts Mean Opinion Score (MOS) with high accuracy using a large dataset collected from video streaming sessions	Measuring QoE remains challenging due to subjective user perception, diverse network conditions, and the complexity of collecting large-scale real-time network data

The comparative analysis of the recent literature shows that there is a robust research interest in adaptive, intelligent and QoE-oriented video streaming system especially in dynamic and next generation network environment. An example is adaptive bandwidth-sharing strategies, which seek

to effectively distribute network resources by balancing both the static and dynamic policies in order to improve the QoE in real-time video delivery (George & Joseph, 2025). Likewise, AI-driven adaptive streaming systems can dynamically scale video resolution and buffering policies to

current network dynamics, which can greatly enhance video playback quality, but still relies on the quality of data gathering and processing (Tarik and Ibrahim, 2025). The heterogeneous environment and variability in user behavior in the context of future 5G and 6G networks have complicated predicting QoE, and researchers are turning to more precise deep learning models to predict it more accurately (Mahmood et al., 2025). Moreover, SDN-based solutions show themselves to be able to increase the performance of the network with centralized control and active distribution of resources, thereby positively affecting such crucial parameters as latency, throughput, and fairness (Alhatim and Jalal, 2026). Moreover, QoE assessment models based on machine learning, including random forest algorithms, offer high prediction precision, exploiting several network parameters, but still have issues with subjective perception, and scalability in real-time (Panahi et al., 2024). On the whole, these papers suggest that although much has been achieved in terms of maximizing the performance of video streaming, the issues of real-time flexibility, predicting QoE correctly, and effectively implementing it in dynamic settings have not been properly addressed.

Introduction to Video streaming technologies

The development of video streaming technologies has changed greatly the way multimedia content is conveyed via modern networks, and adaptive and intelligent systems are becoming key in ensuring Quality of Experience (QoE). Modern streaming systems are also heavily dependent on Adaptive Bitrate (ABR) methods, where video quality is dynamically changed according to the real-time network conditions, which include the availability of bandwidth, latency, and packet loss, to provide smooth playback (Raza & Qureshi, 2024). More recent developments also combine edge computing with Software Defined Networking (SDN) to promote a more efficient streaming by allowing real-time traffic control, low latency, and optimization of resource allocation nearer to end-users (Liang et al., 2025). Moreover, machine learning paradigms are becoming a popular tool to forecast network behavior and subjective quality of

experience to support proactive adjustments of video streams and reduce buffering delays (Woo et al., 2024). New studies in the 5G and 6G landscape also focus on cross-layer optimization, in which network, transport, and application layers coordinate to ensure the stability of video delivery under the conditions of extreme dynamism (Sidhu et al., 2025). In addition, current streaming systems are configured to integrate content delivery networks (CDNs), edge nodes, and smart controllers to process high-resolution video like 4K and 8K content effectively, yet latency variation difficulties and bandwidth constraints continue to be a problem (Kim et al., 2025). All in all, video streaming technologies are quickly transforming to adaptive, AI-relative, and QoE-focused frameworks to satisfy the increased demand of high-quality and continuous multimedia services.

SDN, Mininet & Openflow

Software Defined Networking (SDN) has become a revolutionary paradigm of the current networking through the separation of the control plane and data plane, and the centralized and programmable control of the network to achieve a better performance and flexibility. The use of protocols like OpenFlow is essential in SDN frameworks since they enable the controller to interact with switches in the network and dynamically install flow rules to traffic and allocate resources efficiently (Martinez et al., 2023). Mininet is a popular network emulator to model SDN-based topologies, offering an affordable and scalable platform to experiment with network behavior under controlled conditions, including bandwidth constraints, latency, and congestion conditions (Martinez et al., 2023). Recent reports point out that Mininet can be integrated with SDN controllers such as Ryu to completely monitor traffic in real time, dynamically route traffic, and accurately manipulate network parameters, which is especially important when analyzing multimedia applications (video streaming, in particular) (Hao et al., 2024). Moreover, SDN-based architectures based on OpenFlow switches have shown considerable enhancement in throughput, latency, and QoE optimization with the ability to make adaptive

traffic control and intelligent decisions (Bourquia et al., 2024). Generally, SDN, Mininet and OpenFlow used in combination gives a strong experimental platform to investigate the behaviour of networks and optimize video streaming systems in a dynamic environment.

Ryu Controller, Traffic Monitoring and streaming

The Ryu controller is a key component of SDN-based multimedia environments, which provides programmable control of the network, real-time traffic monitoring and dynamic flow control, using a Python based architecture and OpenFlow support. It enables researchers to attach their own flow rules, gather fine-grained network statistics, and modify bandwidth allocation or routing choices with the prevailing network conditions, enhancing the overall Quality of Experience (QoE) in video streaming application (Hao et al., 2024). The system can be used together with traffic monitoring applications like iPerf to create controlled background traffic to model congestion and determine the effects of competing flows on streaming performance with different bandwidth and latency constraints (Kumar et al., 2025). Moreover, there is a wide adoption of streaming applications, such as VLC media player, to simulate the real-world video streaming, and it is possible to assess application-level QoE, including startup delay, buffering, and smoothness of playback (Hao et al., 2024). More recent research also notes that by integrating Ryu with monitoring scripts and analytics frameworks, one can continuously monitor the behavior of a network and make decisions based on the data to adaptive streaming (Souza et al., 2024). On the whole, the combination of the Ryu controller with traffic monitoring and streaming tools offers a versatile and holistic platform to analyze and optimize SDN-based video streaming system in a dynamically changing network environment.

