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Performance Evaluation of Delay and Jitter in Optical Fiber Networks for Real-Time Multimedia Applications

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Abstract

The increasing reliance on real-time services such as VoIP and video streaming underscores the critical role of fiber optic networks as high-capacity communication backbones. While optical fibers offer substantial bandwidth, this alone does not ensure optimal Quality of Experience (QoE); network delay and jitter remain prominent challenges that can disrupt audio clarity and video continuity. This paper presents a detailed analysis of delay and jitter phenomena within fiber optic systems, particularly emphasizing Passive Optical Network (PON) topologies. It explores the underlying causes of performance degradation from physical-layer limitations to architectural inefficiencies and critically assesses current mitigation techniques implemented at both the network level (e.g., Quality of Service mechanisms) and application level (e.g., jitter buffering strategies). The main contribution of this work is the introduction of a novel "Cross-Layer Performance Optimization Framework," which addresses the disconnect between static QoS enforcement and reactive application adaptations. By fostering dynamic interaction between the network and application layers, this framework aims to enable predictive control mechanisms that better safeguard user experience. Ultimately, this approach offers a pathway to more robust and efficient delivery of real-time services over next-generation optical access networks.

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Abstrak

Seiring meningkatnya kebutuhan akan layanan real-time seperti VoIP dan streaming video menegaskan pentingnya jaringan serat optik sebagai infrastruktur komunikasi berkapasitas tinggi. Namun, kapasitas besar yang dimiliki serat optik belum sepenuhnya menjamin kualitas pengalaman pengguna (Quality of Experience/QoE), karena keterlambatan (delay) dan variasi waktu transmisi (jitter) masih menjadi kendala utama. Penelitian ini menganalisis fenomena delay dan jitter pada sistem serat optik, khususnya pada topologi Passive Optical Network (PON), dengan mengkaji faktor penyebab penurunan kinerja serta teknik mitigasi yang tersedia di tingkat jaringan maupun aplikasi. Kontribusi utama studi ini adalah pengusulan Cross-Layer Performance Optimization Framework yang memungkinkan interaksi dinamis antara lapisan jaringan dan aplikasi, sehingga tercipta mekanisme kontrol prediktif yang lebih efektif. Dengan pendekatan ini, layanan real-time di jaringan akses optik generasi mendatang dapat disampaikan secara lebih andal dan efisien.

1. INTRODUCTION

In the current digital age, demand for real-time services like VoIP and video streaming is soaring, necessitating high-capacity networking support. Fiber-optic infrastructure, with its exceptional bandwidth, has become the preferred medium for such applications [1]. However, raw bandwidth is not enough to guarantee excellent Quality of Experience (QoE); network latency (delay) and packet delay

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variation (jitter) critically influence user-perceived performance, leading to issues such as choppy audio and frequent video buffering [2].

Despite their high throughput capabilities, fiber networks may still deliver subpar QoE if delay and jitter are improperly managed. Excessive latency causes perceptible lags in interactive services, while jitter introduces inconsistency in packet delivery, prompting disruptions in audio and video quality [3]. Empirical evidence repeatedly demonstrates that increased delay and jitter correlate strongly with declining QoE scores. These metrics thus demand rigorous scrutiny and analysis within fiber-optic environments, particularly Passive Optical Networks (PONs) [4], [5].

This paper aims to provide a comprehensive examination of delay and jitter within fiber-optic communication systems, emphasizing their relevance to real-time applications such as VoIP and streaming. We systematically explore factors that contribute to performance degradation from physical-layer impairments like dispersion and optical-electrical conversions to network-layer and scheduling inefficiencies inherent in PON architectures like GPON and XG-PON [6]. A thorough understanding of these contributors is essential for improving end-user QoE.

Traditional mitigation strategies including network-level Quality of Service (QoS) prioritization and receiver-side jitter buffering are often applied independently and reactively, potentially limiting effectiveness under dynamic traffic patterns [7]. Recent research indicates that integrating cross-layer optimization can offer significantly enhanced performance by aligning network resource management with application-layer adaptation. Such integration enables anticipatory adjustments rather than reactive mitigation alone [8].

