Impact of Congestion Control on Mixed Reality Applications

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ABSTRACT

The rapid increase in popularity of Virtual Reality (VR) and Augmented Reality (AR) has paved the way for the development of new applications that have the potential to revolutionize the current landscape of industries such as entertainment, education, and healthcare. A core component required to enable the development of these prospective applications is the ability to stream immersive videos in high quality with ultra-low latency. As a significant percentage of VR video traffic is expected to be delivered over mobile networks, it is important to evaluate if these networks are capable of supporting immersive video streaming. Although next-generation mobile networks offer the ultra-high bandwidth capabilities required to support AR/VR applications, it is currently unclear if current Congestion Control Algorithms (CCAs) are capable of effectively utilizing these networks to meet the strict throughput and latency requirements demanded by these applications. This paper aims to evaluate the performance of existing CCAs for such AR/VR applications. We study the performance of five prominent CCAs to evaluate: (i) the performance of these CCAs in 3G, 4G, and 5G environments for streaming current VR videos; and (ii) the performance of these CCAs in simulations with the expected bandwidth requirements of future AR/VR applications.

CCS CONCEPTS

• **Networks** → Transport protocols; **Network simulations**; **Network performance analysis**; **Mobile networks**;

KEYWORDS

Mixed Reality, Congestion Control, Measurement

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1 INTRODUCTION

VR video streaming has been labelled as one of the most important applications for 5G as it would enable the deployment of exciting applications in numerous fields such as entertainment, education, and healthcare. Applications that could potentially leverage the immersive capabilities of VR along with the ability of VR streaming to bridge geographical boundaries include live sports events in VR, VR music shows and concerts, VR tours of famous places, simulation-based learning, and collaboration spaces. In fact, 5G has already begun to transform Virtual Reality as some of these experiences have already become available. For example, a basketball game in 2018 was streamed live in Virtual Reality for a small group of fans to experience the game in VR as if they were sitting courtside [14].

VR video streaming is expected to run largely over mobile networks, as it is estimated that 71% of the world's population now has access to mobile connectivity [1]. The capacity improvements in next-generation networks enable these networks to provide the necessary bandwidth for deploying wireless applications such as streaming in Virtual Reality (VR) and Augmented Reality (AR) which can require extremely high data rates ($\tilde{3}00$ Mbps) for a smooth and high-quality experience. However, current congestion control protocols are not optimized for such applications. A thorough analysis of the performance of CCAs for AR/VR streaming is necessary to identify the limits of what the current state-of-the-art is able to achieve, identify which CCAs should be used for such applications, and identify the weaknesses in CCAs that would need to be resolved to push the frontiers of AR/VR streaming. We chose five prominent CCA for the analysis described below.

Legacy loss-based CCAs like TCP Reno and TCP Cubic are inadequate for performing optimally in highly varying 5G environments. The *de facto* congestion control algorithm is TCP Cubic, which treats packet loss as the signal for congestion in the network. Cubic fails to deliver adequate performance when link outages and capacity variations are introduced (reasonably common in high-capacity 5G channels). When combined with a highly varying underlying channel with fixed buffers, the performance of Cubic degrades significantly, leading to long delays and sub-optimal throughput, as shown multiple times in related research [30, 31]. Recently, new congestion control schemes have been proposed to overcome Cubic's limitations. BBR [9], developed by Google, overcomes this limitation of legacy CCA, and due to this, it is gradually gaining popularity and threatening to overtake Cubic as the default CCA, with an estimated 40% of internet traffic being BBR traffic in 2022 [25]. In addition, we chose two other recently proposed state-of-the-art (SotA) algorithms for highly variable network conditions, which are Vivace [12] and Allegro [11].

For our evaluation, we capture the network traffic generated while streaming 8K VR videos that are currently available, and we simulate a replay of that traffic in an emulated mobile network environment using Mahimahi [22]. In order to simulate mobile network environments, we capture 3G, 4G, and 5G network traces from real-world measurements. Then we repeat this experiment for traffic that requires the expected bandwidth of future AR/VR applications. Our results show that in low-bandwidth 3G environments, BBR

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consistently maintains a high throughput while maintaining low delays, whereas if the network environment has the required bandwidth capacity to stream the video, then Vivace is able to maintain high throughputs while also maintaining the lowest latency in most cases. The results are discussed in detail in Section 4.

In summary, in this work, we explore the question of whether current CCAs are capable of supporting the wave of new VR applications that have the potential to transform many experiences for people. We perform an evaluation of the performance of CCAs for VR streaming applications and discuss the results and how they can be improved. Our evaluation is focused on metrics of E2E throughput and latency instead of video metrics. In future work, we aim to evaluate actual VR applications using more QoE metrics. [1]

2 RELATED WORK

In anticipation of the new AR/VR applications that have the potential to significantly impact how people experience the world in their daily lives, an increasing amount of research is being conducted on AR/VR and the ability of current network infrastructure at each layer to support these applications. The two primary avenues being researched to improve AR/VR streaming are video optimization techniques to reduce the required amount of data that needs to be sent and network improvements to support the high bandwidth and low latency requirements, with a focus on mobile networks. Several papers have studied the feasibility of these applications and proposed solutions to the existing challenges faced in their development and deployment.

