Innovative Algorithms for Prioritised AR/VR Content Delivery

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***Abstract*—This paper proposes, describes and analyses two innovative approaches which make use of the Multipath Transmission Control Protocol (MPTCP) and its multiple flows for prioritised AR/VR content delivery. The first approach involves delivery of prioritised data using a fixed subflow and therefore establishment of a *virtual private channel (VPC)* for sending data. The second approach introduces a novel *QoS on-the-fly (QoSF)* algorithm that evaluates all subflows' delivery performance and dynamically selects one of them to deliver the prioritised content with the lowest latency. Both algorithms are assessed in single-homed and multi-homed configurations and present different performance improvements in comparison to the classic MPTCP. While QoSF algorithm demonstrates the best performance in scenarios where the delivery latency variation between subflows is high, the VPC algorithm has the best results in scenarios where this variation is smaller.**

***Index Terms*—MPTCP, QoS, AR/VR, prioritised content delivery**

I. Introduction

The last few years have seen Augmented Reality (AR)/Virtual Reality (VR) technologies gaining momentum with a predicted international market of $150 billion by 2020 [1]. Their economic importance is the focus of a Goldman Sachs research [2] which describes AR/VR and associated content delivery as fundamental in the activity context of giant market players such as Microsoft (i.e. HoloLens[1]), Facebook (i.e. Oculus-Rift[2]) and Apple (i.e. Apple VR Project[3]). Apart from these, top universities, such as Harvard[4] and MIT[5], start-ups and other companies are also interested in AR/VR. The Khronos[6] international consortium alone has more than 100 companies working on royalty-free and open standard APIs for AR/VR.

AR/VR is now present in a broad range of areas, which vary from education (e.g. simulations applied to diverse academic areas) to cognitive rehabilitation (e.g. activities to explore temporal and spatial orientation, concentration, etc.) [3], from medical training and visualisation (e.g. non-invasive data collection and renderisation) to military aircraft navigation and operation (e.g. turret guided by pilot head position), and entertainment (e.g. interactive environment games) [4].

As the relevance of AR/VR becomes more evident, so does the concern about the challenges to make AR/VR reach the market, given its stringent performance requirements [5]. For example, a low visual feedback can negatively impact the experience of animation and high latency can give you the feeling of losing control [6], causing effects similar to motion sickness.

Although current networks offer significant improvements for rich content delivery, there are still challenges for supporting AR/VR content distribution. Demands of up to 5.2Gbps bandwidth per user and an end-to-end round-trip time (RTT) in the order of one millisecond are a couple of examples [7], [8]. Next-generation networks (i.e. 5G) target 300Mbps bandwidth for dense urban broadband and RTT of 10ms [9] only.

One solution is the prioritisation of some of AR/VR components to reduce the risk of jeopardising user perceived quality of experience. These components involve positional and/or interaction component information, such as Inertial Measurement Unit (IMU), Global Positioning System (GPS) and infrared tracking data [10].

In order to address these limitations and to use network infrastructure resources better, this paper proposes two novel approaches for prioritised AR/VR content delivery that explore the subflow-related features of the Multipath Transmission Control Protocol (MPTCP) standardised by the Internet Engineering Task Force (IETF) under RFC 6824 [11].

The two proposed solutions are the *Virtual Private Channel (VPC)* algorithm delivering prioritised data using a fixed subflow, and the *QoS on-the-fly (QoSF)* algorithm evaluating in near real-time the subflows' delivery performance and suggesting the best subflow to deliver prioritised content (lowest latency). Both algorithms are modelled, simulated and assessed using the Network Simulator v3 (NS-3) and an open source MPTCP implementation [12].

This paper is organised as follows. Section II presents the related works. Both proposed VPC and QoSF algorithms' prioritised approaches are described in Section III. The simulation-based test environment and test scenarios are presented and testing results are analysed in Section IV. The conclusion and plans for future works are described in Section V.

