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Enhancing Real-Time Video Streaming Quality via MPT-GRE Multipath Network

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Abstract: The demand for real-time 4K video streaming has introduced technical challenges due to the high bandwidth, low latency, and minimal jitter required for high-quality user experience. Traditional single-path networks often fail to meet these requirements, especially under network congestion and packet loss conditions, which degrade video quality and disrupt streaming stability. This study evaluates Multipath tunnel- Generic Routing Encapsulation (MPT-GRE), a technology designed to address these challenges by enabling simultaneous data transmission across multiple network paths. By aggregating bandwidth and adapting dynamically to network conditions, MPT-GRE enhances resilience, maintains quality during network disruptions, and offers throughput nearly equal to the sum of its physical paths' throughput. This feature ensures that even if one path fails, the technology seamlessly continues streaming through the remaining path, significantly reducing interruptions. We measured key video quality metrics to assess MPT-GRE's performance: Structural Similarity Index Measure (SSIM), Mean Squared Error (MSE), and Peak Signal-to-Noise Ratio (PSNR). Our results confirm that the MPT-GRE tunnel effectively improves SSIM, PSNR, and reduces MSE compared to single-path streaming, offering a more stable, high-quality viewing experience. Our results indicate that analyzing the SSIM, MSE, and PSNR values for 4K video streaming using the MPT tunnel demonstrates a significant performance improvement compared to a single path. The improvement percentages of the SSIM and PSNR values for the MPT tunnel are (29.05% and 29.04%) higher than that of the single path, while MSE is reduced by 81.17% compared to the single path.

Keywords: MPT-GRE; streaming; tunnel; 4K; SSIM; MSE; PSNR

Academic Editor: Liyuan Liu

Received: 16 December 2024
Revised: 15 January 2025
Accepted: 23 January 2025
Published: 25 January 2025

Citation: Al-Imareen, N.; Lencse, G. Enhancing Real-Time Video Streaming Quality via MPT-GRE Multipath Network. *Electronics* **2025**, *14*, 497. https://doi.org/10.3390/electronics14030497

1. Introduction

The need for high-quality video streaming, particularly real-time 4K video, has increased with the growth of digital platforms, remote communication, and entertainment services, which deliver high-resolution video in real-time. However, meeting these demands presents challenges due to substantial bandwidth requirements, latency sensitivity, and jitter over traditional single-path networks. In response, multipath communication protocols have emerged as a promising solution to enhance the reliability, throughput, and efficiency of data transmission in such environments. Video streaming has become one of the primary uses of communication networks. It is estimated that 65.93% of Internet traffic is attributed to video streaming [1–3]. Video streaming has become globally popular for applications ranging from entertainment to online education and work, though consistently providing high-quality streaming services remains challenging for smart devices due to their limited computational capacity, energy supply, and the highly dynamic nature of wireless channels [3,4].

Multipath networking, where data are distributed across multiple network paths simultaneously, offers several advantages over traditional single-path systems. By aggregating bandwidth from various paths and utilizing path variety, multipath protocols can reduce congestion, lower latency, and enhance resilience against packet loss or network failures. The ability to enhance overall throughput and maintain stable network performance is especially valuable for real-time applications like 4K video streaming, which require high data rates and low-latency communication to maintain video quality [5–8].

Despite their promising benefits, multipath networks also face various challenges. These include managing packet scheduling, ensuring fair resource allocation across paths, especially in complex network environments, and efficiently selecting optimal paths. While multipath routing improves performance through better reliability and higher throughput, it still encounters challenges with packet scheduling and path selection in complex environments [9]. Advancements in network optimization, congestion control, and technology development are crucial to fully realizing the potential of multipath networks. These solutions are vital to the flexibility and efficiency of multipath networks for high-performance applications such as high-quality video streaming, underscoring the need for further research and development in this area. One promising solution to these challenges is the MPT-GRE library, which encapsulates data packets across several network paths. This library also enables efficient packet reordering mechanisms, allowing for robust and seamless transmission even in network variability [10]. The positive impact of multipath networks on real-time 4K video streaming remains a critical area of research to develop protocols or techniques that handle all network conditions, especially concerning evaluating video quality metrics such as throughput, jitter, and delay under the massive growth of dynamic network usage [11].

Many multipath solutions face challenges due to path heterogeneity, where variations in latency, jitter, and packet loss across different paths result in out-of-order packet delivery. This situation requires complicated reordering mechanisms, which can add extra processing overhead and delay. Some multipath approaches do not achieve optimal throughput aggregation, even using multiple paths, because of ineffective congestion control strategies, asymmetrical paths, and poor packet scheduling [9,12]. In contrast, MPT-GRE addresses this limitation. MPT-GRE includes an optimized packet reordering mechanism that reduces the effects of path heterogeneity. By adjusting reorder window parameters based on current network conditions, MPT-GRE minimizes latency and jitter.

Furthermore, MPT-GRE effectively distributes traffic across multiple paths, enhancing congestion control and load-balancing strategies to maximize overall throughput. Our previous studies have shown that the tunnel throughput is roughly equal to the combined throughput of the two paths. This significantly improves data transmission rates, especially for high-bandwidth applications like 4K video streaming.

While MPT-GRE provides significant advantages for improving network throughput and minimizing quality degradation, its use in transmitting high-resolution video has some limitations. The overhead associated with GRE encapsulation and tunneling can lead to higher bandwidth consumption, potentially offsetting the benefits of multipath aggregation, especially in constrained network environments. Also, variations in path characteristics, such as high packet loss rates or high latency, can also adversely affect synchronization, resulting in fluctuations in video quality.

The main contributions of this paper are as follows:

- An evaluation of real-time 4K video streaming performance in MPT-GRE multipath networks by calculating and comparing widely used video quality metrics SSIM, MSE,

and PSNR before and after transmission via the first path (single path) and MPT-GRE tunnels (multipath) to measure the solution's effectiveness.
- A demonstration of the benefits of throughput aggregation in the MPT-GRE network for enhancing 4K video streaming quality.

The paper evaluates the performance and efficiency of real-time 4K video streaming using the MPT-GRE multipath network by comparing video quality when streamed through a single path versus the MPT-GRE tunnel. Video quality metrics SSIM, MSE, and PSNR were chosen for their complementary strengths in measuring signal fidelity, perceptual quality, and pixel-level error, providing a comprehensive assessment of video quality under multipath network conditions. These metrics demonstrate how the tunnel's throughput aggregation can significantly enhance video streaming quality.

2. Related Work

Video streaming has become a hot topic in recent years, with multipath communication technologies emerging as a promising solution to mitigate communication system breakdowns during data transmission. Implementing these technologies in Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) protocols has proven effective in enhancing network reliability and performance, particularly for real-time video streaming.

Ghufran Baig et al. [13] presented Jigsaw, a system designed to address the challenges of live 4K video streaming over wireless networks using commodity devices. They proposed a layered video coding technique that adapts efficiently to the variable throughput of wireless links, a GPU-based video coding implementation to optimize processing on commodity devices, and the combined use of Wi-Fi and WiGig networks through delayed video adaptation and intelligent scheduling. The researchers evaluated Jigsaw's performance through real-world experiments and emulation, demonstrating improved video quality with increased SSIM.

B. Almasi et al. [10] examined the performance of the MPT-GRE in the UDP multipath communication environment in response to network failures, specifically evaluating its resilience in maintaining video stream transmission during interruptions. Their analysis assessed the system's effectiveness in reducing the adverse effects of both scheduled and unexpected breakdowns, with Wi-Fi 3G vertical handovers used during various failure scenarios. Results indicated that video transmission using TCP flow was largely uninterrupted during scheduled breakdowns, demonstrating TCP's scalability under controlled conditions. However, unexpected failures caused slight stuttering in the video stream, highlighting the system's sensitivity to unforeseen disruptions. Overall, this study emphasizes the potential of MPT-based multipath communication to enhance the robustness of video streaming. However, some performance impacts remain, particularly with unexpected breakdowns and unbuffered UDP transmissions. Nonetheless, the system shows a capacity for recovery and continued service under challenging network conditions.

Begen et al. [14] developed a set of models for Multiple Description (MD) streaming over multiple paths and proposed a path selection method to optimize video quality for clients. This method selects paths to maximize performance under various network constraints, improving the consistency of streaming quality. In simulations using MPEG-2, the proposed approach demonstrated significant gains in average Peak Signal-to-Noise Ratio (PSNR), with increases ranging from 0.73 to 6.07 dB compared to using only the shortest or maximally link-disjoint paths. These improvements contribute to a more consistent streaming experience for end users. Additionally, the approach outlines the architecture and mechanisms required to implement multipath streaming over conventional IP networks, offering a practical framework for enhancing video performance in multipath environments.

