Utility-Based Multipath Delivery of Prioritized XR Content in a Machine Learning and Network Slicing-enhanced Environment

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***Abstract*—This paper introduces the Utility-Based Multipath Transmission Control Protocol (uMPTCP), an innovative extension of MPTCP designed for prioritized extended reality (XR) content delivery, based on monitored Quality of Service (QoS) network metrics. The proposed approach includes an algorithm that assesses subflows' delivery performance and dynamically selects the most efficient one to deliver prioritized content with reduced latency. A comparison is made against a state-of-the-art solution, the virtual private channel (VPC), and the default MPTCP algorithm. The evaluation considers both single-homed and multi-homed configurations in scenarios with varied bandwidth requirements, including XR. The study is conducted within the framework of the FRADIS project, aimed at providing a comprehensive solution for 5G and beyond heterogeneous network environments. FRADIS integrates machine learning to optimize service-specific approaches, allowing a choice between traffic engineering with network slicing and protocol-based solutions, including the proposed uMPTCP solution. The framework supports a diverse range of services for smart city monitoring, XR applications, e-health solutions and entertainment.**

***Index Terms*—MPTCP, QoS, XR, multipath**

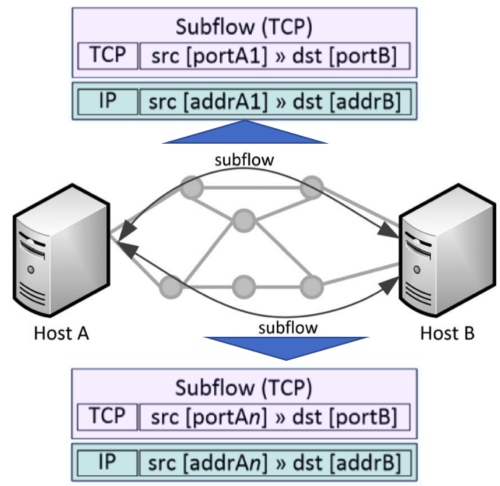


Fig. 1. MPTCP and its subflows

I. Introduction

The rise of sleek and appealing extended reality (XR) glasses, offering novel opportunities for end users, will significantly impact communication service providers (CSPs) in the foreseeable future. Primarily, CSPs must guarantee that forthcoming networks can maintain user experience quality in XR applications. In specific XR scenarios, both uplink (UL) and downlink (DL) bitrates rely on factors such as point cloud resolution, frame rate, and compression level. A feasible operational bandwidth range in the short term would be up to 20Mbps in DL and 10Mbps in UL [1].

Extended Reality (XR) has expanded its presence across diverse domains, including education, cognitive rehabilitation, medical training, visualization, military aircraft navigation, and entertainment [2]. While current networks have made notable advances in facilitating rich content delivery, challenges persist in supporting XR content distribution. These challenges include high bandwidth demands per user and achieving low end-to-end round-trip times (RTT) [3].

An approach towards addressing these issues involves prioritizing certain XR components to mitigate the risk of compromising the user's perceived quality of experience. These components include positional and interaction data provided by the Inertial Measurement Unit (IMU), Global Positioning System (GPS), and infrared tracking data [4]. Therefore, this paper suggests a novel solution for prioritizing XR content delivery, leveraging the subflow-related attributes of the Multipath Transmission Control Protocol (MPTCP) standardized by the IETF [5], illustrated in Fig. 1.

The proposed protocol, the Utility-based Multipath Transmission Control Protocol (uMPTCP), assesses the performance of subflows (data streams within an MPTCP connection) in near real-time and recommends the subflow that is best suited to deliver prioritized content with lower latency. The effectiveness of uMPTCP is evaluated using simulations conducted with Network Simulator (NS-3) and performance is compared to two other existing MPTCP implementations. uMPTCP is proposed in the context of the FRADIS project (FRAmework for performance-aware Differentiated Innovative Services), which is supported by the Science Foundation Ireland Frontiers for the Future programme. FRADIS aims to enhance differentiated service delivery in the 5G and beyond heterogeneous network environment with algorithms and protocols for dynamic management of performance, network slicing, multipath delivery, energy consumption, and quality trade-offs based on specific service requirements.