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[1] HoloLens, https://www.microsoft.com/en-gb/hololens
[2] OculusRift,https://www.oculus.com/rift/
[3] Apple-VR-Project,https://www.macrumors.com/roundup/apple-vr-project
[4] Harvard AR/VR, https://i-lab.harvard.edu/arvr/
[5] VR @ MIT, https://innovation.mit.edu/resource/vr-mit/
[6] The OpenXR™ working group, https://www.khronos.org/openxr

II. RELATED WORKS

The proposed algorithms are deployed at the transport layer of the Open Systems Interconnection (OSI) network stack and work on top of MPTCP. Their goal is to find the best solutions for delivering packets in a prioritised AR/VR content distribution scenario. In this context, the related works present technologies employed in or related to this work, their applications, limitations and performance considerations. The related research works are divided in three subsections: *MPTCP*, *MPTCP-based Solutions* and *AR/VR Content Delivery*.

A. MPTCP

MPTCP is a multipath transport layer protocol which extends TCP typical functionalities to enable data transport over multiple paths concurrently and transparently [11]. It guarantees compatibility with existing applications which follow OSI network stack layers.

In principle, MPTCP connections work similarly to a regular TCP connection except that, when additional communication paths can be established, new TCP sessions are created in parallel (i.e. MPTCP subflows) and managed to behave like regular TCP connections [11].

The MPTCP stack is illustrated in Figure 1, as discussed in [11], [12], [13]. Figure 2 shows a scenario where MPTCP subflows are used to deliver content in a typical multipath network topology [13].

MPTCP backwards compatibility to TCP, its transparency to the higher and lower network layers and its multipath characteristics make MPTCP useful for AR/VR content delivery. Prioritised content delivery requires additional mechanisms to assess the delivery quality of the subflows and select those most suitable for prioritised data transmission.

B. MPTCP-based Solutions

Lately, MPTCP use is expanding, including its adoption by operating systems, such as Solaris and FreeBSD or by Apple's voice recognition system Siri [14]. MPTCP is also increasingly used for the research reported in many scientific papers.

Some researchers explore MPTCP functionalities in heterogeneous mobile and wireless network environments. The QoE-driven energy-aware content delivery for mobile phones (MPTCP-QE) [15] is an application layer solution to manage the trade-off between throughput and energy consumption using an MPTCP congestion window fast recovery strategy to optimize the use of wireless resources. The Reputation-based Load-balancing (RLoad) network selection for wireless environments [16] uses MPTCP to balance the traffic and find the best combination of QoS, cost and energy consumption.

The authors of [17] analysed how actual MPTCP implementations perform and showed that the MPTCP congestion control used does not obviate the need for a better subflow management process. Additionally, their reasoning indicates that an RTT-aware scheduling can offer limited benefits once window control mechanisms already account for RTT. Nevertheless, this paper demonstrates that an RTT-aware algorithm

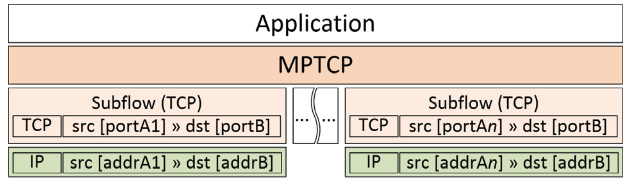

Figure 1: MPTCP stack structure

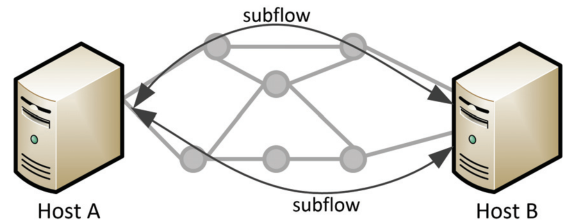

Figure 2: Multipath and subflows

can improve the performance even though it sits on the top of the typical schedulers.