Some researchers sought to develop the Bandwidth-Efficient Multipath Streaming (BEMA) protocol to address the limitations of traditional throughput-oriented and content-agnostic multipath video transport protocols. These older protocols need help managing the high bandwidth demands and delay sensitivity of real-time video streaming. BEMA introduces priority-aware data scheduling to prioritize video packets based on importance and incorporates forward error correction to ensure reliable transmission. Through Exata simulations evaluating real-time H.264 video streaming, BEMA improved key performance metrics, including video PSNR, end-to-end delay, and bandwidth utilization. These enhancements make BEMA a robust solution for delivering high-quality real-time video streaming across diverse wireless network environments, addressing the specific challenges posed by bandwidth and latency constraints [15]. Additionally, the researchers [7] developed a system to improve the Quality of Experience (QoE) for live 4K video streaming using Hypertext Transfer Protocol (HTTP) Adaptive Streaming (HAS). They addressed the challenges of high latency and video freezing during bandwidth fluctuations using the HTTP/2 server push feature and an OpenFlow-based network controller. Their methods reduced live latency and mitigated video freezes, improving user experience in challenging network conditions. Their study concluded that these approaches offer a promising solution to enhance HAS performance in real-time 4K video applications.

Hideaki Matsue et al. [16] experimented with transmitting 4K video over a local 5G uplink. They intentionally introduced packet errors by adding load to the transmission path. This study compared the performance of Real-Time Transport Protocol (RTP) and Secure Reliable Transport (SRT) under different conditions, focusing on Round-Trip Time (RTT), video transmission speed, and subjective video quality. The results showed that RTP performed better in terms of RTT when there was no added load, while the use of SRT resulted in a higher average RTT, especially under heavy load. However, SRT demonstrated greater resilience in maintaining video playback continuity during network strain. This study emphasized the practical importance of Quality of Service (QoS) in prioritizing video transmission, providing valuable insights for network engineers and video transmission professionals. Ultimately, RTP was superior in low-load environments, while SRT excelled in challenging, overloaded conditions.

Based on the previous literature, no prior studies have explored the integration of MPT-GRE with 4K video streaming, and this research is the first to investigate this area. Specifically, our study is new in focusing on MPT-GRE and examines the transmission of 4K video streaming over an MPT-GRE tunnel. This contribution is essential, as it offers new insights into the performance of MPT-GRE for delivering high-resolution video. Unlike previous research, which mainly explores general multipath transport solutions, our work delves into the challenges and benefits of using MPT-GRE to enhance video streaming performance by taking advantage of the tunnel throughput aggregation capability, equivalent to the sum throughput of the two physical paths. This paper provides an in-depth quantitative evaluation of video quality improvements facilitated by MPT-GRE, utilizing widely recognized metrics such as SSIM, MSE, and PSNR. These metrics enable a precise assessment of video quality enhancements achieved through MPT-GRE, setting this work apart from existing multipath solutions and evaluations presented in [6,9,12–15].

3. Overview of MPT-GRE Technology

The traditional TCP/IP protocol stack design restricts communication sessions to a single network interface, even though modern IT devices have multiple interfaces. To improve user experience by increasing throughput and resilience to network failure, a research group at Debrecen University developed a network layer multipath solution called MPT [17]. MPT creates a tunnel over multiple paths using the GRE-in-UDP encapsulation, distinguishing itself from other solutions such as Multipath TCP (MPTCP) and Huawei's GRE Tunnel Bonding Protocol. MPT can function as a router, distributing packets across different networks between the tunnel endpoints to establish a site-to-site multipath connection. MPT is independent of the IP version, making it suitable for IPv6 transition purposes [18].

MPT is an extension of the GRE-in-UDP encapsulation, offering enhanced performance by enabling the load balancing of GRE traffic across multiple paths. A GRE-in-UDP tunnel improves load distribution in Equal-Cost Multipath (ECMP) networks by using the UDP source port, providing additional entropy for ECMP hashing, and distributing traffic more effectively across multiple paths. As illustrated in Figure 1, the MPT architecture extends the GRE in UDP by enabling multiple physical paths. While it shares some similarities with MPTCP in utilizing multiple paths, MPT differs in its underlying technology by relying on UDP as the transport layer and building on GRE in UDP to provide a tunnel IP layer, supporting TCP and UDP protocols. Huawei's GRE Tunnel Bonding Protocol has similar objectives but uses GRE without UDP encapsulation, limiting it to two physical interfaces. MPT's use of GRE in UDP allows it to avoid this limitation, making it a more flexible multipath solution.

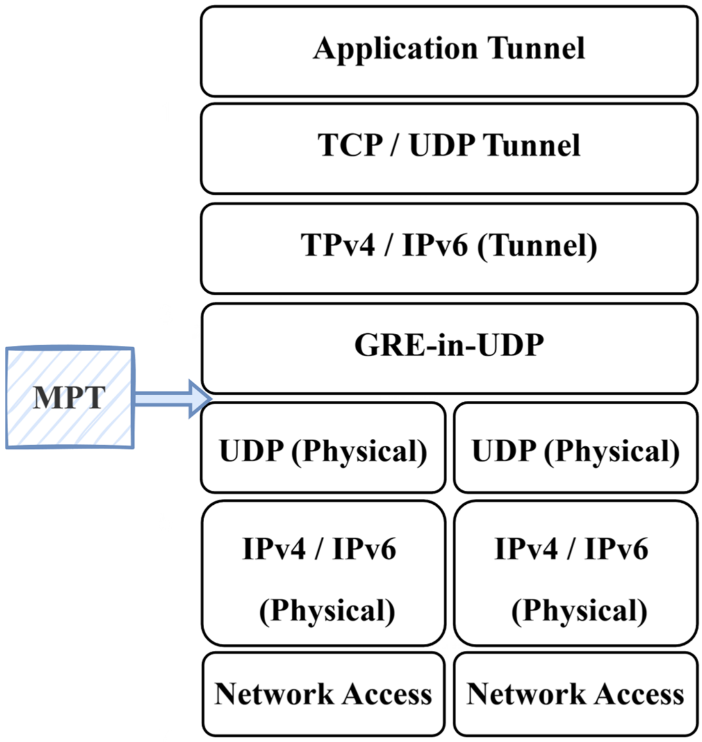

Figure 1. The conceptual architecture of MPT-GRE [17].

Figure 2 illustrates the process of transmitting and receiving data packets in MPT. When a packet is received from the tunnel interface, the MPT software identifies its connection specification. This specification governs the behavior of multipath communication and determines how packets are allocated to available paths. Once a path is selected, the user data packet is encapsulated as a GRE-in-UDP data unit. This encapsulation may optionally include GRE sequence numbers for reordering purposes. The simplest GRE header consists of four octets: 16 bits of zeros and 16 bits for protocol type identification, such as 0x0800 for IPv4 or 0x86DD for IPv6 on the tunnel interface. The GRE-in-UDP data unit is then encapsulated within a UDP/IP data unit for the chosen path, with the destination UDP port number set to 4754, the GRE-in-UDP port. The path definition dictates the IP addresses used, which can be IPv4 or IPv6. After encapsulation, the packet is transmitted through the designated physical interface. When a packet arrives from the physical interface, its destination UDP port number is checked to ensure it matches the GRE-in-UDP port (4754). The MPT software processes the packet by identifying the connection based on the source and destination IP addresses in the tunnel IP header. It then performs various validation checks, such as verifying connection validity, the GRE sequence number, and the GRE key value (if present). If the packet passes all checks and reordering is not required, it is immediately forwarded to the transport and application layers via the tunnel interface. If reordering is enabled and the GRE sequence number reveals missing data units, the packet is temporarily stored in a buffer array for reordering before further transmission [19].

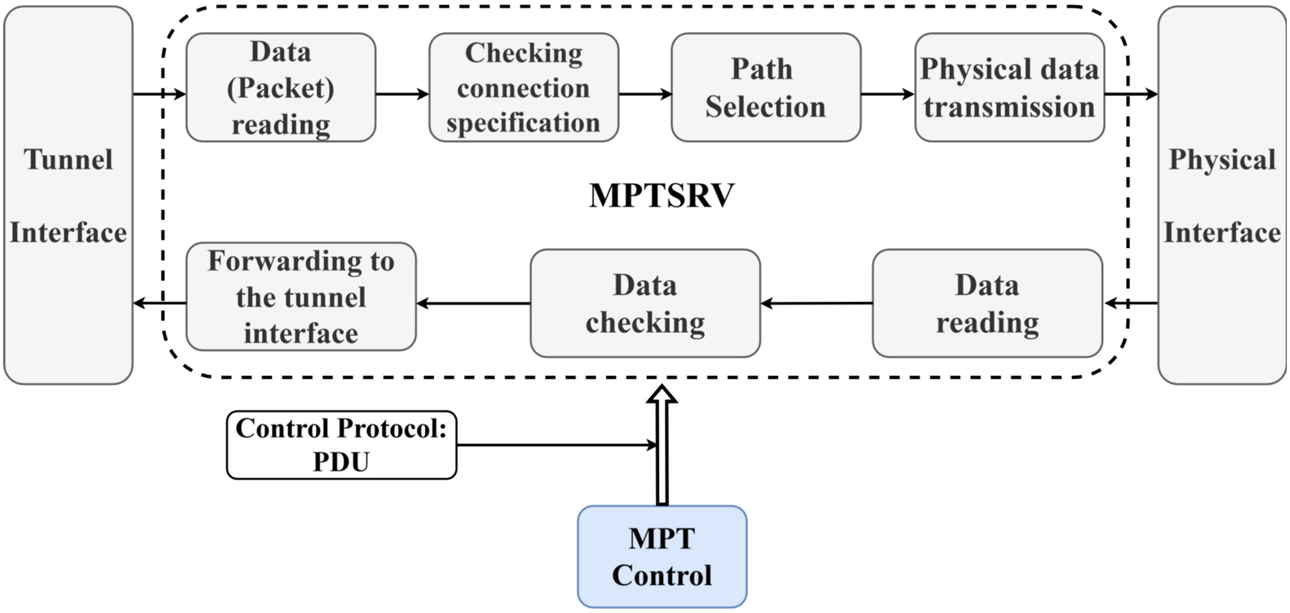

Figure 2. The theoretical process of the MPT-GRE mechanism [17].