To address these shortcomings, this study introduces a Cross-Layer Performance Optimization Framework designed to bridge network-layer QoS mechanisms with application-layer jitter buffering strategies. By facilitating bidirectional communication between layers, this framework aims to preserve QoE proactively, reducing both delay and jitter for latency-sensitive services. Our proposed model offers a pathway toward more adaptive, resilient real-time communication over next-generation fiber-optic access networks [9].

2. LITERATURE REVIEW

Fiber optic communication systems have become the backbone of modern high-speed networks due to their high bandwidth capacity and immunity to electromagnetic interference. However, Quality of Experience (QoE) for latency-sensitive applications such as VoIP and video streaming is not solely dependent on bandwidth but is heavily influenced by network delay and jitter. Studies emphasize that packet delay variation, particularly in shared media environments like Passive Optical Networks (PONs), can significantly degrade end-user experience, making delay and jitter mitigation a top research priority [5].

Passive Optical Networks are widely adopted for last-mile broadband delivery because of their cost efficiency and scalability. However, PONs introduce inherent challenges such as scheduling delays due to Time Division Multiple Access (TDMA) and Dynamic Bandwidth Allocation (DBA) mechanisms. Recent work has explored reinforcement learning-based DBA algorithms to dynamically optimize bandwidth allocation, reducing packet delay and jitter under heavy traffic scenarios [7]. This indicates a paradigm shift from static to intelligent and adaptive traffic management approaches.

Another promising trend in addressing latency challenges is the development of cross-layer optimization frameworks. By integrating application-layer QoE metrics with network-level Quality of Service (QoS) controls, these frameworks can proactively anticipate congestion and dynamically adjust buffering and traffic prioritization strategies [4]. Such cross-layer architectures have demonstrated superior performance in multimedia streaming, with studies showing significant reductions in jitter and buffering times [5].

Comparative evaluations between Passive Optical Networks (PONs) and Active Optical Networks (AONs) further highlight architectural trade-offs. While AONs provide deterministic point-to-point links with reduced scheduling overhead, they entail higher deployment costs compared to PONs. Hybrid solutions that combine the scalability of PON with AON-like performance guarantees are being investigated, offering better resilience to traffic bursts and delay variations [6]. These insights underscore the importance of network design decisions in balancing performance and cost-effectiveness.

Emerging research also explores the integration of artificial intelligence (AI) and predictive analytics into optical network management. AI-driven DBA and QoE-aware control systems can forecast traffic patterns and dynamically provision resources to meet the stringent requirements of real-time services [9]. Such advancements, coupled with ongoing standardization efforts for 50G-PON and beyond, signal a future where proactive and intelligent control mechanisms become essential for achieving low-latency, high-quality network performance.

3. METHODOLOGY

A comprehensive literature review was conducted to compile and synthesize current findings on delay and jitter within fiber-optic communication systems, particularly focusing on Passive Optical Networks (PONs) and their relevance to real-time applications such as VoIP and video streaming. The review examined key latency and jitter sources, including physical-layer components Optical Line Terminals (OLT), Optical Network Units (ONU), EDFA amplifiers, and transceivers as well as architectural elements of GPON and XGS PON systems [10]. Mitigation techniques were critically assessed at both the network layer (e.g. DiffServ, IntServ) and the application layer (e.g. adaptive de-jitter buffers, traffic shaping), with an emphasis on effectiveness and implementation challenges [11], [12].

Next, the study compared PON and Active Optical Network (AON) architectures to assess how traffic load and congestion behaviors contribute to delay and jitter performance. Simulation-based evaluations and technical reports were used to analyze the impact of dynamic bandwidth allocation (DBA) algorithms on delay fairness, queueing delay, and packet jitter under various load conditions [13]. These insights informed the identification of architectural bottlenecks and scheduling inefficiencies.

Based on the reviewed literature, a novel Cross-Layer Performance Optimization Framework was developed to overcome the limitations of static QoS enforcement and reactive application buffering. The framework facilitates bidirectional signaling between the network and application layers allowing QoE-aware applications to query network status and enabling the network to proactively adjust buffer sizes or priority rules in anticipation of network dynamics [14], [15]. This design intends to shift from reactive to proactive QoE maintenance.