Challenges and Limitations

Although SDN-based video streaming systems have been developed, there remain a number of challenges and limitations that limit their successful application and scalability in real-life. A

significant constraint is the use of centralized SDN controllers, like Ryu, that could introduce delays in the control plane and scalability challenges when managing high amounts of dynamic traffic or rapid flow updates (Rahman et al., 2024). Also, virtualized networks such as Mininet are helpful in controlled experimentation but fail to scale to the complexities of networks in the real world, including hardware level delays, unpredictable congestive behavior, and large scale heterogeneous traffic conditions (Martinez et al., 2023). The other essential issue is the accurate mapping of Quality of Service (QoS) parameters to Quality of Experience (QoE) because user experience is very subjective and depends on various non-linear factors, which makes it challenging to estimate quality of experience in real-time (Souza et al., 2024). Moreover, adaptive streaming systems do not tend to stabilize in dynamically changing bandwidth and latency conditions and experience bitrate swings and buffering, which negatively impact user experience (Bourquia et al., 2024). Lastly, introducing more complex technologies like machine learning and edge computing has added complexity to their computational overhead, data demands, and real-time decision-making abilities, which restrict their feasibility in resource-limited settings (Kim et al., 2025). In general, the challenges present above illustrate the necessity in more resilient, scalable, and real-time adaptive frameworks of QoE optimization in SDN-based video streaming systems.

Adaptive Streaming Models with Edge-Assistance

The edge-assisted adaptive streaming models have become an efficient approach to the enhancement of the Quality of Experience (QoE) by placing computational and decision-making power nearer to the end-users in order to minimize the latency and increase real-time responsiveness. Tasks that are performed by edge nodes in these models include caching, transcoding, and adaptive bitrate (ABR) decision-making, which can greatly reduce the use of cloud servers located far away and reduce network congestion (Zhang et al., 2024). Through its closeness to users, edge-assisted systems have the ability to dynamically tune the quality of video, in real-time, depending on the

network state, leading to a more fluid playback experience, fewer buffering occurrences, and more stable bitrate even in changing bandwidth situations (Liang et al., 2025). Moreover, edge computing with Software Defined Networking (SDN) can facilitate intelligent routing of traffic and efficient allocation of resources to dynamically offer streaming services to users depending on their mobility and fluctuations in the network load (Rahman et al., 2023). Nevertheless, even with these benefits, such issues as synchronization between distributed edge nodes, scalability, and the necessity to monitor everything on a constant basis are still prominent problems in the context of large-scale implementation (Zhang et al., 2024). Altogether, edge-assisted adaptive streaming is a good prospect of the next generation of multimedia delivery systems since it can be used to integrate low-latency processing with adaptive network optimization and thus to improve user experience.

QoE Prediction and Measurement Frameworks

QoE prediction and measurement models are extremely important in the contemporary video streaming systems because they allow estimating the quality perceived by the user in terms of network and application-level parameters. In these models, measures of throughput, latency, jitter, packet loss, buffering incidences, and bitrate changes are usually combined to model and forecast Quality of Experience in real time (Souza et al., 2024). Recent progress has brought about machine learning and deep learning models, such as Random Forest, LSTM, and hybrid models, to enhance the accuracy of predictions, as they can capture complex and non-linear relationships between QoS indicators and user satisfaction (Panahi et al., 2024; Kim et al., 2025). Also, cross-layer frameworks integrate network, transport, and application layer data to allow a more detailed evaluation of streaming performance and improve decision-making in adaptive streaming systems (Sidhu et al., 2025). Nonetheless, even with these advances, QoE is difficult to measure due to user subjectivity, the variability of content type and the inability to train and validate models using large-scale real-time data (Panahi et al., 2024). In

general, the frameworks of QoE prediction are required to facilitate the intelligent, data-driven optimization of video streaming, yet more development is required to make it scalable, accurate, and applicable to the real world.