4. MPT Configuration Guidelines

The MPT configuration files contain essential information that can be divided into two primary groups: general information for the MPT server and connection specifications.

The configuration file is organized into multiple sections, with the "general" section being mandatory. This section defines the fundamental operational parameters required for the MPT server's functionality. Specifically, it specifies the total number of tunnels to be created, whether remote commands from other MPT servers are accepted for establishing connections not defined in local configuration files, the local command port used for communication with the MPT client, and the command timeout value.

Each tunnel is described in a separate section and includes parameters such as its unique name and the Maximum Transmission Unit (MTU) crucial for determining packet size (calculated as 1500 minus the combined sizes of the Path IP header, UDP header, and GRE header) and both IPv4 and IPv6 addresses, with at least one address required. A single tunnel can be utilized by multiple connections, with each connection uniquely identified by the IP addresses of its two endpoints, ensuring they belong to the same IP version.

The connection specifications are organized into three main sections: "connection", "paths", and the optional "networks" section. The "connection" section defines essential attributes, including a unique connection name, permissions for sending and receiving updates, the IP version (IPv4 or IPv6), local and remote IP addresses, and various port numbers used for data communication and control commands, including the GRE-in-UDP port number (4754) [20].

Additionally, this section specifies the number of paths and networks associated with the connection, with a minimum path count of one and a maximum value that is implementation dependent. The initial status of the connection is also indicated, where a value of zero denotes an active connection. The authentication type is specified to determine whether control communication requires authentication. Optional parameters include the reorder window, which enables packet reordering based on GRE sequence numbers; the maximum buffer delay for ordered packet transmission; and an authentication key for secured communication, though some algorithms may not require it.

The "paths" section contains detailed path definitions, which include the physical interface name (e.g., eth0, wlan0), the IP version, the public and remote IP addresses, and the gateway IP for reaching the peer. A weight parameter is included to allocate transmission capacity proportionally when per-packet-based mapping, with values ranging from 1 to 10,000. The initial status of the path can be set as "up" for active use or "down" for deactivation. Additional optional path parameters include the interface's private IP address. A keepalive mechanism monitors path availability by transmitting periodic messages and a dead-time threshold that marks a path as inactive after a prolonged absence of keepalive responses. There is also a weight-in parameter for adjusting path priorities on the peer side and a command default option that designates a specific path for control command communication.

The optional "networks" section further refines routing configurations by specifying network definitions through IP versions, source and destination addresses, and prefix lengths. This section enables multipath Internet connectivity by defining 0.0.0.0/0 as the destination address, where the source address corresponds to the tunnel's assigned IP.

These structured configurations collectively ensure the efficient operation of the MPT server, optimized tunnel management, and robust multipath communication capabilities.

5. Waterloo Streaming QoE Database

The Waterloo Streaming Quality of Experience (QoE) Database III (SQoE-III) [21], comprising 20 pristine, high-quality videos with a resolution of 1920 × 1080, was selected to encompass a wide range of content, including humans, plants, natural scenes, architecture, screen content, and computer-generated scenes. Among these, RushHour, TallBuildings, and TrafficAndBuilding were sourced from the SJTU 4K video dataset [22], with each video lasting 10 s. Detailed specifications for these videos are provided in Table 1. Additionally, spatial information (SI) and temporal information (TI) offer an approximate measure of video complexity. The video sequences exhibit significant variation in spatio-temporal complexity and span a broad range within the SI-TI space. Each video was encoded with an x264 encoder into eleven different representations and bitrates (235, 275, 560, 750, 1050, 1750, 2350, 3000, 4300, 5800, and 7000 kbps). The videos were processed using a set of algorithms and different conversions, considering 13 different network conditions to evaluate video streaming performance.

Additionally, subjective assessments conducted by 34 individuals provide valuable insights into user perceptions of streaming quality. SQoE-III is notable for its large size, variety, and comprehensive evaluation of the streaming experience, making it a valuable resource for researchers and practitioners. Figure 3 shows screenshots of the original video sources. It is important to note that the SQoE-III data were created using a range of source resolutions and distortion methods to ensure a natural representation of real-world strategies. We also selected some videos from external 4K sources outside the database [23].

Table 1. Specifications and variation in reference videos [21].

Name	FPS	SI	TI	Description
BigBuckBunny	30	96	97	Animation, high motion
BirdOfPrey	30	44	68	Natural scenes, smooth motion
Cheetah	25	64	37	Animal, camera motion
CostaRica	25	45	52	Natural scenes, smooth motion
CSGO	60	70	52	Game, average motion
FCB	30	80	46	Sports, average motion
FrozenBanff	24	100	88	Natural scenes, smooth motion
Mtv	25	112	114	Human, average motion
PuppiesBath	24	35	45	Animal, smooth motion
RoastDuck	30	60	84	Food, smooth motion
RushHour	30	52	20	Human, smooth motion
Ski	30	61	82	Sports, high motion
SlideEditing	25	160	86	Screen content, smooth motion
TallBuildings	30	81	13	Architecture, static
TearsOfSteel1	24	53	66	Movie, smooth motion
TearsOfSteel2	24	56	11	Movie, static
TrafficAndBuilding	30	66	15	Architecture, static
Transformer	24	72	56	Movie, average motion
Valentines	24	40	52	Human, smooth motion
ZapHighlight	25	97	89	Animation, high motion

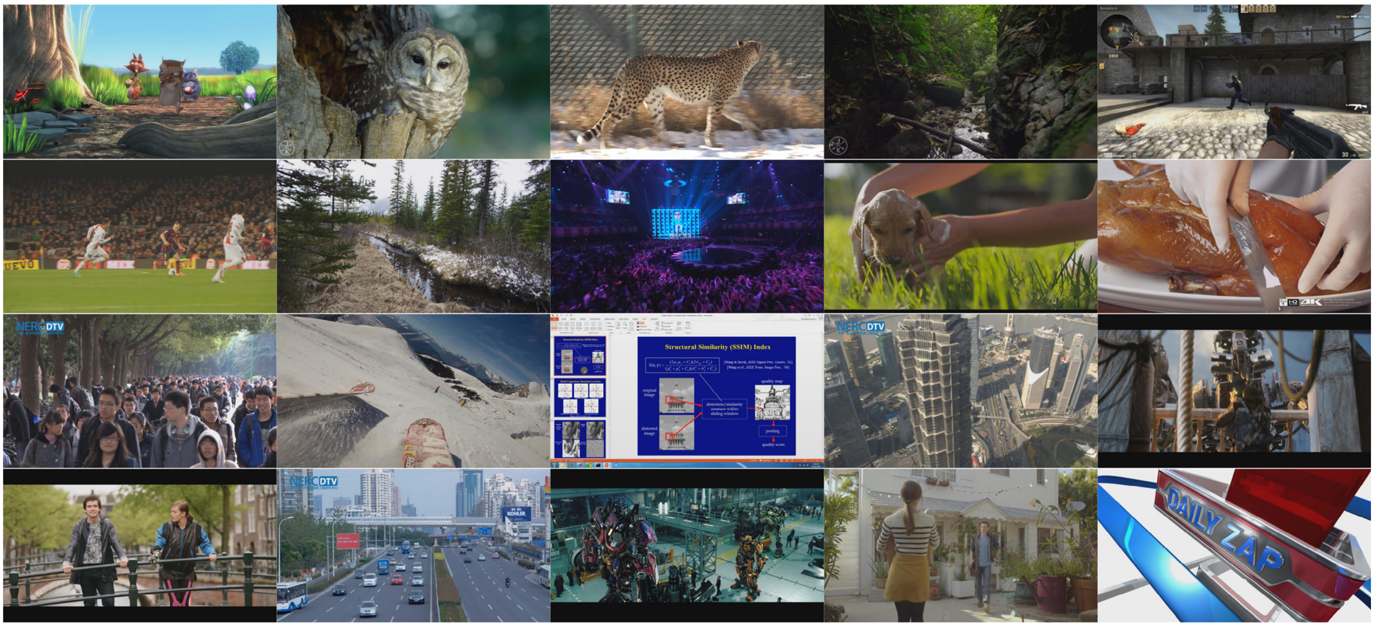

Figure 3. A snapshot of Waterloo Database video sequences [21].