This paper is organised as follows. Section II presents the related works. The FRADIS framework is described in Section III. Section IV details the uMPTCP protocol. The simulation environment, test scenarios and results are presented in Section V. Conclusions and future work are available in Section VI.

II. Related Works

The objective of the proposed solution is to identify improved methods for transmitting packets in a prioritized XR content MPTCP distribution setting. The following literature discusses technologies pertinent to this research, along with their applications, constraints, and performance implications.

A. MPTCP

The Multipath Transport Control Protocol (MPTCP) is a transport layer protocol that enhances the traditional TCP by facilitating concurrent data transport over multiple paths, thereby improving throughput [6]. Operating in a connection-oriented manner and designed to be transparent to both applications and networks, MPTCP allows the establishment of multiple sub-flows for a single connection session between two hosts. In the context of mobile devices within a 5G heterogeneous network delivery environment, MPTCP can simultaneously utilize multiple interfaces and network access technologies, enhancing network delivery performance, robustness, and resource utilization [7]. MPTCP's support for multipath transmissions proves beneficial for load balancing, and it ensures continuous data transmission as long as at least one sub-flow is available [8]. Noteworthy is the work of Chen et al. [9], introducing an Energy-aware Multipath-TCP-based Content Delivery Scheme (eMTCP) that optimizes QoS and energy consumption by offloading the data stream between two network interfaces (LTE and WiFi) in a heterogeneous wireless environment.

B. MPTCP-Based Solutions

A major limitation of MPTCP lies in its lack of consideration for different traffic characteristics. Proposed solutions aim to address this limitation, including an energy-aware MPTCP extension [10] and a performance-oriented solution [11]. These solutions focus on efficient network delivery based on either energy or performance goals, irrespective of traffic requirements. Other approaches concentrate on supporting specific traffic types [12] or specific features, such as reliability [13]. Given the diversity of traffic types, there is a need for a dynamic solution that can identify traffic types and distribute traffic to optimally meet their requirements.

After analyzing MPTCP implementations, the authors in [14] found that existing congestion control mechanisms do not eliminate the need for improved subflow management. Furthermore, their findings suggest that RTT-aware scheduling offers limited benefits when combined with window control mechanisms that already incorporate RTT information. Despite this, the paper demonstrates that an RTT-aware algorithm can still provide performance improvements even when layered on top of existing schedulers.

Several studies explore the use of MPTCP in diverse mobile and wireless networks. RLoad [15] leverages MPTCP in wireless environments to balance traffic and find the optimal combination of Quality of Service (QoS), cost, and energy consumption through network selection based on reputation. MPTCP-QE [16], an application-layer solution, manages the trade-off between throughput and energy consumption for mobile phones by optimizing wireless resource usage through an MPTCP congestion window fast recovery strategy.

An open-source default MPTCP model [17] based on NS-3 was developed adhering to the principles of transparency and TCP backward compatibility outlined in IETF RFC 6824. The solution proposed in our paper extends upon this NS-3-based implementation. Furthermore, we conduct a comparison between our solution and the default protocol.

The Virtual Private Channel (VPC) [18] tailors MPTCP's load balancing to prioritize specific packets. It reserves one subflow exclusively for prioritized traffic, while regular packets are routed through the remaining subflows. This separation ensures prioritized packets receive preferential treatment on a dedicated path. To improve subflow selection for prioritized traffic, the algorithm leverages MPTCP's default round-robin load balancing and congestion control behavior. Initial subflows experience the highest traffic volume. This state-of-the-art approach serves as one of the benchmarks for evaluating the effectiveness of the novel solution presented in our paper.