Methodology

Research Design

The current research will use a quantitative, experimental research design to explore the trade-off between bandwidth usage and latency in video streaming in a Software Defined Networking (SDN) setting. Experimental studies are especially appropriate to conduct this study because it is possible to manipulate the independent variables, including bandwidth and latency, and monitor their direct influence on Quality of Experience (QoE) measures, including startup delay, buffering events, and playback smoothness (Lyko et al., 2024; Uddin et al., 2025). The new studies highlight that experimental and simulation-based models give more valid indications of real-time network behavior than purely theoretical or predictive models, particularly in dynamic 5G and 6G networks (Sidhu et al., 2025; Woo et al., 2024). Additionally, QoE-based assessment models are consistent with the current state of multimedia studies, in which user-based performance metrics are emphasized over the conventional Quality of Service (QoS) metrics (Omar, 2024). Previous research also points out that controlled experimental environments allow for effective mapping network parameters to user-perceived quality, which allows more accurate and reproducible outcomes (Rahman et al., 2023). Thus, the quantitative experimental design is deemed to be the most suitable in fulfilling the aims of this study.

The paper also utilizes a system design based on SDN architecture to provide flexibility, scalability, and accurate control over network conditions through a simulation-based system design. Recent studies commonly use simulation tools like Mininet with SDN controllers like Ryu to model real-world network conditions to study the behavior of traffic, bandwidth allocation, and changes in latency under conditions of controlled conditions (Hao et al., 2024; Bourquia et al.,

2024). Moreover, recent streaming research suggests the necessity to combine the tools of traffic generation and monitoring, including VLC and iPerf, to replicate the conditions of realistic multimedia workloads and test QoE performance in the conditions of congestion and different throughputs (Kumar et al., 2025, Kausar, et al,2025). Recent developments also reflect the importance of SDN in facilitating dynamic flow control and adaptive routing necessary to analyze the bandwidth-latency trade-offs in real-time streaming applications (Liang et al., 2025). Previous research also supports that SDN environments simulated present an affordable and reproducible platform to test multimedia systems without necessarily having complex physical infrastructure (Martinez et al., 2023). In this way, the selected design combines both experimental and simulation-based approaches to the analysis to guarantee the correct, adaptable, and scalable study of QoE in SDN-based video streaming systems.

Rationale of the Design

The need to precisely investigate the cause and effect relationship between bandwidth, latency, and Quality of Experience (QoE) in video streaming systems underlies the rationale behind the adoption of experimental and simulation-based design in the current study. Compared to observational or purely theoretical methods, the experimental designs also imply the possibility of controlling the parameters of the network, which makes it possible to measure the effect on the perceived performance of the user (Lyko et al., 2024; Uddin et al., 2025). Recent research has highlighted that real-time streaming environments are quite dynamic, and thus need to be under test conditions to isolate the impacts of various variables like throughput, delay, and packet loss (Sidhu et al., 2025; Woo et al., 2024). Also, QoE-oriented studies emphasize that user experience depends on a variety of interacting factors, and it is necessary to use a structured experimental design that allows achieving repeatability and consistency of findings (Omar, 2024). Previous studies also justify the use of controlled conditions in multimedia performance evaluation because

the researchers are allowed to make direct correlations between QoS variables and QoE results with greater precision when using controlled settings (Rahman et al., 2023). Thus, the experimental design is valid because it offers a valid and systematic approach to analyzing the bandwidth versus the latency trade-off in SDN-based streaming systems.

Moreover, the SDN-based simulation environment is appropriate in that it enhances flexibility, scale, and centralized control of the behavior of networks, which are crucial to studying contemporary multimedia systems. Recent studies indicate SDN provides dynamic traffic control and adaptive routing, and it is possible to adjust network resources in real-time depending on the changing conditions, which is essential to guarantee stable video streaming performance (Hao et al., 2024; Bourquia et al., 2024). To further enhance the design, the Mininet includes simulation tools that are cost-effective and reproducible to emulate a real-world network setting, including congestion, bandwidth constraints, and latency variability (Kumar et al., 2025). Also, recent research emphasizes the idea that the integration of SDN and traffic monitoring and streaming solutions is a holistic approach to assessing QoE with realistic workloads (Liang et al., 2025). Past studies also affirm that SDN environments simulated are generally endorsed to be experimentally validated based on their capability to recreate complex network setups without the need to incur high costs of physical setups (Martinez et al., 2023). Consequently, the chosen design is justified by the fact that it will supply precise, adaptable, and scalable analysis of QoE optimization in SDN-managed video streaming systems.

Specific Own Design

This study design is specifically designed to be developed on the basis of such a controlled SDN-based experimental testbed that will allow the systematic analysis of the impact of bandwidth and latency on the Quality of Experience (QoE) in video streaming. The implementation of the system is based on the Mininet network emulator and the Ryu SDN controller to establish a

programmable and centralized network, in which the traffic flows can be dynamically controlled. This layout enables the control of important network parameters like bandwidth constraints, delay, and packet loss with accuracy and at the same time captures QoE metrics like startup delay, buffering events, and smoothness of playback (Hao et al., 2024; Kumar et al., 2025). Recent research underlines that SDN-based architectures offer greater flexibility in terms of managing multimedia traffic, allowing real-time flow controllability and adaptive routing decisions that are critical to streamline the performance of the streaming (Bourquia et al., 2024; Sidhu et al., 2025). Additionally, by incorporating streaming applications like VLC and traffic generators like iPerf, it is possible to emulate the real-life network conditions, which makes the experimental setting closely resemble the conditions in the real-life streaming (Woo et al., 2024). The application of such integrated simulation frameworks is also supported by previous studies in terms of its ability to accurately estimate QoE in the conditions of different networks (Martinez et al., 2023). In this way, the design offers a solid and repeatable framework to study bandwidth-latency trade-offs in SDN-managed settings.