6. Video Quality Assessment Metrics

Video quality assessment metrics are essential for evaluating video content's fidelity and perceptual quality [24]. One such metric is as follows:

- The Structural Similarity Index Measure (SSIM) evaluates the structural similarity between two images by measuring luminance, contrast, and structure. SSIM ranges from -1 to 1, where 1 indicates perfect similarity. The index is calculated using a formula that incorporates the mean, variance, and covariance of the original and processed images, represented by μx, μy, $\sigma x2$, $\sigma y2$, and σxy. The formula for SSIM is shown in Equation (1):

$$SSIM(x,y) = \frac{(2\mu x\mu y + c1)(2\sigma xy + c2)}{\left(\mu_x^2 + \mu_y^2 + c1\right)\left(\sigma_x^2 + \sigma_y^2 + c2\right)} \quad (1)$$

where *c1* and *c2* are constants used to stabilize the division when dealing with a weak denominator.

- Mean Squared Error (MSE) evaluates the average squared difference between corresponding pixels of the original and processed videos, providing a quantitative measure of reconstruction accuracy. Often used alongside SSIM, MSE is calculated by averaging the squared differences in pixel values between the original and processed images, as shown in Equation (2):

$$MSE = \frac{1}{mn}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}(I(i,j) - K(i,j))^2 \quad (2)$$

where I and K represent the intensity values of the corresponding pixels in the original and processed images, and m and n are the dimensions of the images.

These metrics enable objective comparisons between encoding methods, supporting informed decision-making in video processing applications like compression, streaming, and transmission optimization.

- Peak Signal-to-Noise Ratio (PSNR) is expressed in decibels (dB) and compares the peak signal power to the power of the noise, thus quantifying the level of degradation introduced during compression or transmission. It is computed as the ratio of the maximum possible pixel value squared (usually 255 for 8-bit images) to the MSE between the original and processed images, as shown in Equation (3):

$$PSNR = 10.\log_{10}\left(\frac{MAX^2}{MSE}\right) \quad (3)$$

7. Experimental Test Environment

7.1. Hardware and Infrastructure Setup

A test system was established to measure and analyze video streaming performance in the MPT-GRE multipath network, as illustrated in Figure 4. The experiment utilized two Dell PowerEdge R620 servers were sourced from Dell Technologies, based in Round Rock, United States with the following specifications:

- Memory: 4 × 8 GB 1333 MHz DDR3 SDRAM
- Processors: Two 6-core Intel Xeon E5-2620 processors clocked at 2.00 GHz
- Network Interface Card (NIC): Intel quad-port Gigabit Ethernet controller, with two ports engaged for testing purposes.

The two interfaces were connected through a Cisco Catalyst 3550 switch manufactured by Cisco Systems, Inc., Thailand, with bandwidths limited to 5 Mbps and 20 Mbps. Two independent physical paths (eth1, eth2) were established between the interfaces, with corresponding IP addresses assigned within the experimental network.

The experiment's bandwidth settings were designed for real-world network conditions, incorporating various path capacities, adaptive bandwidth fluctuations, and constraints specific to 4K video streaming. We configured paths with 5 Mbps and 20 Mbps transmission speeds with the proper weights (weight_out) for these paths.

The MPT-GRE software created the tunnel (tun0) between the two servers, which operated on the Ubuntu 22.04.4 LTS (Jammy Jellyfish) Linux operating system. This experimental setup aimed to assess the effectiveness of the MPT-GRE tunnel in real-time 4K video streaming. Performance was evaluated using videos from the Waterloo Streaming QoE Database, with quality metrics SSIM, MSE, and PSNR employed to quantify improvements in streaming quality.

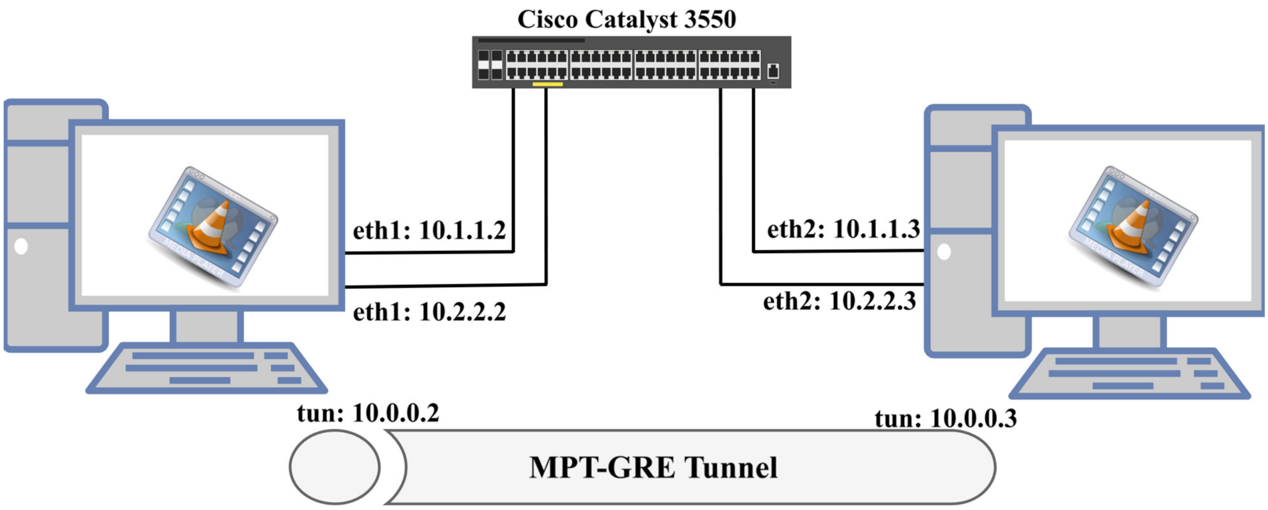

Figure 4. MPT-GRE multipath network topology of real-time 4K video streaming.

7.2. VLC Media Player Software Configuration

Video LAN Client (VLC) Media Player [25] was configured with specific settings to optimize video transmission and playback performance for streaming and receiving video over both the MPT-GRE tunnel and a single path. The following steps outline the adjustments made to facilitate the video streaming process:

(1) *Video Source Selection*: The video file was first added to the stream on the source machine, which acts as the server in this experiment.

(2) *Transcoding Configuration*: To ensure compatibility and efficient streaming, the H.264 codec was selected for video transcoding, and the MP3 codec was chosen for audio. These codecs were selected due to their widespread use in video streaming and ability to balance compression and quality.

(3) *Destination Setup*: The MPT-GRE tunnel address or the IP address of the first path was specified as the destination for video transmission, along with a designated port number. Using specific port numbers helped segregate traffic between single-path and multipath scenarios.

(4) *Protocol Selection*: HTTP protocol was employed for video streaming in single-path and multipath environments. This choice was made because HTTP adaptive streaming is commonly used for reliable video delivery across diverse network conditions.

(5) *Video Recording at the Destination*: On the destination machine, VLC's recording feature was utilized to save the video received through either the MPT-GRE tunnel or the first path address. This allowed for the post-transmission analysis of the video quality and performance.

7.3. MPT Software Configuration

The MPT software's configuration is crucial for the experimental setup, especially for enabling the MPT-GRE tunnel functionality. The version used in this experiment is mpt-gre-lib64-2019.tar.gz, a 64-bit version specifically designed for multipath GRE over UDP transport, available from a repository [26]. The MPT installation directory contains two main configuration files that need modification to ensure the proper operation of the MPT-GRE multipath system across the network infrastructure.

1. Interface Configuration:
   The first configuration file, conf/interface.conf, contains critical parameters related to the network interfaces and tunnels. The following adjustments have been made:
   (a) *Local Command UDP Port Number*: Defines the port for managing communication between the MPT software and the network interfaces.
   (b) *Interface Number and Tunnel Information*: Specifies the interface number, maximum transfer unit, and acceptance of remote requests. It also defines the tunnel interface's name and assigns an IPv4 address and a prefix length to indicate the subnet.
   (c) *Tunnel Management*: Details the management of the tunnel interface, ensuring that the software can handle traffic routes through the MPT-GRE tunnel effectively.

A similar configuration was applied to the second server's interface to maintain consistency in the setup, enabling a fully functional multipath environment.

2. Tunnel and Connection Configuration:
   The second configuration file, conf/connections/IPv4.conf, organizes the logical connections and defines the paths for data transmission. Each MPT-GRE tunnel is organized into separate connection files, specifying the relevant IP addresses for both tunnel endpoints. The configuration utilizes IPv4 encapsulation within an IPv4 GRE tunnel, enabling the multipath routing of video packets between the two servers across multiple physical network paths. Constant-length data fields ensure consistent packet formatting for GRE encapsulation.