Finally, Kheirkhah et al. [12] have produced and offered for public research an open-source NS-3-based MPTCP implementation, which follows the IETF RFC 6824 approach of transparency and TCP backward compatibility. This NS-3-based MPTCP open-source implementation is used in the simulation environment for algorithm modelling and testing in this paper.

C. AR/VR Content Delivery

The research described in [18], [19] focuses on new messaging protocols for the communication in virtual environments. Both works suggest updatable queue abstraction approaches to improve communication by addressing non-blocking messages ($state$ or $event$) and blocking messages ($command$ message)

A better message obsolescence management and improved message queuing policy offer relative performance improvements, but they do not take into consideration any prioritisation policy for different types of information.

AR/VR data flows can also be decomposed in components of different types, demanding different priorities for different types of components, such as positioning information (e.g. IMU, GPS or infrared tracking data) or interaction information (e.g. joystick or movement trackers).

So, being able to manage the messages (e.g., deletion or resequencing) can be an advantage but it presents a limitation when the message cannot be manipulated and it can still block the process or affect its performance.

Although the number of works addressing prioritised AR/VR content delivery is still low, an extensive number of top quality papers propose adaptive content delivery algorithms which can also be employed to deliver AR/VR content. For instance, the Quality-Oriented Adaptive Scheme (QOAS) [20], [21], BitDetect mechanism [22], EcoLearn solution [23], EAMGBL approach [24] and the evolved QoE-aware energy-saving device-oriented adaptive scheme (E3DOAS) [25] perform diverse quality and energy-aware adaptive delivery.

Other papers explore ways to overcome limitations and improve performance in their areas of application. Such works include a load balancing algorithm based on a novel priority-based approach for heterogeneous wireless networks employing real-time traffic load measurements and reallocation of resources, balancing Quality of Service (QoS) and multiple applications and device-related characteristics [26].

There are also standardisation efforts [27], despite several surveys noting lack of best practices or standards that would support AR/VR developments [28], [29]. ISO and IEC intend to standardise an AR reference model [30], IEEE AR-LEM group works on an AR learning experience model standard (P1589) [31] and IEEE VRAR group makes progress on different aspects for VR and AR (P2048) [32] standards.

III. Prioritised AR/VR Delivery using MTCP

This paper uses MPTCP to improve the RTT performance of selected packets during prioritised AR/VR content delivery. This prioritisation is important for AR/VR applications especially when user interaction is expected. As some types of information are essential for the user interaction experience [18], [19], they must be distinctly handled.

Prioritised packets for AR/VR content could carry for instance IMU or GPS data, as mentioned in [10]. The size of this data is comparatively small but requires higher priority (especially for interactive applications) when compared with video data components.

In this context, the paper proposes the VPC and QoSF algorithms that exploit the MPTCP subflow diverse characteristics to perform prioritised AR/VR data delivery. The VPC algorithm sends the priority data using a fixed subflow, employed for this purpose only, and the rest of data is delivered using the remaining subflows. The QoSF algorithm estimates in near-real time the subflows' delivery performance (based on subflows' RTT values) and dynamically suggests the subflow with the lowest latency to deliver the priority data.

A. VPC Algorithm

The VPC algorithm alters MPTCP's default load balancing policy to preserve one of the n available subflows ($n>1$) to send prioritised packets only, while the remaining subflows are used for the regular operation.

When a priority packet is identified, the algorithm directs it to a fixed subflow. Otherwise, for a regular packet, the algorithm employs the original MPTCP load-balanced delivery protocol and transmits it using the remaining subflows - as shown in Figure 3.

To select the fixed subflow, an analysis was made considering the typical traffic distribution caused by the MPTCP load balance algorithm (round-robin) and congestion control.

For this analysis, configurations varying from 1 to 8 subflows were tested using the same amount of data. Typically, as can be seen in Figure 4, the latest established subflow in the pool carries the lowest amount of traffic and the ones established first carry most traffic.