Moreover, the proposed design is based on multi-scenario experimental design, in which various bandwidth rates (e.g., 1 Mbps, 2 Mbps, and 5 Mbps) and latency conditions (e.g., induced delays and packet loss) are systematically applied to determine the overall effect on streaming performance. The experiments are performed in a controlled and repeatable manner, which enables them to compare it in other situations and provide consistency in the findings (Lyko et al., 2024; Uddin et al., 2025). Recent studies note that multi-variable experimentation in QoE research is essential because user experience depends on the combination of various network parameters and not on a single parameter (Sidhu et al., 2025; Liang et al., 2025). Continuous monitoring and logging mechanisms based on controller statistics and application-level data are also included in the design in order to create a direct correlation between the network behavior and the results of QoE (Souza et al., 2024). The previous research

also proves that repeated trials and controlled variables in structured experimental designs are the cornerstones to guarantee the validity and reliability of multimedia performance analysis (Rahman et al., 2023, hannan et al, 2025). Consequently, the suggested design can not only facilitate the close examination of bandwidth and latency trade-offs but also can guarantee scientific rigor, reproducibility, and practical value in SDN-based video streaming research.

Data Collection

In this study, the data collection method is a controlled experimental technique that relates to an SDN-enabled simulation environment, in which both the network-level and application-level data are regularly documented. Mininet and Ryu controller logs record network parameters like bandwidth usage, latency, jitter, and packet loss, whereas Quality of Experience (QoE) parameters such as startup time, buffering, and smooth playback are recorded by VLC streaming logs. Recent research indicates that the integration of network and application-level measures can offer a holistic perspective on streaming performance and user satisfaction (Hao et al., 2024; Kumar et al., 2025; Sidhu et al., 2025). Also, the automated logging and monitoring tools will guarantee data collection in real time and reliability in various test conditions (Souza et al., 2024). Previous studies also underpin the employment of controlled data collection settings to form proper relationships between QoS parameters and QoE results (Rahman et al., 2023). Thus, this method guarantees consistent, systematic, and repeatable data collection to analyze.

Population

This study population is characterized by the number of video streaming sessions, held in the SDN-governed setting, and not human participants, since the study adheres to the system-based experimental design. The units of analysis are each streaming session, and conditions of the network are varied to observe how they affect QoE. Recent studies further highlight the tendency of simulation-based studies to conceive population in terms of system-generated instances

or network scenarios to assess performance under different conditions (Lyko et al., 2024; Uddin et al., 2025; Woo et al., 2024). Moreover, SDN-based experiments can be employed to create numerous virtual hosts and traffic flows and in fact, increase the population scope in a controlled environment (Bourquia et al., 2024). Previous research also validates that a definition of population as experimental situations is suitable in multimedia and network performance research (Martinez et al., 2023). The population, therefore, is made up of any possible streaming situation that can be produced in the SDN testbed.

Sampling

A purposive sampling method is used in this study where certain levels of bandwidth and latency conditions are chosen to reflect real network conditions. Sampling will be performed based on design of various experimental cases, including 1 Mbps, 2 Mbps and 5 Mbps bandwidth, induced latency, and packet loss cases. According to recent studies, the purposive and scenario-based sampling is suitable in the network study experiment to assess the performance of the system when specific conditions are predetermined (Lyko et al., 2024; Uddin et al., 2025; Sidhu et al., 2025). Through this method, critical performance thresholds and QoE differences can be analyzed in detail (Woo et al., 2024). Previous research also supports the idea that the validity of experimental results in multimedia systems can be increased with the help of scenario-based sampling (Martinez et al., 2023). Therefore, the sampling plan will provide focused and significant analysis of bandwidth-latency trade-offs.

Software

The experimental environment is based on a set of open-source software to establish a versatile and reproducible SDN-based environment. Mininet is employed to emulate the network, Ryu to implement the SDN controller, VLC to stream video and iPerf to generate baseline traffic. Recent research indicates that the development of such integrated software environments allows simulating multimedia traffic realistically and precisely measuring QoE indicators (Hao et al.,

2024; Kumar et al., 2025; Bourquia et al., 2024). Also, automation, monitoring, and data analysis are performed with Python scripts, which increases the efficiency and repeatability of the system (Souza et al., 2024; Kamal, et al 2024). Previous studies also confirm that open-source SDN tools can be used to carry out cost-effective and scalable experiments (Martinez et al., 2023). Hence, the chosen software packages offer a strong and effective platform of conducting the study.