Previous work has provided detailed documentation of these configuration settings on GitHub [27]. These configurations form the backbone of the MPT software's ability to aggregate and manage multiple network paths, enabling more reliable and efficient video transmission across the MPT-GRE tunnel. By setting up and adjusting the MPT software with these parameters, the experiment can evaluate the effects of MPT-GRE on video streaming performance in real time. This configuration ensures that video data are split and transmitted over multiple paths, offering improved resilience against network failures and potentially enhancing the overall quality of the end-user experience.

To conduct the experiment and ensure controlled network conditions, the transmission speed of both network paths was set to x Mbps using the Traffic Control (tc) command, where x represents the transmission speeds as follows:

tc qdisc add dev eth1 root tbf rate xmbit burst 32 kbit latency 100 ms

This setup enforces a consistent bandwidth limit on each path, allowing for a more accurate analysis of the MPT-GRE tunnel's performance in a controlled network environment. The video streaming process was initiated from the first Dell PowerEdge R620 server, which acted as the sender, with the VLC media player handling video playback and streaming. The H.264 codec was chosen for its efficiency in video compression and widespread use in streaming applications. The HTTP protocol was used to stream the video over both the single path and the MPT-GRE tunnel. HTTP is commonly chosen for video streaming due to its compatibility and ease of use in networked environments.

On the receiver side, the video stream was collected via two methods. First, the video was received at the tunnel's destination IP address (10.0.0.2) through the MPT-GRE tunnel (tun0), achieving a throughput approximately equal to the sum of the two physical paths. Second, the video was received via the single network path (first path) at IP address 10.1.1.2. VLC's recording feature was used to record the video received through either the MPT-GRE tunnel or the first path. The recorded video files were evaluated using a custom Python 3.10 script that calculated the average SSIM, MSE, and PSNR values, which are publicly available on GitHub [28], created by the authors, as shown in Algorithm 1.

Algorithm 1: Video Quality Evaluation

Input:
- Original video *O*, Streamed video *S*.

Output:
- Average PSNR, SSIM, Average MSE.

Steps:

Step 1:
- Create empty lists for storing PSNR, SSIM, MSE values.
- Initialize frame_count to 0.

Step 2:
- Open and load *O*, *S* for processing.

Step 3: While (frames are available from both videos) do:
- Read the current frame of both the *O* and *S*.
- If no more frames are available, exit the loop.
- Convert frames F_i of O, *S* to grayscale.
- Calculate PSNR, SSIM, MSE between frames of *O*, *S*.
- Append the calculated metrics to PSNR, SSIM, MSE lists.
- Store the F_i as the F_{i-1} for the next iteration.
- Increase frame_count by 1.

Step 4:
- Once all frames have been processed, close the video files.

Step 5:
- Calculate average PSNR, SSIM and MSE from their lists.

Step 6:
- Open a text file for each video.
- Write (video name, and average PSNR, SSIM, MSE values).
- Close the file.
- Output a message indicating that the metrics saved to the file.

End

8. Evaluation of Video Streaming Performance

We conducted two separate experiments to evaluate the quality of real-time video streaming over the MPT-GRE network layer multipath communication library. We measured video quality metrics in each experiment before and after transmission through two network configurations: single-path transmission using the first physical path and multipath transmission using the MPT-GRE tunnel.

In the first scenario, we assessed the quality metrics SSIM, MSE, and PSNR for 20 videos at the highest resolution in the Waterloo database, 1920 × 1080, with a bitrate of 7000 Kbps and a transmission speed of 5 Mbps. Analyzing the SSIM results in Figure 5 shows that the MPT-GRE tunnel effectively maintains video quality, for instance, in the "BirdOfPrey" video, the SSIM metric calculated between the original video and the video transmitted via the single path is 0.6911, indicating a noticeable decline in structural similarity. In contrast, the SSIM value between the original video and the video transmitted using the MPT-GRE tunnel is 0.9855, demonstrating significantly higher structural similarity. This improvement proves the tunnel's ability to maintain video quality more effectively than the single path.

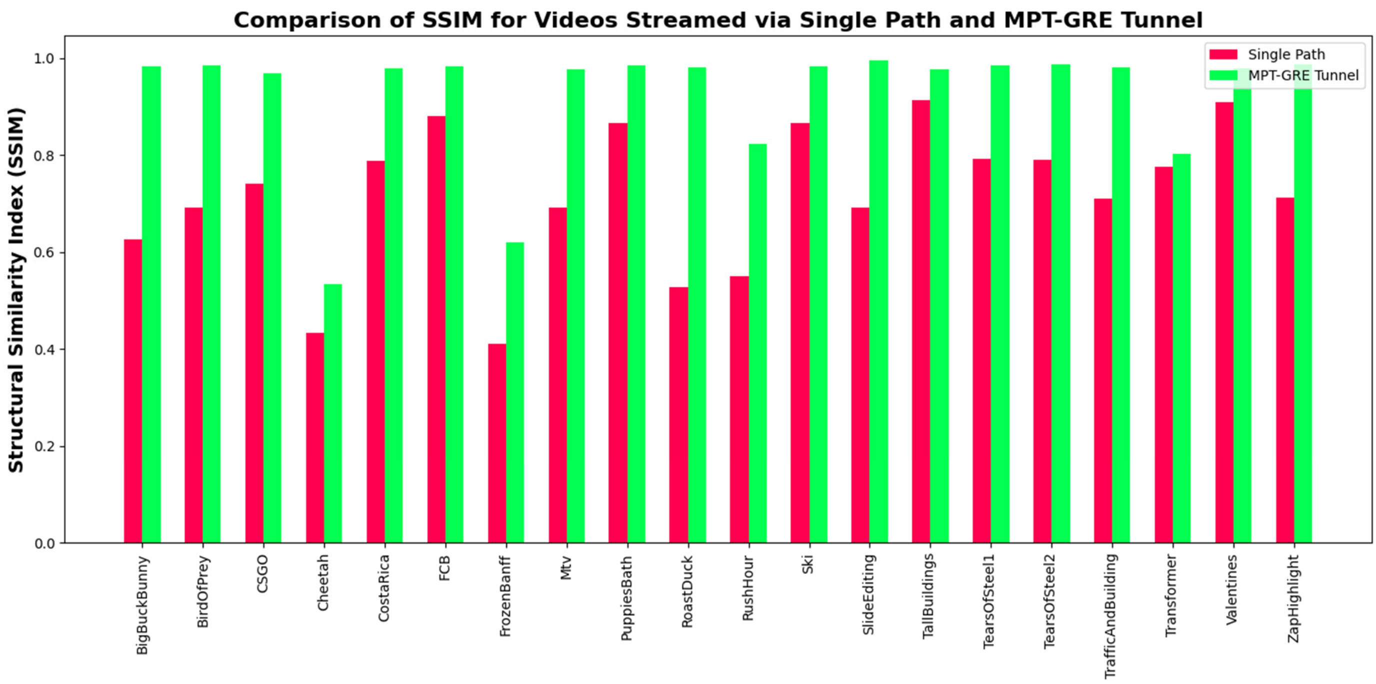

Figure 5. SSIM comparison for different videos streaming via the single path and MPT-GRE tunnel.

Another example is the "TallBuildings" video for evaluating the impact of transmission methods on video quality. When transmitted via a single path, the SSIM value is 0.9129, reflecting a reasonable structural quality loss. While this reduction is less pronounced compared to other videos, it still signifies the limitations of single-path streaming in preserving video fidelity. Conversely, the MPT-GRE tunnel achieves an SSIM of 0.9775, closely approximating the original video's structural similarity. This minimal reduction highlights the tunnel's effectiveness in maintaining the original video's structure and visual fidelity. Thus, for the "TallBuildings" video, the MPT-GRE tunnel once again outperforms the single path, ensuring that video quality remains nearly identical to the original. This performance demonstrates that the MPT-GRE tunnel preserves video quality with less degradation in the SSIM metric.

The MSE metric results, shown in Figure 6, support the findings from the SSIM analyses. The "BirdOfPrey" video contrasts the performance of the two transmission methods when assessed through MSE values. The single path yields a significantly higher MSE of 163.5632, reflecting significant quality degradation during streaming. The MPT-GRE tunnel achieves a substantially lower MSE of 54.3437, approximately one-third of the single-path's value. This comparison underscores the tunnel's efficiency in minimizing video quality loss, as its MSE is considerably closer to the ideal level, preserving the original video's integrity far more effectively than the single path. This performance presents the tunnel's capability to provide more reliable and higher-quality video streaming.