C. XR Content Delivery

The work presented in [19] explored new messaging protocols for virtual environments, proposing an "updatable queue abstraction" to handle both non-blocking informational messages (e.g., state updates or events) and blocking command messages. While this improves message processing and queuing, it lacks a crucial feature: prioritizing different types of information. XR data can be broken down into components with varying importance, such as critical positioning data (IMU, GPS, or infrared tracking) and interaction information (joystick or movement trackers). Managing messages through deletion or resequencing can be beneficial, but it has limitations. If a message cannot be manipulated, it might still block or negatively impact processes.

QoEMultiSDN [20] is a QoE-aware architecture that leverages MPTCP and segment routing to ensure optimal video quality for end-users. It routes MPTCP video subflows over multiple disjoint shortest paths with built-in network protection and recovery.

The MRLIA [21] MPTCP congestion control scheme is suited for real-time XR devices, effectively reducing reordering delays while ensuring fair utilization of network resources. When integrated with XR devices utilizing the MPEG DASH protocol, MRLIA provides enhanced performance.

III. The FRADIS Framework

The architecture of FRADIS, illustrated in Fig. 2 consists of three main components: Network Slice Management, QoS-based Traffic Control and Service-dependent Adaptive Content Delivery.

In Network Slice Management, FRADIS employs a hierarchical distributed SDN-based architecture, enabling dynamic control of Key Performance Indicators (KPIs) for multiple flows with varying QoS demands. For the purpose of managing network slices, FRADIS will incorporate a Slice Management component tailored to differentiated traffic exchange. In this context, 5G Slice Stream (5GSS) is an innovative resource allocation solution, specifically tailored to elevate streaming performance and address the unique requirements of three distinct slices with different streaming types—DASH, VR, and Gaming.

In QoS-based Traffic Control, FRADIS performs QoS-based traffic control at its transport layer, with sub-flows for different service types and dynamic traffic characteristics-oriented data transport. The Utility-based Multi-path Transport Control Protocol presented in this paper is part of this component. Diverse parameters related to network performance and QoS are monitored in order to compose a QoS utility function. QoS utility functions enables controlled content delivery while considering diverse QoS parameters. These functions trigger a QoS aware-algorithm for content classification.

Regarding Service-dependent Adaptive Content Delivery, FRADIS supports diverse types of applications in its application layer. FRADIS provides interactive support for rich-media applications. In this context, TOPVR [22] is a collaborative trajectory-oriented viewport prediction solution for both on-demand and live 360° VR video streaming. TOPVR solution can be readily deployed in VRSliceFlex solution that focuses on processing large bursts of packets for 360° video, VR and gaming applications in the context of active RAN slicing within the 5G network architecture. Multi-sensory effects are also supported in FRADIS with OmniScent [23] which 360° videos to multiple olfaction dispensers. A version with integrated neural networks perform image recognition on 360° video frames and trigger appropriate scents automatically.

Regarding real-time video adaptation, Fuzzy Logic-based Adaptive Multimedia StrEaming (FLAME) solution [24] is adaptable to diverse video client settings and QoE goals, using interactive membership functions and fuzzy rules, leading to reduced model complexities and training overheads. Taking a stride beyond, Fuzzy Reinforcement Learning Driven Improved Video QoE (FRED-ViQ) approach leverages both the fuzzy and Deep Reinforcement Learning (DRL) techniques for enhanced streaming experiences. A DASH-based adaptation solution, 360-ADAPT [25] works within FRADIS leveraging DASH to dynamically adjust streamed 360° media content with the goal to increase the quality of immersive viewer experience, while maintaining high quality audio.

Finally, FRADIS provides the capability for applications to dynamically select between the proposed SDN-based NetSli solutions, and the uMPTCP approach, for delivering differentiated content based on its specific requirements. This dynamic selection occurs at the Edge through an innovative machine learning approach with Deep Reinforcement Learning (DRL) framework via the Innovative Performance-aware DRL (IP-DRL).