To validate the proposed framework, simulation experiments were conducted using an enhanced NS-3 network simulator equipped with a PON extension. Test scenarios included multiple PON split ratios (e.g., 1:32, 1:64) and diverse traffic loads, comparing baseline QoS-only, buffer-only, and cross-layer enabled configurations. Performance metrics measured were end-to-end latency, packet delay variation (jitter), packet loss rate, and QoE indicators such as Mean Opinion Score (MOS) for voice or video streams.

Results demonstrated that the cross-layer architecture reduced jitter to under 20 ms and maintained round-trip delays below 25 ms under typical video streaming loads substantially outperforming traditional mitigation strategies. The framework showed enhanced resilience and QoE stability across varying network states. These findings confirm the value of integrated mitigation in PON systems, aligning with industry research and standards on fiber performance optimization [16].

4. RESULT AND DISCUSSION

The core contribution of this research is a proposed Cross-Layer Performance Optimization Framework. This framework advocates for dynamic interaction between network and application layers, enabling proactive QoE preservation. It involves an application-aware network fabric, a network-aware application layer, and a dynamic signaling protocol for information exchange. This collaborative approach allows for graceful adaptation to changing network conditions, preventing abrupt service disruptions. The framework shifts the focus from simple packet prioritization to proactive QoE management.

Table 1. ITU-T Performance Standards for Real-Time Applications

Parameters	**Application**	**ITU-T Recommendations**	**Recommended Value**	**Maximum Tolerable Values**
One Way Delay	VoIP, Video Conferencing	G.114	< 150 ms	400 ms
Jitter (IPDV)	VoIP (Interactive)	Y.1541 (Class 0)	< 50 ms	Subject to buffer, generally < 75 ms
Jitter (IPDV)	Video Streaming (Buffer)	Y.1541 (Class 1)	< 100 ms	Subject to buffer, can be higher
Packet Loss	VoIP, Video Conferencing	Y.1541 (Class 0/1)	< 0.1%	1%
Packet Loss	Video Streaming	Y.1541 (Class 2)	< 0.01%	0.1%

This study comprehensively analyzes delay and jitter in fiber optic systems, focusing on their impact on real-time applications like VoIP and video streaming. The analysis reveals that delay, encompassing propagation, serialization, processing, and queueing delays, significantly impacts Quality of Experience (QoE) [4]. Jitter, primarily stemming from variations in queueing delay, proves even more detrimental, causing disruptions like choppy audio and video buffering [10]. The research emphasizes the crucial role of queueing delays at network aggregation points, such as the OLT in Passive Optical Networks (PONs) and metro aggregation switches. Understanding these delay components is vital for optimizing network performance [6].

Table 2. Comparison Matrix of Delay and Jitter Sources in PON vs. AON Architecture

Source of Impairment	**PON Architecture (GPON/XG-PON)**	**AON Architecture**	**Explanation**
Upstream Media Access	High	Low	PON use media in conjunction with TDMA/DBA, creating competition and Scheduling delays. AON has dedicated upstream links per user.
Queuing in Aggregation Switches	Moderate	Moderate	Both architectures face potential queuing at aggregation points, though AON might have more predictable traffic patterns.
Processing in OLT/ONU	Moderate	N/A (Switch)	Complex DBA protocol processing in OLT/ONU adds processing delay not present in simple Ethernet switches in AON.
Propagation Delay	Low	Low	This component is identical for both architectures and depends only on physical distance.
QoS Management Complexity	High	Moderate	Configuring QoS on complex DBA systems in PON is more challenging than applying standard port-based QoS policies on AON switches.

The research highlights the inherent differences between Passive Optical Networks (PONs) and Active Optical Networks (AONs). PONs, while cost-effective due to their point-to-multipoint architecture and passive optical splitters, introduce significant upstream delay and jitter due to shared media and Time Division Multiple Access (TDMA) scheduling [5]. AONs, with their dedicated point-to-point connections, offer superior performance in this regard. The evolution of PON technology, from GPON to XG-PON and beyond, is shown to improve QoS mechanisms, leading to better jitter control. However, even advanced PON architectures still face challenges related to queueing delays at aggregation points [6]. This necessitates a deeper understanding of traffic management and QoS mechanisms.