For a deeper understanding, an analysis of the "Tall Buildings" video demonstrates how transmission paths impact video quality. Streaming through a single path results in an MSE of 126.8007, indicating a moderate quality degradation level. However, this degradation is less severe than in other videos under similar conditions. In contrast, the MPT-GRE tunnel achieves a significantly lower MSE of 69.7457, representing a notable improvement over the single path. This reduction emphasizes the tunnel's ability to effectively minimize quality loss and maintain a higher level of video fidelity. This result demonstrates the tunnel's effectiveness in mitigating quality degradation compared to the single path.

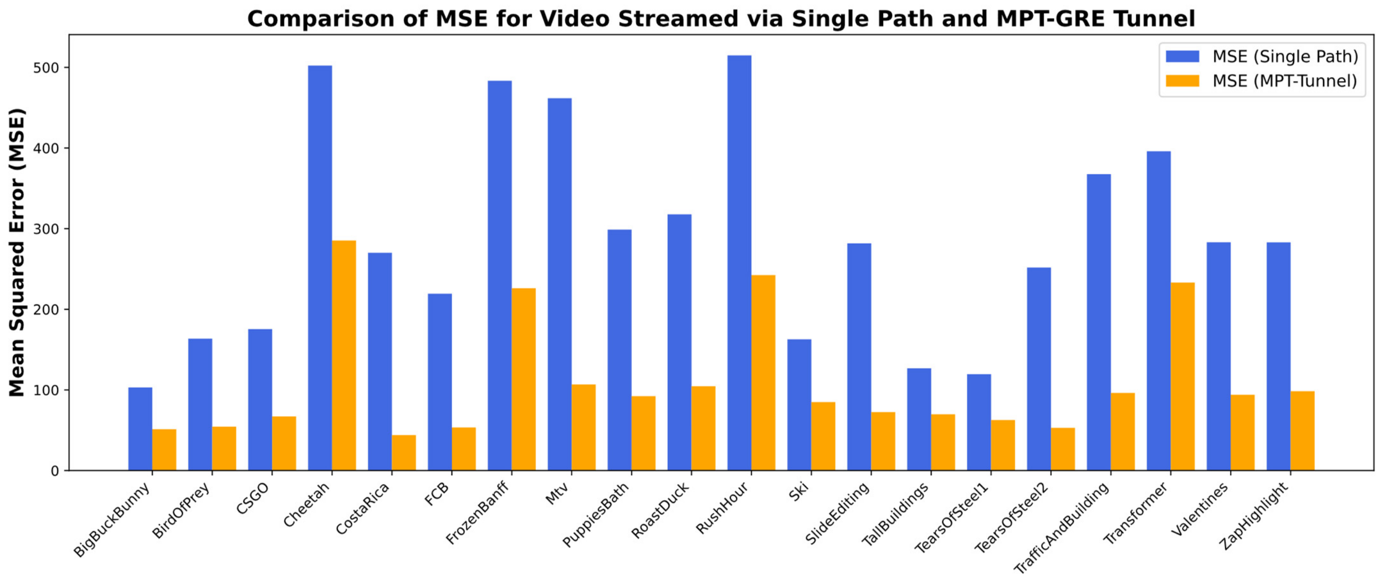

Figure 6. MSE comparison for different videos streaming via the single path and MPT-GRE tunnel.

Analyzing the PSNR results in Figure 7 illustrates the advantage of the MPT-GRE tunnel over the single-path method in preserving video quality. For instance, in the case of the "BirdOfPrey" video, after transmission through the single path, the PSNR metric calculated between the original video and the video transmitted via the single path is 30.1183 dB. Conversely, the same video streamed through the MPT-GRE tunnel exhibited an improvement in video quality with a PSNR value of 41.8681 dB. This result shows that the MPT-GRE tunnel retained a PSNR closer to the original, indicating that the tunnel's multipath capabilities are highly effective in mitigating quality degradation during transmission compared to the single-path method.

The "TallBuildings" video demonstrates the benefits of using the MPT-GRE tunnel over a single video stream path. This video is high quality and has well-defined details. Videos featuring architectural structures, like tall buildings, often contain intricate textures, lines, and contrasts, making them especially sensitive to degradation during streaming. The PSNR metric calculated between the original video and the video transmitted via the single path is 33.1323 dB. In contrast, the MPT-GRE tunnel demonstrated much better preservation of the original video quality, with a post-transmission PSNR of 37.6791 dB, with an improvement percentage of 14%. This result indicates that the tunnel effectively mitigated the impact of network fluctuations.

After analyzing the results in the first scenario, it is evident that MPT-GRE tunneling outperforms the single path in all cases by reducing video quality degradation, as indicated by higher SSIM, PSNR values, and lower MSE values.

This superior performance helps preserve the original resolution of the video, ensuring that viewers experience sharper visuals and finer details, even in high-resolution streams with minimal quality loss.

In the second scenario, we evaluated the video quality metrics SSIM, MSE, and PSNR for seven 4K resolution videos from [23], using the same setup and configuration for video streaming as in the first scenario and a transmission speed of 20 Mbps. The experimental results demonstrate that the MPT-GRE tunnel is feasible and effective for real-time 4K video streaming applications, outperforming existing single-path methods.

By analysis, the SSIM values in Table 2 provide further evidence of the MPT-GRE tunnel's effectiveness in maintaining video quality during real-time 4K streaming on the first path. For instance, the video with index 5 shows that after streaming, the SSIM on the single path is 0.6520, indicating a significant decrease in quality. In contrast, when streamed through the MPT-GRE tunnel, the SSIM is 0.9811, demonstrating a high structural similarity between the original and streamed video. This suggests minimal perceptual degradation and preservation of video quality close to the original content.

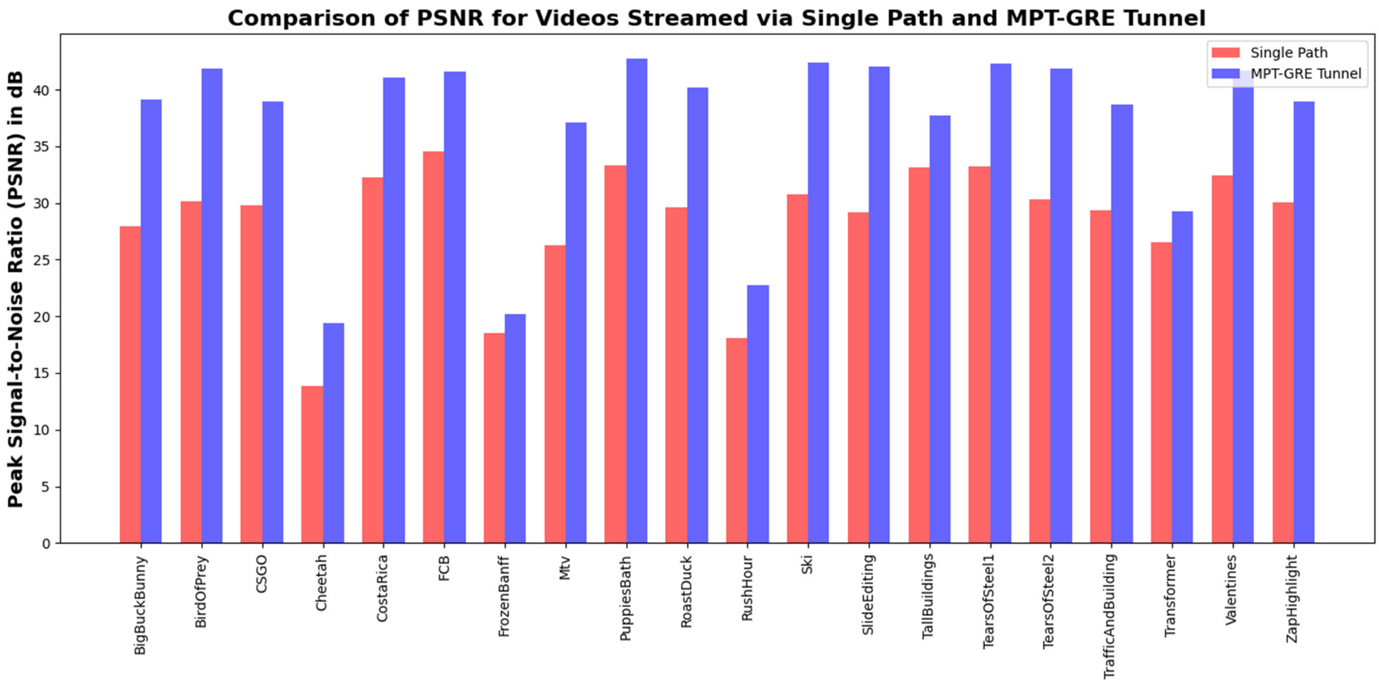

Figure 7. PSNR comparison for different videos streaming via the single path and MPT-GRE tunnel.

Table 2. Comparison of SSIM For 4K videos streaming via the single path and MPT-GRE tunnel.