IV. XR Priority Content Delivery with uMPTCP

In this paper, MPTCP is employed to enhance the RTT performance of specific packets within prioritized XR content

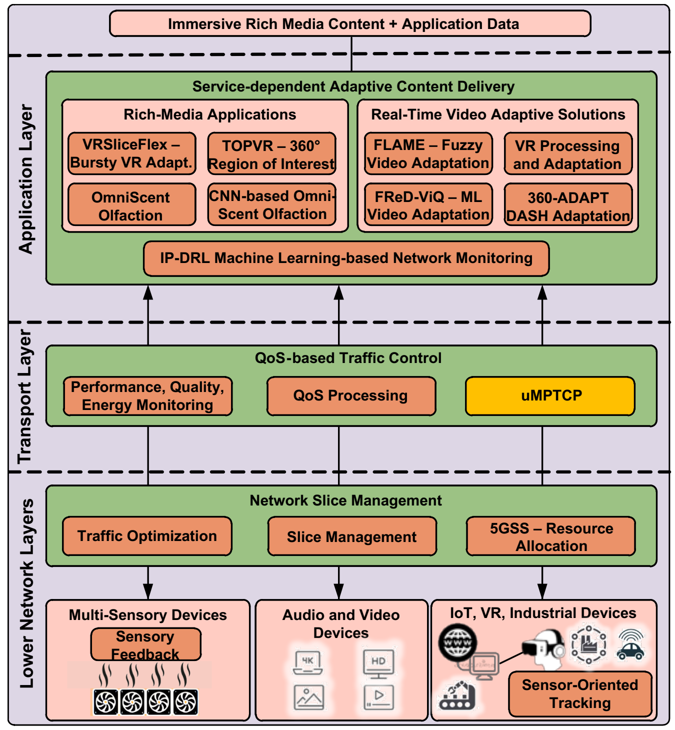


Fig. 2. uMPTCP within the FRADIS Architecture

delivery, also integrated into the FRADIS framework. Prioritization becomes important for XR applications, particularly during user interactions. Certain types of packets support the user interaction experience, thus necessitating distinct handling.

XR content, particularly interactive applications, often include important smaller data packets such as IMU or GPS data (as noted in [4]) compared to larger video components. These smaller packets require low latency and priority for optimal performance.

To address this need, this paper proposes uMPTCP, a solution that leverages the diverse characteristics of MPTCP subflows to prioritize XR data delivery. uMPTCP dynamically analyzes subflow performance in near real-time (using as input metrics RTT values and priority packets) and recommends the subflow with the lowest latency for transmitting prioritized data.

A. uMPTCP Algorithm

uMPTCP avoids dedicating a single subflow for prioritized packets. Instead, it dynamically selects the most suitable path for each packet based on real-time monitoring. During operation, uMPTCP continuously tracks the Round-Trip Time (RTT) of each subflow. As seen on Algorithm 1, when a prioritized packet arrives, uMPTCP analyzes the historical RTT data for each subflow using linear regression. The subflow with the lowest slope in its RTT trend is chosen for transmission, as this trend indicates the most stable and likely lowest future latency.

Equation 1 calculates the slope of the linear regression line, which indicates the trend in future RTT values. It uses a set of n (number of samples used in the linear regression), where

(x_i, y_i) represents the i_{th} time value (x) and its corresponding RTT value (y).

$$slope = \frac{n\left(\sum_{i=1}^{n} x_i y_i\right) - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{n\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i\right)^2} \quad (1)$$

Upon identifying the suitable subflow, uMPTCP dynamically overrides MPTCP's default load-balancing for prioritized packets, transmitting them exclusively through the chosen subflow. Regular data continues to be delivered using the standard MPTCP load-balancing protocol.