Results and Discussion

This study offers empirical findings about the effects of bandwidth and latency changes on the Quality of Experience (QoE) under SDN-based video streaming systems. The results of the experiment show that bandwidth availability has a prevailing role in the determination of streaming performance especially on high-resolution video content. In a limited bandwidth situation, high-rate streams have a longer stutter and more frequent buffering delays, resulting in poor user experience, whereas low-rate streams continue to play with only a few interruptions. These results align with more recent studies suggesting that adaptive bitrate streaming and bandwidth optimization are the key aspects in the delivery of video in dynamic networks (Woo et al., 2024; Sidhu et al., 2025; Kim et al., 2025). Furthermore, the findings support the claim that QoE cannot be measured successfully based on conventional QoS measurements only, since playback stability and buffering behavior have a considerable impact on user perception (Omar, 2024). The idea that effective bandwidth management is a direct factor in achieving better QoE through stall frequency and playback continuity is also supported by previous research (Rahman et al., 2023). Thus, the findings support the assertion that bandwidth is one of the determinants of QoE especially in SDN-controlled streaming systems.

Besides bandwidth, the experimental findings also reveal the significant role of latency and network impairments on the performance of streaming. Delay and packet loss greatly influenced high-resolution video streams as they caused unstable playback and higher buffering, but low-resolution video streams proved more resilient to the same

conditions. Such results are in agreement with recent literature that highlights that latency and jitter are significant factors that affect the deterioration of QoE, particularly in real-time and high-definition streaming (Lyko et al., 2024; Uddin et al., 2025; Sidhu et al., 2025). Moreover, the findings also indicate that bandwidth-latency interaction is a critical factor to consider when the quality of streaming is in question, which underlines the idea of cross-layer optimization of

the contemporary multimedia system (Liang et al., 2025). Previous studies confirm that network impairments increase the adverse impact of low bandwidth, so if not addressed properly, the effect of impaired network can exponentially degrade the QoE (Martinez et al., 2023). Therefore, the results of this paper highlight the need to collaboratively optimize bandwidth and latency using SDN-controlled mechanisms to ensure consistent and quality video streaming.

Experimental Results

Table 2 Streaming Performance under Different Bandwidth Conditions

Bandwidth	Video Type	Resolution	Startup Delay	Buffering	QOE
1 Mbps	High	3840×2160	~ 3 Sec	Continues	Poor
1 Mbps	Low	640x360	~ 1 Sec	None	Excellent
2 Mbps	High	3840×2160	~ 2.5 Sec	4-5 Times	Poor
2 Mbps	Low	640x360	~ 1 Sec	None	Excellent
3 Mbps	High	3840×2160	~ 2-3 Sec	Continues	Poor
3 Mbps	Low	640x360	~ 1 Sec	None	Excellent

The findings of the experiment and the results clearly indicate that there is a close correlation between the bandwidth availability, video resolution, and Quality of Experience (QoE) in the SDN-based video streaming environment. At lower bandwidth rates (1 Mbps) high-resolution video (3840×2160) suffers severe performance decline, a longer startup time (~3 seconds) and constant buffering, leading to low QoE. By contrast, low-resolution video (640x360) performs well even under these same conditions with only a small startup time (approximately 1 second) and no buffering resulting in great QoE. Even with the bandwidth of 2 Mbps and 3 Mbps, high-resolution video remains buffering (4-5 times or

continuous), which means that the moderate bandwidth remains to be not enough to sustain high-bitrate streaming. At the same time, the low-resolution video has always provided fluid playback at any bandwidth without failure. These results indicate that increased video resolutions demand significantly more bandwidth to sustain desirable QoE, whereas lower bitrate videos can endure adverse network environments. In general, the findings validate the significance of bandwidth when affecting the performance of streaming, and the lack of bandwidth causes catastrophic deterioration of QoE, especially when high-definition content is used.

Graphical Analysis

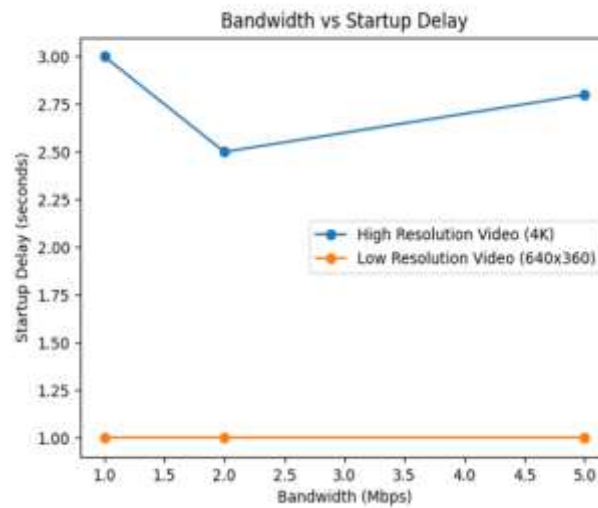


Figure 1 Bandwidth vs Startup Delay

The graph representing the relationship between Bandwidth and Startup Delay, therefore, shows that the relationship is obviously inverted between the available bandwidth and the startup delay, particularly when it is high-resolution video streams. Startup delay of high-resolution content decreases a little with increased bandwidth, but still is much higher than that of low-resolution video at all bandwidths. The lowest bandwidth (e.g. 1 Mbps) has the longest startup time (about 3 seconds) high-resolution video because it has no data transfer capacity to pre-load initial video blocks. Since the improvement in the startup delay