Index	SSIM (Single Path)	SSIM (MPT Tunnel)
1	0.9004	0.9804
2	0.6344	0.9228
3	0.6642	0.9383
4	0.9077	0.9877
5	0.6520	0.9811
6	0.8280	0.9828
7	0.6113	0.7931

For more details, the analysis of the SSIM for the video with index 4 reveals noteworthy results regarding the impact of the multipath networks on video quality. After transmission over a single path, the SSIM value is observed to be 0.9077, indicating a moderate degradation in video quality. However, when the video is streamed through the MPT-GRE tunnel, the SSIM is 0.9877, suggesting a much smaller reduction in quality, giving more reasonable evidence of the tunnel's ability to mitigate video quality degradation more effectively than the single path. The comparison emphasizes the potential benefits of utilizing MPT-GRE tunnels for enhanced video quality in multipath network environments.

The SSIM analysis shows a statistically significant improvement in structural similarity when using the MPT tunnel compared to the single path. The mean SSIM value for the MPT tunnel is 0.9409, which is considerably higher than the single path's value of 0.7426, which means that the MPT tunnel does a better job of preserving the original video's structural integrity.

The 95% confidence intervals reinforce this result, as the MPT tunnel's SSIM values range between 0.8763 and 1.0055, compared to the broader and lower range of the single path (0.6215 to 0.8636). This means greater consistency in video quality when using MPT.

The paired t-test statistics are −5.1983, with a p-value of 0.0020. The low p-value (<0.05) [29] indicates a statistically significant difference between the two transmission methods. The results support the conclusion that MPT significantly improves video quality compared to single-path transmission, minimizing structural degradation and maintaining visual fidelity.

The MSE values in Table 3 highlight performance differences between a single path and the MPT-GRE tunnel in preserving 4K video quality. Higher MSE values generally indicate a greater loss of quality during transmission, while lower values reflect better preservation of the original video.

Table 3. Comparison of MSE For 4K videos streaming via the single path and MPT-GRE tunnel.

Index	MSE (Single Path)	MSE (MPT Tunnel)
1	88.1834	8.1812
2	210.4927	92.0566
3	261.3947	11.4122
4	21.9226	7.9225
5	265.5961	9.1485
6	165.9958	7.1631
7	183.8081	56.2438

The data suggest that the MPT-GRE tunnel consistently outperforms the single path in limiting error increases. For example, an analysis of the video with index 1 shows a significant difference in video quality between the MPT-GRE tunnel and the single path. The Mean Squared Error (MSE) for videos streamed through the MPT-GRE tunnel is 8.1812, indicating a relatively minor degradation in quality compared to the original video. In contrast, the MSE for the same video transmitted over the single path is 88.1834, demonstrating a substantial increase in error and a noticeable degradation in visual fidelity. Similarly, in the video with index 5, the MSE for the MPT-GRE tunnel is low at 9.1485, which indicates minor distortion and a high level of video quality preservation. In contrast, when the video is streamed over a single path, the MSE increases dramatically to 265.5961, reflecting a significant deterioration in video quality. This improvement further emphasizes the tunnel's capacity to handle high-quality 4K videos, minimizing quality loss even when the original video had low error rates.

The analysis of MSE demonstrates a considerable reduction in error when employing the MPT tunnel compared to a single-path transmission. The mean MSE for the single path is 171.0562, whereas the MPT tunnel reaches a significantly lower 27.45, significantly improving video quality.

The 95% confidence intervals further highlight this difference. The confidence interval for the single path (88.38 to 253.73) is much broader and higher than that of the MPT tunnel (−3.60 to 58.49). The negative lower bound in the MPT tunnel's confidence interval means that some variations approach near-zero error, supporting the tunnel's capability to minimize distortion.

The paired t-test statistics of 4.34, with a p-value of 0.00488, confirm that this difference is statistically significant ($p < 0.05$). This result strongly supports that the MPT-GRE tunnel significantly enhances video streaming quality by reducing distortion and error rates.

The MSE values suggest that the MPT-GRE tunnel significantly reduces transmission errors and preserves the overall quality of 4K video streams compared to a single path. This evidence indicates that the tunnel is better suited to handle the high bandwidth demands of 4K videos, providing a more reliable solution for maintaining video fidelity during transmission.

Analyzing the results in Table 4, we observed that the MPT-GRE tunnel outperforms the single path in every case. For example, the MPT-GRE tunnel consistently delivers PSNR values better and higher than the single path, as seen in videos with index 4 (41.7848 vs. 45.7863) and index 7 (27.5024 vs. 28.7276), by a difference of (4.0015 dB and 1.2252 dB), respectively. This means that the PSNR of the tunnel increased by (9.58% and 4.45%), respectively, over the single path in these cases. This evidence demonstrates the tunnel's ability to handle the high-bandwidth demands of 4K video streaming, ensuring near-original quality for viewers.

Table 4. Comparison of PSNR for 4K videos streaming via the single path and MPT-GRE tunnel.

Index	PSNR (Single Path)	PSNR (MPT Tunnel)
1	32.4868	38.4877
2	26.0574	37.6904
3	24.5569	37.1987
4	41.7848	45.7863
5	26.7675	37.9238
6	32.1704	42.7770
7	27.5024	28.7276

In addition, videos with high differences in PSNR between the single path and the tunnel, such as the video with index 3 (24.5569 on the single path vs. 37.1987 on the MPT-GRE tunnel) and the video with index 6 (32.1704 on the single path vs. 42.7770 on the MPT-GRE tunnel), where the percentage improvements were (51.5% and 33%), respectively, show significant improvements when streamed through the MPT-GRE tunnel.

The statistical analysis shows a significant improvement in PSNR when using the MPT tunnel compared to the single path. The mean PSNR for the MPT tunnel is 38.37 dB, which is considerably higher than the 30.19 dB recorded for the single path. This suggests that the MPT tunnel offers enhanced video quality. Furthermore, the 95% confidence intervals support this finding; the single path has a wider margin of error of ± 5.49 dB, while the MPT tunnel has a more precise margin of ± 4.91 dB, indicating that the performance of the MPT tunnel is more stable. The paired t-test yielded a statistic of -4.90 and a p-value of 0.0027, confirming that the observed difference is statistically significant ($p < 0.05$), indicating a statistically significant difference between the two transmission methods, showing that the MPT tunnel greatly enhances PSNR compared to the single path.

The PSNR values indicate that the multipath approach successfully maintains the original video quality. Additionally, the MPT-GRE tunnel benefits from multiple paths, which aggregate throughput, reduce congestion, and handle packet loss more effectively than a single path. Distributing packets over several paths helps sustain higher throughput, directly contributing to better video quality. Higher throughput minimizes interruptions, reduces jitter, and ensures a consistent data flow, preventing the quality degradation often observed with a single path

From the results in both scenarios, SSIM, MSE, and PSNR metrics confirm that MPT-GRE tunneling outperforms single-path video metrics, particularly for high-quality video streaming. SSIM assesses structural similarity, with values closer to 1 representing higher similarity and good quality. In contrast, MSE calculates the mean squared difference between original and transmitted pixel values, where lower values indicate better quality. Together, these metrics demonstrate that MPT-GRE provides a more reliable and higher-quality streaming experience than single-path, leveraging its high throughput to reduce errors and delays, maintain video quality, and offer users a satisfying viewing experience.

Additionally, the MPT-GRE tunnel benefits from multiple paths, which aggregate throughput, reduce congestion, and handle packet loss more effectively than a single path. Distributing packets over several paths helps sustain higher throughput, directly contributing to better video quality. Higher throughput minimizes interruptions, reduces jitter, and ensures a consistent data flow, preventing the quality degradation often observed with a single path.

9. Conclusions and Future Work Direction

This paper addressed the challenge of delivering 4K video streams over multipath networks, focusing on streaming high-quality video through the MPT-GRE multipath network layer solution. The MPT-GRE tunnel achieves a throughput that closely approximates the combined throughput of its physical paths. Our results demonstrate that the MPT-GRE multipath network is efficient and effective for real-time 4K video streaming. An analysis of key quality metrics SSIM, MSE, and PSNR confirmed that the throughput aggregation of the MPT-GRE tunnel can significantly enhance streaming quality in real time, particularly for high-resolution videos. Streaming through a single path led to noticeable decreases in SSIM, PSNR values, and increases in MSE, indicating reduced video quality. In contrast, video streamed through the MPT-GRE tunnel exhibited only slight variations in these metrics, with SSIM, MSE, and PSNR values often nearly identical to those of the original pre-streamed video. These findings show that the MPT-GRE tunnel consistently outperforms single-path transmission in maintaining superior video quality. It is especially valuable for applications like live streaming, online gaming, and video conferencing, where consistent, high-quality video delivery is essential. The MPT-GRE tunnel offers a reliable solution for platforms requiring high-performance video across diverse and unstable network conditions.

Some of the future research directions include calculating more advanced metrics, such as Video Multi-Method Assessment Fusion (VMAF) for 8K video streaming and integrating with 5G.