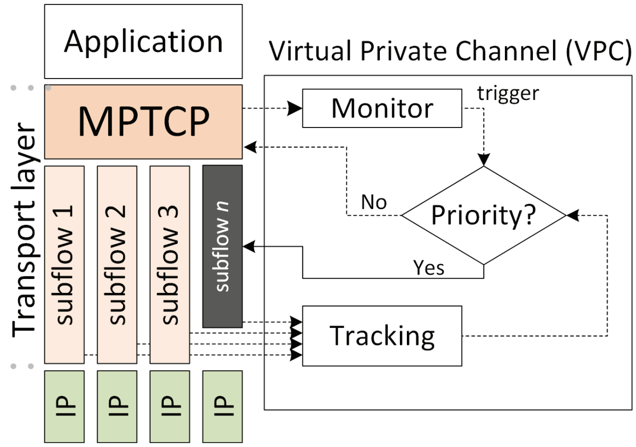

Figure 3: VPC algorithm principle illustration

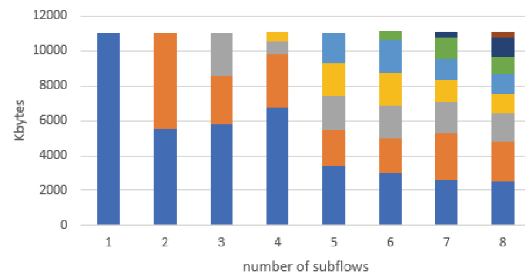

Figure 4: Throughput for each subflow test set (single-homed)

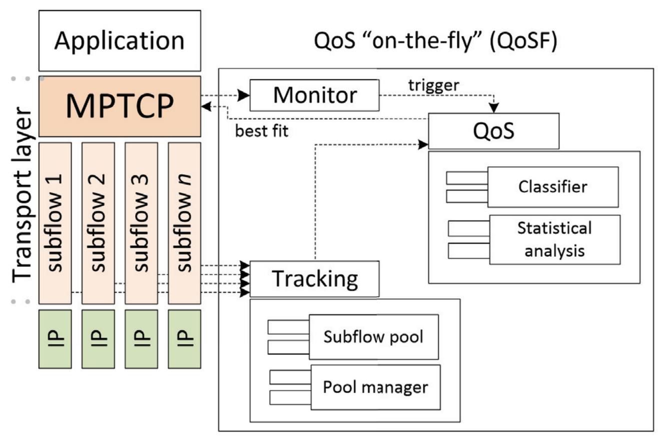

Figure 5: QoSF algorithm principle illustration

B. QoSF Algorithm

Unlike VPC, the QoSF algorithm does not use a fixed subflow. Firstly, during operation, the algorithm keeps track of the RTT values for each subflow. Then, when a prioritised packet is detected, the QoSF algorithm performs the subflow selection and delivers the packet over the selected subflow.

This selection, as shown in Figure 5, is based on each subflow's RTT historical data. A linear regression is calculated for each subflow and the subflow with the lowest slope value is suggested as the best fit. On this account, the smaller the linear regression's slope is for the subflow, the better are the prospects that this subflow will deliver the lowest latency in the next transmission.

Algorithm 1: QoSF algorithm.

```
Result: Sends the priority packets dynamically using the
        best subflow available.
Input: Packet to send, PKT; default load balance
       algorithm, Alg; number of objects per queue,
       Size; number of subflows, QS, vector with
       subflows's history, Pool
sid = Alg.nextSubflowId
if PKT is urgent then
    smallestSlope = Double.infinity()
    foreach Queue in Pool do
        slope, sumX, sumXsquare, sumXY, b, sumY,
         sumYsquare = 0
        n = Queue.size()
        foreach obj in Queue do
            sumX += obj.time
            sumXsquare += pow(obj.time, 2)
            sumY += obj.RTT
            sumXY += (obj.time * obj.RTT)
        end
        slope = ((n * sumXY) - (sumX * sumY)) / ((n *
         sumXsquare) - pow(sumX, 2))
        if slope < smallestSlope then
            sid = Queue.subflowId
            smallestSlope = slope
        end
    end
end
sendPacket(PKT, sid)
if !Pool.contains(Queue(sid)) then
    initialise Queue for sid
    Pool ← Queue
end
Pool.Queue(sid).add(PKT.time, PKT.RTT)
if Pool.Queue(sid).size > Size then
    remove first object from Pool.Queue(sid)
end
```