is low with higher bandwidth (23 Mbps), high-bitrate content requires much more bandwidth to be run well. On the other hand, low-resolution video has a fixed low startup time (approximately 1second) regardless of variation in bandwidth which implies its effectiveness and adaptability in employing networks with a limited resource base. In totality, the graph confirms that although an increase in the bandwidth can reduce the startup delay, it is more pronounced in lower bitrate streams, although high-resolution streaming is still sensitive and needs a significantly larger bandwidth to successfully come to a start.

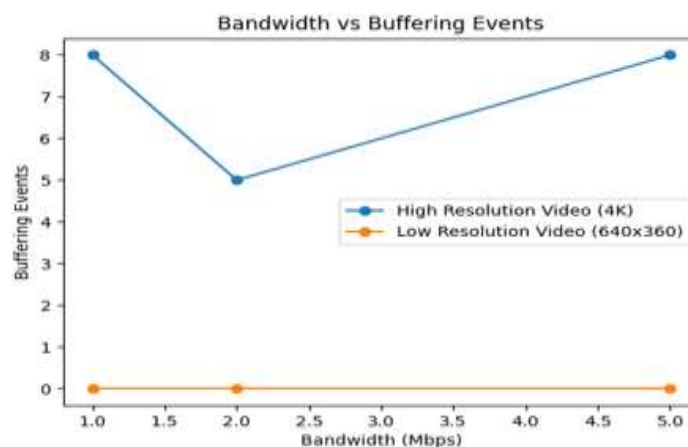


Figure 2 Bandwidth vs Buffering Events

The graph that depicts Bandwidth vs Buffering Events is a clear indication that buffering behavior is very dependent on the bandwidth availability as well as video resolution. When bandwidth is limited, high-resolution video is subject to frequent and continual buffering, which is the indication that the network capacity at hand is inadequate to support the needed data rate to support smooth video playback. Buffering events of high-resolution content are still important even when bandwidth is increased to moderate levels, indicating that high-bitrate streams are highly bandwidth-intensive to remove interruptions.

Conversely, video of low resolution shows the same performance during all bandwidth settings and no buffering incidents were recorded, indicating its efficiency and low resource usage. This means that low-bitrate streams are less sensitive to bandwidth limitations and can still continue playing even in restricted network conditions. In general, the graph validates that buffering is an important QoE indicator that is directly dependent on bandwidth constraints and that lack of bandwidth causes serious playback disruptions, especially with high-definition video content.

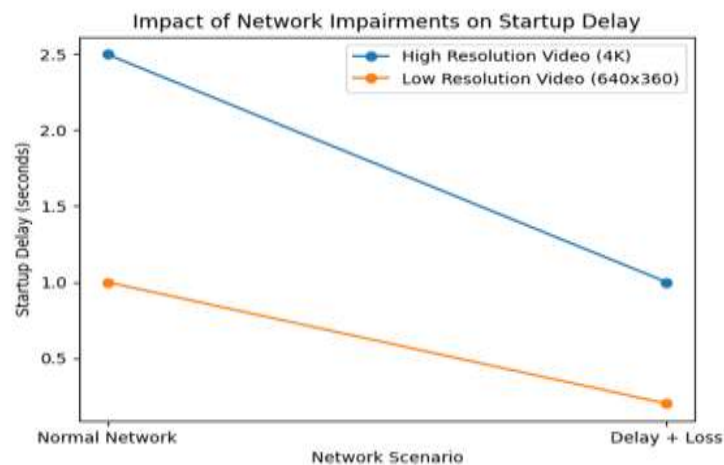


Figure 3 Impact of Network Impairments

The graph used to demonstrate effects of network impairments on startup delay indicates a significant variation in the performance in various network conditions of both high and low-resolution video streams. At typical network operating conditions, the high-resolution video has a larger start-up delay (approximately 2.5 seconds) than low-resolution video (approximately 1 second) because of its high data needs. But on adding network impairments, like delay and packet loss, it seems that the startup delay of both video types reduces, with high-resolution dropping to about 1 second and low-resolution to about 0.2 seconds. This surprising pattern could point to the fact that the poor network conditions caused the initial buffering to be less or the effective bitrate delivery to be less, resulting in a quicker playback

start, but at the expense of the overall video quality and stability during playback. Although the startup delay is lower in this case, these conditions generally lower the overall Quality of Experience (QoE) by causing more buffering and playback delays. The graph therefore indicates that startup delay, in isolation, is not an adequate measure of QoE, and should be used in conjunction with buffering and smoothness of playback to comprehensively evaluate streaming performance when there are network impairments.