V. Simulation-Based Testing

To evaluate the proposed solution's performance, the NS-3 simulation utilizes a point-to-point model with constant link properties. All nodes are tested in terms of RTT and Throughput in 3 scenarios using links with 1, 10, and 20 Mbps data rates with a consistent 5ms delay.

Custom applications, MpTcpBulkSender at node n0 and MpTcpPacketSink at node n7, are employed. These applications, built upon standard NS-3 implementations, are designed to transmit and receive simulated XR content data at the network's maximum capacity using MPTCP.

The simulation explores two configurations for each data rate scenario: single-homed and multi-homed.

Single-homed Configuration: 8 MPTCP subflows are utilized. MPTCP automatically selects the shortest path from the server to the client: $n_0 \leftrightarrow n_1 \leftrightarrow n_7$.

Multi-homed: 3 MPTCP subflows are utilized. MPTCP automatically selects the from the available paths from the server to the client: $n_0 \leftrightarrow n_1 \leftrightarrow n_7$; or $n_0 \leftrightarrow n_2 \leftrightarrow n_3 \leftrightarrow n_7$; or $n_0 \leftrightarrow n_4 \leftrightarrow n_6 \leftrightarrow n_7$.

In the single-homed case, a single network device is available, and subflows utilize different ports on that interface. Conversely, multi-homed configurations have multiple devices, with all subflows using the same port on each.

Three algorithms are evaluated and compared within these configurations: the proposed uMPTCP, the state-of-the-art VPC algorithm, and the classic MPTCP with basic round-robin load balancing, all running for 150s. The simulation model prioritizes one packet every 500, reflecting the typical ratio of higher-priority data such as GPS and IMU compared to video data in XR applications. [4].

A. Results: Single-Homed Scenarios

Table I presents average results obtained from all subflows of uMPTCP algorithm, the VPC and the default MPTCP algorithms. uMPTCP achieves the highest throughput in all single-home scenarios, at the cost of a slightly higher RTT.

Fig. 3 and Fig. 4 demonstrate the comparison of RTT values (in milliseconds) and subflow choices for XR priority packets in Default, VPC, and uMPTCP solutions in a single-homed setup across 1, 10, and 20 Mbps bandwidths. The proposed uMPTCP solution consistently achieves lower RTT values compared to Default and VPC. For instance, in Fig. 3a (1 Mbps bandwidth), uMPTCP has an RTT of 872.96 ms, while VPC observes an RTT of 926.64 ms. Similarly, in Fig. 3b (10 Mbps bandwidth), uMPTCP observes 127.8 ms RTT compared to 129.19 ms for the Default MPTCP solution. This trend continues with 20 Mbps bandwidth (Fig. 3c), where uMPTCP observes an average RTT value of 74.30 ms compared to 74.88 ms for the Default solution. This notable reduction in RTT demonstrates the effectiveness of uMPTCP in improving network performance, especially for latency-sensitive XR applications.

Fig. 4 illustrate subflow choices over a 150-second simulation for Default, VPC, and uMPTCP solutions at 1, 10,

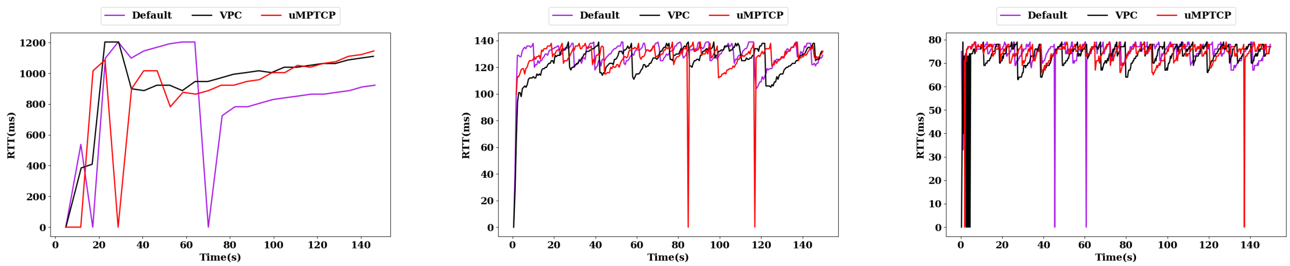
Algorithm 1 Subflow Selection for Prioritized XR Packets