Algorithm 1 describes in detail how QoSF chooses the subflow (based on the subflows' RTT historical data kept in a queue structure for future calculations). Equation 1 describes how the slope for the linear regression is calculated.

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

Where $slope$ is the slope of the linear regression indicating the trend for the next value of RTT, n is the number of samples used for the linear regression calculation and x_i and y_i represent the i_{th} values of x (time value) and y (RTT value).

Then, after choosing the best fit subflow, the QoSF algorithm modifies dynamically the MPTCP's default load-balanced packet delivery and sends the priority packets using this subflow. The regular data is delivered using the original MPTCP load-balanced delivery protocol.

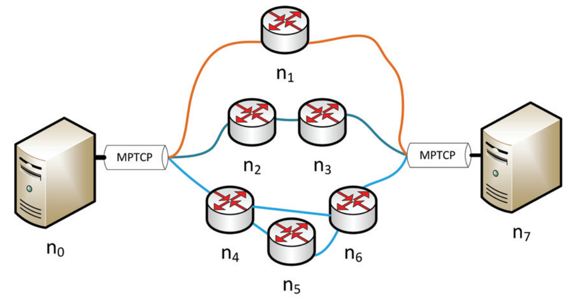

Figure 6: Testbed topology

IV. Simulation-Based Testing

The proposed algorithms evaluation employs NS-3 modelling and simulations, based on an NS-3 open source MPTCP implementation [12]. Figure 6 shows the simulated topology. It uses a point-to-point model and all nodes are connected using links with 1Mbps data rate and 2ms delay. This configuration reduces simulation complexity, but still offers realistic performance results, as shown in Figures 7, 8 and 9.

MpTcpBulkSender and MpTcpPacketSink applications are installed at n_0 and n_7, respectively. Both applications are extensions of the applications found in a typical NS-3 implementation. They send and receive simulated AR/VR content data as fast as possible over the network using MPTCP. The simulation considers single-homed and multi-homed configurations, as follows:

- Singled-homed: 8 subflows in a configuration where the MPTCP selects the shortest way from server to sink - in this case: $n_0 \leftrightarrow n_1 \leftrightarrow n_7$.
- Multi-homed: 3 subflows in a configuration where the MPTCP selects the available paths from server to sink - in this case:
  - $n_0 \leftrightarrow n_1 \leftrightarrow n_7$.
  - $n_0 \leftrightarrow n_2 \leftrightarrow n_3 \leftrightarrow n_7$.
  - $n_0 \leftrightarrow n_4 \leftrightarrow n_6 \leftrightarrow n_7$.

Single-homed and multi-homed configurations refer to the number of available devices for the MPTCP subflows. In a single-homed configuration, only one device is available and the subflows are established using different ports. In a multi-homed configuration, more devices are available and the subflows use the same port. The remaining settings (i.e. data rate, delays, etc.) are the same.

In these configurations, three algorithms are tested and compared: the proposed VPC and QoSF, and the classic MPTCP algorithm (using basic round-robin load balancing).

In the simulation model, packet prioritisation involves one packet at every 500 packets (a ratio between IMU and GPS data on one hand and video data on the other hand for typical AR/VR applications [10]).