This study has shown that Quality of Experience (QoE) is greatly degraded by bandwidth constraints, especially when using high-resolution video streams, which has been found in previous empirical and simulation-based studies. The experimented rise in startup delay and continuous

buffering during low bandwidth conditions can be compared to the recent studies that high-bitrate streaming demands a great amount of bandwidth to be able to maintain playback stability and prevent interruptions (Woo et al., 2024; Sidhu et al., 2025; Kim et al., 2025). Equally, the research conducted on adaptive bitrate streaming affirms that lack of adequate bandwidth causes frequent quality deterioration and buffering, and eventually, user satisfaction is minimized (Uddin et al., 2025). The existing results also reinforce previous studies that bandwidth is a major determinant of QoE, with the effective allocation of bandwidth positively affecting stall events and playback continuity (Rahman et al., 2023). Additionally, the uniformity of low-resolution video in all bandwidth conditions in this study aligns with earlier research that proposed low-bitrate streams were more robust to the network conditions and could sustain stable QoE even with constrained resources (Omar, 2024). Therefore, the findings are a great confirmation of the single-variable correlation between bandwidth and QoE and its importance in the performance of multimedia streaming.

Besides bandwidth, the experiment shows the combined impact of latency and network impairments on streaming performance, which agrees with multi-variable (cross-layer) models suggested in the literature. These results indicate that the effect of latency and packet loss on high-resolution video playback is substantial, which is consistent with the findings of the recent literature that delay and jitter are major factors influencing the decrease in the quality of experience in real-time streaming systems (Lyko et al., 2024; Sidhu et al., 2025; Liang et al., 2025). Moreover, the interdependence between bandwidth and latency in this experiment proves the relevance of unified optimization strategies because any gains in one metric are not substantial to maintain a stable QoE (Woo et al., 2024). These findings align with previous research that highlights that joint QoS-QoE modeling is required to foresee user experience with dynamic network conditions (Martinez et al., 2023). Moreover, the presence of resilience of low-resolution streams in impaired conditions confirms the previous studies that

suggested adaptive and lower bitrate streaming methods to be more resilient in heterogeneous networks (Rahman et al., 2023). Thus, the findings of this research both justify the current single-variable models and enlarge multi-variable models by showing how the bandwidth, latency, and video resolution interact critically to determine the overall QoE.

Discussion

The results of this research work make a valuable contribution to the theory of multimedia networking driven by the Quality of Experience (QoE) by supporting the current models which correlate the Quality of Service (QoS) parameters with the perceived Quality of Experience (QoE). The findings validate that the bandwidth and latency have a combined impact on the streaming performance that aligns with recent cross-layer and QoE-focused frameworks that consider the interplay of various network variables instead of only considering single effects (Sidhu et al., 2025; Liang et al., 2025; Woo et al., 2024). In theoretical terms, the paper reinforces the thesis that QoE is a multidimensional construct that is determined by the bitrate, delay, and buffering dynamics, which is consistent with contemporary adaptive streaming concepts. Nonetheless, the results also contradict some predictive models that presuppose that sufficient bandwidth is enough to guarantee acceptable QoE since the results indicate that even middle bandwidth rates (2 to 3 Mbps) are not enough to support streaming of high-resolution under dynamic conditions (Uddin et al., 2025). Moreover, although past research indicates that even more sophisticated machine learning-based prediction models of QoE can be used to optimize streaming performance, the current study reveals that the absence of real-time network control (e.g., SDN) can render even the most sophisticated performance prediction model ineffective with regards to accommodating performance variability in practice (Kim et al., 2025). Prior background literature also justifies the necessity of combined QoS-QoE models but frequently lacks experimental validation in controlled SDN settings, which this research manages to accomplish (Rahman et al., 2023).

Therefore, the research contributes to the theory by verifying and expanding multi-variable models of QoE and outlining the shortcomings of other single-parameter and predictive models.

Literature and practical-wise, the findings are consistent with the previous empirical results and can provide practical advice on how the results can be applied to the real world. The experimentally found high quality video performance in low-resolution video under limited bandwidth supports the current literature that emphasizes the applicability of adaptive bitrate streaming in ensuring consistent QoE in heterogeneous network conditions (Woo et al., 2024; Lyko et al., 2024; Sidhu et al., 2025). Also, the results of the study support previous research that highlights the fact that network impairments, including latency and packet loss, can be a major performance killer in high-bitrate streaming, which underlines the value of dynamically managing traffic (Martinez et al., 2023; bajwa et al 2023). Nonetheless, the study also has a counterargument that shorter startup delay in impaired conditions does not necessarily imply better quality of experience, which is somewhat disproved by some previous assumptions that lower delay correlates with better user experience (Omar, 2024). In practice, deploying an SDN-based testbed offers solid proof that centralized control systems can be exploited to dynamically control bandwidth and latency, which can provide better streaming performance than conventional static networks (Bourquia et al., 2024). The research also demonstrates the practical constraints of high-resolution streaming to network variations and the necessity of smart resource allocation measures in practice. Thus, the research has value to the literature since it supports proven results, refutes simplistic ideas of QoE, and offers useful information on SDN-based optimization of contemporary video streaming systems.