Result: Priority Packets sent by the best available subflow.
Input:
Packet to send (packet), Default load balancing algorithm (defaultAlg), Maximum history items per subflow (historySize), Number of subflows (numSubflows), Subflow history repository (subflowHistory)

```
initialSubflowId = defaultAlg.nextSubflowId()
if packet is urgent then
    lowestSlope = ∞
    for each subflowHistoryItem in subflowHistory do
        slope = 0, sumX = 0, sumXSquared = 0, sumXY = 0, sumY = 0 numHistoryItems = subflowHistoryItem.size()
        for each historyItem in subflowHistoryItem do
            sumX += historyItem.time
            sumXSquared += historyItem.time * historyItem.time
            sumY += historyItem.RTT
            sumXY += historyItem.time * historyItem.RTT
        end for
        slope = (numHistoryItems * sumXY - sumX * sumY) / (numHistoryItems * sumXSquared - sumX * sumX)
        if slope < lowestSlope then
            initialSubflowId = subflowHistoryItem.subflowId
            lowestSlope = slope
        end if
    end for
end if
sendPacket(packet, initialSubflowId)
if subflowHistory does not contain a history for initialSubflowId then
    Create a new subflowHistoryItem for initialSubflowId
    Add the new subflowHistoryItem to subflowHistory
end if
subflowHistory.get(initialSubflowId).add(packet.time, packet.RTT)
if subflowHistory.get(initialSubflowId).size > historySize then
    Remove the oldest history item from subflowHistory.get(initialSubflowId)
end if
```

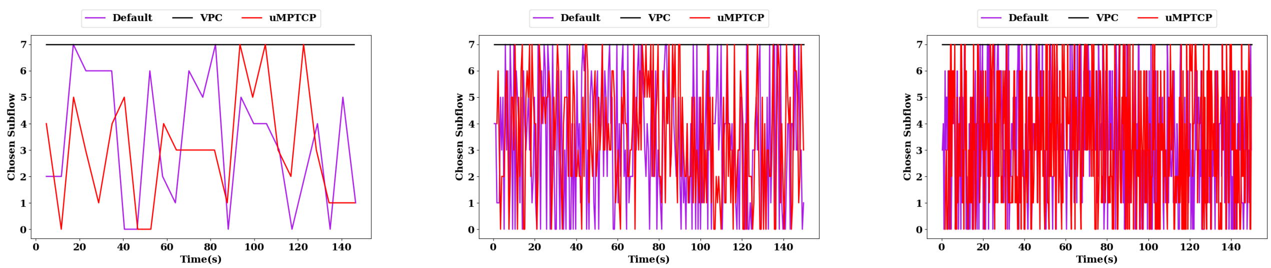
TABLE I
SIMULATION RESULTS

	1Mbps				10Mbps				20Mbps			
	Throughput (Kbps)		RTT (ms)		Throughput (Kbps)		RTT (ms)		Throughput (Kbps)		RTT (ms)	
	Single	Multi	Single	Multi	Single	Multi	Single	Multi	Single	Multi	Single	Multi
VPC	**1004.29**	628.83	**932.97**	**35.25**	10024.24	6286.84	**90.82**	**20.43**	19965.17	11403.72	**59.12**	**19.59**
Default	**1004.29**	**1003.43**	959.86	35.63	10026.32	**10034.20**	92.71	20.44	20043.97	17698.55	61.45	**19.59**
uMPTCP	**1004.29**	**1003.43**	961.44	35.63	**10026.45**	**10034.20**	93.31	20.44	**20069.02**	**17698.93**	68.71	**19.59**