The results of the tests in this topology for *single* and *multi-homed* implementations are discussed in subsections IV-A and

Table I
ALGORITHMS' RTT PERFORMANCE - SINGLE-HOMED CONFIGURATION

MPTCP			VPC			QoSF		
time (s)	RTT (ms)	thru (B)	time (s)	RTT (ms)	thru (B)	time (s)	RTT (ms)	thru (B)
23.8	713	1964	23,9	760	1842	24,2	444	3153
29.6	736	1902	29,8	690	2029	30,0	502	2789
35.5	771	1816	35,6	690	2029	35,8	549	2550
41.3	795	1761	41,4	736	1902	41,6	584	2397
47.1	818	1711	47,3	748	1872	47,5	619	2262
52.9	842	1663	53,1	771	1816	53,3	643	2177
58.8	853	1641	58,9	795	1761	59,1	713	1964
64.6	912	1535	64,8	807	1735	64,9	748	1872
70.4	923	1517	70,6	807	1735	70,7	795	1761
76.2	947	1478	76,5	818	1711	76,5	807	1735
82.0	959	1460	82,3	818	1711	82,3	830	1687
87.9	982	1426	88,1	853	1641	88,1	853	1641
93.7	1005	1393	94,0	853	1641	94,0	888	1577
99.5	1029	1361	99,8	865	1618	99,8	935	1497
105.4	1029	1361	105,6	877	1596	105,6	970	1443
111.2	1064	1316	111,4	877	1596	111,4	1005	1393
117.0	1076	1301	117,3	912	1535	117,2	1017	1377
122.8	1099	1274	123,1	912	1535	123,1	1040	1346
128.7	1122	1248	129,0	923	1517	128,9	1064	1316
Average RTT								
930ms ± 123ms			816ms ± 69ms			790ms ± 187ms		
Average Throughput								
1533B ± 213B			1728B ± 151B			1891B ± 516B		

IV-B. The results in Table I include RTT and throughput values for the prioritised packets when VPC, QoSF and MPTCP algorithms are employed in *single-homed* implementation.

The columns on Table I are the test results for the default algorithm (control data), the VPC algorithm (fixed subflow) and QoSF algorithm (best fit subflow). Apart from the VPC algorithm (where the subflow is fixed), the results for the default and QoSF algorithms are subject to a dynamic allocation.

A. Algorithm Assessment in Single-homed Setting

The results for the single-homed configuration is shown in Table I. During this operation, RTT of different subflows vary according to congestion window, load balancing algorithms, receive window variations, etc.

The results from Table I enable comparison between VPC, QoSF and MPTCP algorithms. It can be noted how VPC outperforms MPTCP in terms of RTT by more than 12% on average and has a 17% peak. QoSF outperforms MPTCP in terms of RTT by more than 15% on average and has a 30% peak. In terms of throughput VPC outperforms MPTCP by up to 12% for the prioritised packets, and QoSF outperforms MPTCP by up to 23%.

It is important to highlight that when RTT variation is higher, QoSF offers better performance improvement. Otherwise, the VPC algorithm offers better results, as illustrated in Figure 7.

Notwithstanding the analysis of a potential transient state can be misleading, a broader analysis shown in Figure 8 covers the steady state of the process and the RTT variations for the three algorithms demonstrates that the prioritisation of packets

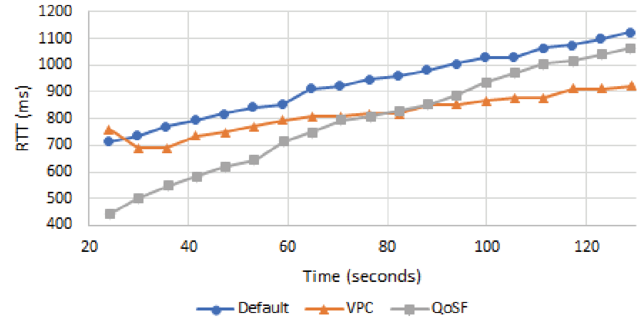

Figure 7: VPC and QoSF Algorithms' RTT performance.