Conclusion

The results of this paper strongly support the empirical facts that bandwidth and latency are very important factors that determine Quality of Experience (QoE) in SDN-based video streaming systems. The findings support the argument that

high-resolution video streams are very sensitive to bandwidth constraints, where the startup delay and sustained buffering are higher in constrained bandwidth, whereas low-resolution streams are stable in playback over different network conditions. The results of the study correspond to the latest findings that highlight the role of adaptive bitrate streaming and effective bandwidth allocation in the process of delivering multimedia without issues (Sidhu et al., 2025; Woo et al., 2024; Kim et al., 2025). Theoretically, the research supports the idea that QoE is not dependent on any particular parameter but instead is a result of the interplay of various network parameters, such as bandwidth, latency, and bitrate (Liang et al., 2025). Nevertheless, the findings also point out a severe shortcoming of existing models based on the moderate bandwidth as a sufficient condition to stream in high-quality since the experimental results have shown that even 23 Mbps cannot support stable high-resolution video playback (Uddin et al., 2025). The importance of effective resource management is also supported in the previous literature but is not always experimentally proven in SDN context, which is effectively achieved in this study (Rahman et al., 2023). Thus, the research paper makes a contribution to the field by confirming the existence of multi-variable QoE models and delivering experimental data of bandwidth versus latency trade-offs in controlled SDN scenarios.

Besides theoretical contribution, the study provides meaningful literature and practical contribution by proving that SDN-based architectures are effective to control network resources towards better streaming performance. Running a Mininet and Ryu-based testbed offers a reproducible and flexible platform of studying the real-time network behavior, which is in line with recent papers that recommend programmable networking in the context of multimedia optimization (Bourquia et al., 2024; Lyko et al., 2024; Sidhu et al., 2025). The results also prove that low-bitrate streaming strategies are more robust in constrained and impaired network conditions, which supports the previous research on adaptive streaming methods (Woo et al., 2024). The study questions the assumption that

minimized startup delay is a positive sign of improved QoE, though, network impairments can artificially minimise startup delay at the expense of overall playback stability (Omar, 2024). In practice, the findings imply that service providers are to consider the dynamic allocation of bandwidth and the latency control techniques (especially SDN-based control tools) to streamline the performance in the real-life scenario (Martinez et al., 2023). Therefore, the research is valuable both in terms of confirming the literature and providing practical information that can guide the development of smart, QoE-based video streaming systems.

Future Research Directions

The future study must build on the present one by integrating new analytic and intelligent optimization models to improve on the prediction of QoE and network performance in dynamic networks. Although this research follows a controlled experimental SDN design, future research can incorporate machine learning and deep learning algorithms like LSTM, reinforcement learning, and predictive analytics to allow real-time adjustments of bandwidth and latency parameters (Kim et al., 2025; Sidhu et al., 2025; Liang et al., 2025). Moreover, considering 5G/6G and edge-assisted architectures would enhance the realism of the multimedia ecosystem of the present day with user mobility and heterogeneous networks playing a crucial role in QoE (Woo et al., 2024). Methodologically, the present research is constrained by the use of simulation-based settings (Mininet and Ryu), which might not be able to effectively represent all complexities of a network in the real-world, including large-scale traffic variability and hardware-level limitations (Martinez et al., 2023). Additionally, the lack of human-centric QoE validation, e.g., subjective user feedback or Mean Opinion Score (MOS), is a shortcoming of the ability to fully describe the perceived user experience (Rahman et al., 2023). Thus, to enhance the generalizability and practicality of results, hybrid methods a combination of experimental, simulation, and user-based

evaluation techniques should be used in future research.

The managerial and practical implications of the findings of this study are that it is essential to implement adaptive and smart network management approaches in order to maximize video streaming performance in real-life applications. The SDN-based architectures can also assist service providers and network operators in deploying dynamic bandwidth allocation and latency control systems that would guarantee stable QoE under different network conditions (Bourquia et al., 2024; Lyko et al., 2024; Sidhu et al., 2025). Moreover, the findings indicate that the priorities of adaptive bitrate streaming and edge computing solutions can largely contribute to the overall user experience by minimizing buffering and enhancing the stability of playback, especially with high-resolution content (Woo et al., 2024). Nevertheless, other practical issues, like the cost of infrastructure, scalability, and the complexity of implementing AI-based optimization structures to the current systems, must be also taken into account by organizations (Kim et al., 2025). Moreover, the work is contextually constrained to a controlled experimental setting as opposed to a particular nation or mass implementation, limiting its immediate relevance to the different real world markets. Consequently, the subsequent research and management practice should be based on practice-oriented implementation, cross-country ratification, and scalable storage plans to achieve the maximum potential of video streaming systems based on QoE.

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