Author Contributions: All authors contributed to the study's conception and design. Material preparation and testbed building by N.A.-I., with valuable support from G.L. The first draft of the manuscript was written by N.A.-I., and all authors commented on previous versions of the manuscript. Conceptualization: G.L.; methodology: N.A.-I.; formal analysis and investigation: N.A.-I.; writing—original draft preparation: N.A.-I.; writing—review and editing: G.L. and N.A.-I.; resources: N.A.-I. and G.L.; supervision: G.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The Public GitHub repository of the first author contains several configuration settings files of MPT and scripts that were used to build the experiments: https://github.com/NaseerAJabbar/MPT_Connections_files (accessed on 28 March 2023). The Python script to calculate the average SSIM, MSE, and PSNR values for recorded video files: https://github.com/NaseerAJabbar/4k_video_metric (accessed on 3 November 2024).

Acknowledgments: The authors thank Brant von Goble from Széchenyi István University for proofreading the English-language version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jesús-Azabal, M.; Soares, V.N.G.J.; Galán-Jiménez, J. ML-Enhanced Live Video Streaming in Offline Mobile Ad Hoc Networks: An Applied Approach. *Electronics* **2024**, *13*, 1569. [CrossRef]
2. Apostolopoulos, J.G.; Tan, W.T.; Wee, S.J. *Video Streaming: Concepts, Algorithms, and Systems*; HP Laboratories Report HPL-2002-260; HP Laboratories: Palo Alto, CA, USA, 2002; pp. 2641–8770. [CrossRef]
3. Yang, C.; Lin, C.; Su, Y. Improving Quality of Service for Video Streaming Applications in Multi-Radio Wireless Mesh Networks Based on CLO and MDC. In Proceedings of the 8th International Conference on High Performance Compilation, Computing and Communications, China, Guangzhou, 9 June 2024; pp. 108–113. [CrossRef]
4. Xing, M.; Xiang, S.; Cai, L. A Real-Time Adaptive Algorithm for Video Streaming over Multiple Wireless Access Networks. *IEEE J. Sel. Areas Commun.* **2014**, *32*, 795–805. [CrossRef]
5. Laghari, A.A.; Imran, M.; Laghari, R.A.; Marchal, Y.; Crespi, N.; Tran, N.H.; Nguyen, M. The State of Art and Review on Video Streaming. *J. High Speed Netw.* **2023**, *29*, 211–236. [CrossRef]
6. Xing, Y.; Chen, H.; Zhang, J.; Li, M.; Xu, J. A Low-Latency MPTCP Scheduler for Live Video Streaming in Mobile Networks. *IEEE Trans. Wirel. Commun.* **2021**, *20*, 7230–7242. [CrossRef]
7. Petrangeli, S.; van der Hooft, J.; Wauters, T.; Huysegems, R.; Rondao Alface, P.; Bostoen, T.; De Turck, F. Live Streaming of 4K Ultra-High Definition Video over the Internet. In Proceedings of the 7th International Conference on Multimedia Systems, Klagenfurt, Austria, 10–13 May 2016; pp. 1–4. [CrossRef]
8. Chiwariro, R.; Thangadurai, N. Wireless Multimedia Sensor Networks Based Quality of Service Sentient Routing Protocols: A Survey. *Int. J. Adv. Comput. Sci. Appl.* **2019**, *10*, 293–299. [CrossRef]
9. Corbillon, X.; Aparicio-Pardo, R.; Kuhn, N.; Texier, G.; Simon, G. Cross-Layer Scheduler for Video Streaming over MPTCP. In Proceedings of the 7th International Conference on Multimedia Systems (MMSys 2016), Klagenfurt, Austria, 10–13 May 2016; pp. 65–76. [CrossRef]
10. Almasi, B.; Kosa, M.; Fejes, F.; Katona, R.; Pusok, L. MPT: A Solution for Eliminating the Effect of Network Breakdowns in Case of HD Video Stream Transmission. In Proceedings of the 6th IEEE Conference on Cognitive Infocommunications (CogInfoCom 2015), Gyor, Hungary, 19–21 October 2015; pp. 121–126. [CrossRef]
11. Hamidouche, W.; Cocherel, G.; Le Feuvre, J.; Raulet, M.; Déforges, O. 4K Real-Time Video Streaming with SHVC Decoder and GPAC Player. In Proceedings of the 2014 IEEE International Conference on Multimedia and Expo Workshops (ICMEW 2014), Chengdu, China, 14–18 July 2014; pp. 1–2. [CrossRef]
12. Ito, K.; Nakazato, J.; Fontugne, R.; Tsukada, M.; Esaki, H. Enhancing Real-Time Streaming Quality through a Multipath Redundant Communication Framework. In Proceedings of the 2024 IFIP Networking Conference (IFIP Networking), Thessaloniki, Greece, 3–6 June 2024; pp. 1–10. [CrossRef]
13. Baig, G.; He, J.; Qureshi, M.A.; Qiu, L.; Chen, G.; Chen, P.; Hu, Y. Jigsaw: Robust Live 4K Video Streaming. In Proceedings of the 25th Annual International Conference on Mobile Computing and Networking, Los Cabos, Mexico, 21–25 October 2019; pp. 1–16. [CrossRef]
14. Begen, A.C.; Altunbasak, Y.; Ergun, O.; Ammar, M.H. Multi-Path Selection for Multiple Description Video Streaming over Overlay Networks. Signal Process. *Image Commun.* **2005**, *20*, 39–60. [CrossRef]
15. Wu, J.; Yuen, C.; Cheng, B.; Yang, Y.; Wang, M.; Chen, J. Bandwidth-Efficient Multipath Transport Protocol for Quality-Guaranteed Real-Time Video Over Heterogeneous Wireless Networks. *IEEE Trans. Commun.* **2016**, *64*, 2477–2493. [CrossRef]
16. Matsue, H.; Nishizima, T.; Urasawa, H.; Bairaku, R.; Soya, H.; Mamaguchi, K. Transmission Performance of 4K High Resolution Real-Time Video Streaming Signal for a Local 5G Uplink. In Proceedings of the 35th General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS 2023), Sapporo, Japan, 19–26 August 2023; pp. 1–4. [CrossRef]
17. Almási, B.; Lencse, G.; Szilágyi, S. Investigating the Multipath Extension of the GRE in UDP Technology. *Comput. Commun.* **2017**, *103*, 29–38. [CrossRef]
18. Szilágyi, S.; Bordán, I.; Harangi, L.; Kiss, B. Throughput Performance Comparison of MPT-GRE and MPTCP in the Gigabit Ethernet IPv4/IPv6 Environment. *J. Electr. Electron. Eng.* **2019**, *12*, 57–60.
19. Lencse, G.; Szilagyi, S.; Fejes, F.; Georgescu, M. MPT Network Layer Multipath Library. 2022. Available online: https://datatracker.ietf.org/doc/html/draft-lencse-tsvwg-mpt-10 (accessed on 17 June 2022).
20. Almási, B.; Kósa, M.; Fejes, F.; Katona, R.; Kelemen, T.; Püsök, L. MPT—GRE in UDP based Multipath Communication Library, User Guide; 2015; pp. 1–17. Available online: https://irh.inf.unideb.hu/~szilagyi/wp-content/uploads/mpt/usermanual.pdf (accessed on 27 September 2015).
21. Duanmu, Z.; Rehman, A.; Wang, Z. A Quality-of-Experience Database for Adaptive Video Streaming. *IEEE Trans. Broadcast.* **2018**, *64*, 474–487. [CrossRef]
22. Song, L.; Tang, X.; Zhang, W.; Yang, X.; Xia, P. The SJTU 4K Video Sequence Dataset. In Proceedings of the Fifth International Workshop on Quality of Multimedia Experience (QoMEX), Klagenfurt, Austria, 3–5 July 2013; pp. 34–35. [CrossRef]
23. Pexels. Free Stock Videos. 2024. Available online: https://www.pexels.com/ (accessed on 12 May 2024).

24. Sara, U.; Akter, M.; Uddin, M.S. Image Quality Assessment through FSIM, SSIM, MSE, and PSNR—A Comparative Study. *J. Comput. Commun.* **2019**, *7*, 8–18. [CrossRef]
25. VideoLan. VLC Media Player. 2024. Available online: https://www.videolan.org/ (accessed on 7 April 2024).
26. Fejes, F. MPT—Multi-Path Tunnel. 2019. Available online: http://github.com/spyff/mpt (accessed on 9 October 2019).
27. Al-Imareen, N.; Lencse, G. MPT Connections Files. 2023. Available online: https://github.com/NaseerAJabbar/MPT_Connections_files (accessed on 28 March 2023).
28. Al-Imareen, N.; Lencse, G. 4K Video Quality Evaluation. 2024. Available online: https://github.com/NaseerAJabbar/4k_video_metric (accessed on 3 November 2024).
29. Di Leo, G.; Sardanelli, F. Statistical Significance: P Value, 0.05 Threshold, and Applications to Radiomics—Reasons for a Conservative Approach. *Eur. Radiol. Exp.* **2020**, *4*, 18. [CrossRef]