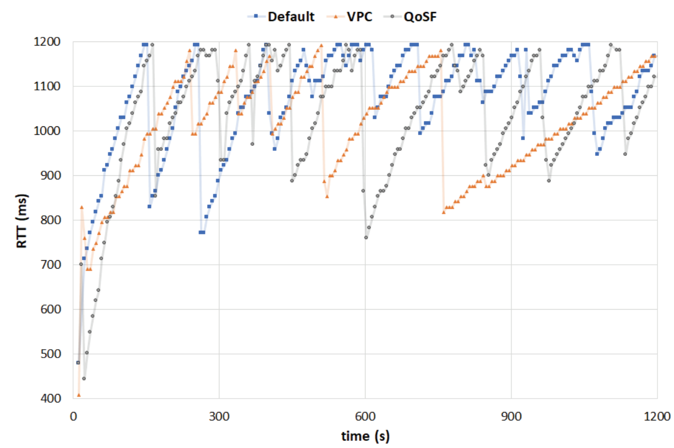

Figure 8: Steady state sampling extension.

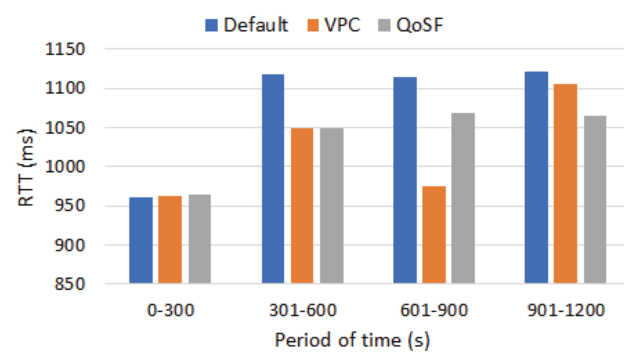

Figure 9: Steady state average values.

still benefits from the VPC and/or QoSF algorithms. In Figure 9, the results are divided into 4 periods and an analysis of the average RTT values is presented. As expected, average and peak values vary during the whole steady process, but a similar behaviour still applies to transient and steady states.

Finally, a packet loss analysis comparing VPC, QoSF and MPTCP shows packet losses of 0.49% for VPC and 0.46% for QoSF - levels acceptable for most applications [33].

B. Algorithm Assessment in Multi-homed Settings

For the multi-homed configuration, the tests show insignificant RTT variation and the results remain steady. For this reason, QoSF algorithm does not offer improvements, whereas the VPC algorithm offers an outstanding improvement, reducing the RTT by up to 90% (the dedicated device for VPC has an average 48ms whilst the other devices have an average 538ms). However, this comes at a higher cost, affecting significantly the overall throughput performance.

It is important to highlight that this approach is not detrimental to the idea that the MPTCP throughput must have at least the same throughput as a single TCP connection [11], [34]. On the contrary, this is a valuable option in cases where the application requirements demand higher performance for specific packets.

V. Conclusions

This paper introduces two novel algorithms denoted virtual private channel (VPC) and QoS on-the-fly (QoSF) for prioritised AR/VR data delivery and compares their performances with that of MPTCP. VPC selects and employs a dedicated subflow for prioritised data transport, while the remaining data is delivered using the other subflows. QoSF evaluates all subflows' performance in near real-time and selects the subflow with the lowest latency for priority data transport.

Testing results in an NS-3 simulated environment indicate RTT performance gains of up to 17% for VPC and up to 30% for QoSF in a single-homed configuration (the VPC and QoSF offer an increased throughput of up to 12% and 23%, respectively, for the prioritised packets) and up to 90% for VPC and very low for QoSF in a multi-homed setup.

Future investigations should adapt and assess the proposed algorithms in other aspects of prioritised AR/VR delivery, including AR/VR video and/or audio component delivery and focusing more on quality of experience aspects.

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