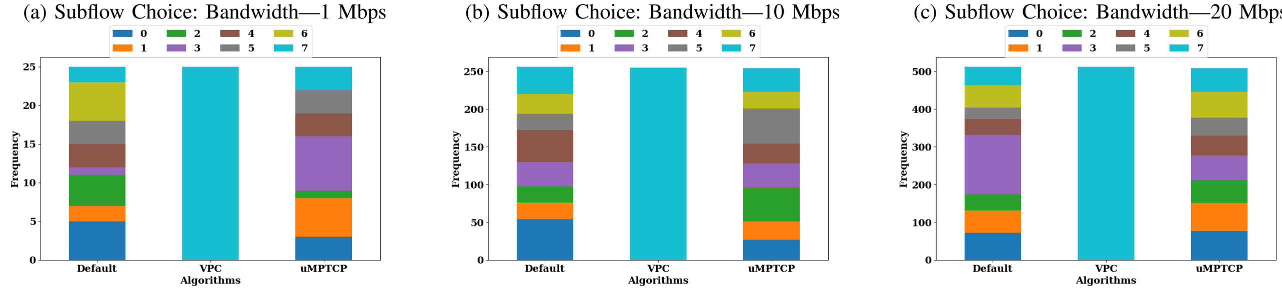


(a) RTT: Bandwidth—1 Mbps (b) RTT: Bandwidth—10 Mbps (c) RTT: Bandwidth—20 Mbps

Fig. 3. Prioritised XR packets - Comparison of RTT: Default vs. VPC vs. uMPTCP in a single-homed setup across 1, 10, and 20 Mbps bandwidths



(a) Subflow Choice: Bandwidth—1 Mbps (b) Subflow Choice: Bandwidth—10 Mbps (c) Subflow Choice: Bandwidth—20 Mbps



(d) Subflow Choice Frequency: Bandwidth—1 Mbps (e) Subflow Choice Frequency: Bandwidth—10 Mbps (f) Subflow Choice Frequency: Bandwidth—20 Mbps

Fig. 4. Prioritised XR packets - Comparison of subflow choices: Default vs. VPC vs. uMPTCP in a single-homed setup across 1, 10, and 20 Mbps bandwidths

and 20 Mbps bandwidth configurations. VPC is configured to exclusively use subflow 7 for urgent packets transmission. Default MPTCP randomly selects subflows for XR packet delivery, while uMPTCP dynamically switches between subflows based on sorted RTT values. Figs. 4d-4f provide histograms of subflow choices for each solution across all bandwidth settings. At 1 Mbps (Fig. 4d), a significant difference is observed between Default and uMPTCP subflow choices. uMPTCP primarily selects subflow 3, while Default favors subflow 6, followed by subflow 0. Interestingly, at higher bandwidths (e.g., 20 Mbps in Fig. 4f), uMPTCP intelligently utilizes all subflows more equitably compared to the Default solution. This intelligent subflow selection likely contributes to the enhanced throughput and lower RTT values achieved by uMPTCP compared to baseline methods.

B. Results: Multi-Homed Scenarios

In the multi-homed configuration, tests revealed minimal RTT (Round-Trip Time) fluctuations, resulting in consistent performance. As evidenced in Table I, uMPTCP consistently delivers the highest throughput across all multi-homed scenarios.

VI. CONCLUSIONS

This paper introduces the nover Utility-based Multipath Transmission Control Protocol (uMPTCP) for prioritised XR data delivery and compares its performance with the default MPTCP algorithm and VPC. uMPTCP continuously evaluates subflow performance in near real-time, dynamically selecting subflows with lowest latency for prioritized XR data. Network Simulator 3-based simulations demonstrate superior performance of uMPTCP in both single and multi-homed scenarios for 1, 10 and 20 Mbps data-rates.

Future work include adding other aspects during subflow selection, such as energy consumption and loss.

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