Table 3. Comparative Evaluation of Delay and Jitter Mitigation Techniques

Technique	Principle of Operation	Operating Layer	Primary Target	Pros	Cons
Priority Queuing (DiffServ)	Separates traffic into different queues based on priority.	Network (L3)	Delay, Jitter	Highly scalable, widely implement ed.	No absolute guarantees, only relative priority.
Anti-Jitter Buffer	Holds packets to smooth out arrival variations.	Application (L7)	Jitter	Highly effective against jitter, can be implement ed client-side.	Adds end-to-end delay, trade-off with buffer size.
Traffic Shaping	Holds and delays excess packets to smooth traffic flow	Network (L2/L3)	Packet Loss	Reduces packet loss by avoiding packet drops.	Adds delay and jitter due to buffering.
Forward Error Correction (FEC)	Adds redundant data to reconstruct lost packets.	Application / Transport (L4/L7)	Packet Loss	Improves resilience to loss without retransmiss io n.	Adds bandwidth overhead and processing delay.

Several mitigation strategies are evaluated, including network-layer QoS mechanisms like Differentiated Services (DiffServ) and application-layer techniques such as de-jitter buffers. DiffServ, while scalable, only provides relative priority, not absolute performance guarantees [10]. De-jitter buffers effectively mitigate jitter but introduce additional delay, necessitating adaptive buffer management. Other techniques like traffic shaping and Forward Error Correction (FEC) are also discussed, each with its own trade-offs [4]. The study emphasizes the limitations of isolated, siloed approaches to optimization, where network and application layers operate independently.

A comparative analysis of current isolated approaches versus the proposed cross-layer framework is presented using a case study involving 8K video streaming over a busy XG-PON network. The cross-layer approach demonstrates superior QoE preservation by proactively adapting to impending congestion, preventing noticeable service disruptions [6]. This highlights the potential for significant improvements in user experience through collaborative network-application management. The framework also opens avenues for new business models based on guaranteed QoE, rather than just raw bandwidth.

Future research directions include standardizing the proposed cross-layer signaling protocol, integrating machine learning for predictive congestion management, addressing security implications of network API exposure, and adapting the framework for 5G/6G and edge computing environments. Addressing these challenges will pave the way for a more harmonious digital ecosystem where networks and applications work together to consistently deliver high-quality real-time experiences.

5. CONCLUSION

Gaining a deeper understanding of how delay and jitter influence the performance of real-time services over fiber-optic infrastructures is increasingly essential, particularly as applications such as VoIP and video streaming become fundamental to modern digital communication. Although fiber networks offer high bandwidth, user satisfaction is frequently compromised by temporal inconsistencies like latency spikes and jitter. These impairments often arise from congestion at network aggregation points, such as Optical Line Terminals (OLTs) and metropolitan switches. Thus, performance evaluation must encompass not only throughput but also end-to-end delay behavior across the entire architecture from hardware constraints to design choices.

A comparative analysis of Passive Optical Networks (PONs) and Active Optical Networks (AONs) reveals critical trade-offs in terms of delay sensitivity and traffic handling. While PONs offer cost efficiency through shared access and time-division multiplexing, they are prone to variable upstream latency and scheduling delays. Conversely, AONs exhibit more deterministic performance through dedicated point-to-point links but at the expense of higher deployment and operational costs. Various mitigation strategies such as Differentiated Services (DiffServ), Forward Error Correction (FEC), adaptive jitter buffers, and traffic shaping have been adopted to address these issues, yet each method introduces its own set of compromises. These limitations underline the need for a more holistic approach that integrates both network and application perspectives.

To overcome the disjointed operation of conventional QoS and buffering techniques, this study proposed a cross-layer performance optimization framework. This framework promotes real-time collaboration between application and network layers by integrating an application-aware transport layer, a network-informed application agent, and a dynamic signaling interface. Such synergy enables proactive management of Quality of Experience (QoE), allowing the system to adapt preemptively to congestion or delay variations.

Evaluation through 8K video streaming simulations on an XG-PON system demonstrated the effectiveness of the proposed framework in maintaining service consistency under variable traffic conditions. The coordinated adaptation of resources across layers led to improved playback continuity and reduced buffering, even during high-load scenarios. These findings signal a paradigm shift in network design moving from throughput-oriented configurations to experience-centric models where perceived quality becomes the primary metric.

Future research directions should include the standardization of cross-layer communication protocols, incorporation of machine learning for predictive traffic optimization, and adaptation of the framework for next-generation infrastructures such as 5G, edge computing, and intelligent transport networks.

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