VR-EXP [13] proposes a uniform experimentation platform for the evaluation of VR Video streaming performance using various VR video optimization techniques under variable network conditions. Perceive [10] utilizes machine-learning techniques to predict the performance of VR video streaming in mobile networks. Hou et al. [19] present an optimization technique to reduce the required bandwidth by only transmitting the video data within the user's field of view (FOV) and predicting the user's head movements based on a deep-learning viewpoint prediction model to enable a smooth experience when the user's head moves and the FOV changes.

Spear [16] presents a platform that includes multiple techniques for designing a resource-efficient and privacy-preserving experience for multi-user AR applications. Kulkarni et al. [20] discuss the impact of Wi-Fi configuration parameters, such as channel width, radio interface, access category, and priority queues, on the Quality of Experience (QoE) for streaming immersive videos. Guo et al. [17] identify and demonstrate the effectiveness of a key component for drastically improving the experience of multi-user AR applications, which is asynchronous SLAM (Simultaneous Localization and Mapping).

AR/VR streaming applications that the current infrastructure is capable of supporting are already starting to be developed and deployed. NextVR [3] is an application developed for the Metaverse, i.e., the VR ecosystem developed by Meta, which claims to provide a platform to "experience the world's greatest sports, music, & entertainment events in virtual reality". In the past, there have been other small-scale demonstrations of VR live streaming big events as well such as the VR stream of a basketball game in the US by Verizon using 5G [14].

In the domain of congestion control research, several protocols have been proposed to solve TCP's performance issues. The most prominent is BBR [9]. Recently, performance-oriented congestion control protocols, i.e., PCC-Allegro [11] and PCC-Vivace [12] were also introduced. Ravid et al. [18] performed a study of how congestion control can impact video streaming QoE. C2TCP [5] is a congestion control algorithm that was developed to prioritize low latency to support new applications that require low latency, such as VR streaming as most existing CCA are throughput-oriented.

Apart from congestion-control solutions, on the transport protocols field QUIC [21] has been recently introduced by Google, integrating ideas from TCP and TLS/DTLS. QUIC is based on UDP, allowing a pluggable congestion control module, with CUBIC as the default choice and BBR as a suggested alternative. At the same time, it borrows several features from SPDY [26]. A deep-learning approach for delay-based congestion control is proposed in [24]. Their DeePCCI algorithm only requires training traffic knowledge of a congestion control variant, using packet-arrival data. It is directly applicable to encrypted (transport header) traffic. Therefore, it is undoubtedly extendable and can also be used with QUIC.

3 RESEARCH METHODOLOGY

To create a consistent testing ground for checking the effectiveness of CCAs in a way that is realistic, repeatable, and reproducible, we use the Zeus framework [8], built on top of the Mahimahi link emulator [23], which is commonly used to test CCAs in a range of network conditions [6, 7, 12, 15, 28]. We used Wireshark [4] to capture the network traffic traces for streaming three VR 360-degree videos in 8K resolution on the DeoVR [2] platform. From the captured traffic traces, we used *tshark* to extract the number of packets sent for each timestamp and created a simple TCP server and client that can read these traces and replay the packet transmissions in the Mahimahi emulation environment under the cellular network conditions for one minute.

We generated channel traces for 3G, 4G, and 5G using a real cellular network using the same trace collection methodology of [27, 29], with a commercial mobile network connection under different mobility scenarios. We use six channels in our evaluation, two of each network type. The selected channels' capacities over time are depicted in the insets of Figures 1-3. The data rates for the original traffic captures of 8K video streams were approximately 30 Mbps.

For simulating future AR/VR application streaming data rates, we modify the server to send packets at a higher data rate of 250 Mbps. For these experiments, we do not evaluate using the 3G traces, as the bandwidth capacity of the 3G channel traces is too small to support such high data rates regardless of the CCA being used. The remaining four channel traces are used for these experiments.

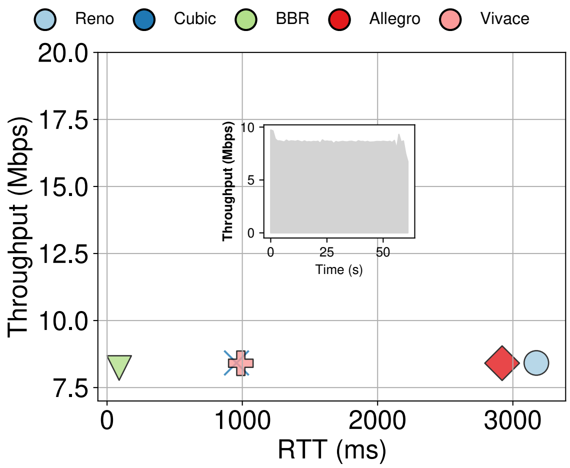
All experiments were conducted on a customized server with an Intel Xeon Bronze 3204 CPU @ 1.90GHz × 12, 15 GiB memory, and the Ubuntu 20.04.3 LTS operating system. The experiments were designed to simulate a client requesting a VR video stream from a server using a given CCA with a one-way propagation delay of 10 ms. We use the Linux kernel TCP implementations of the chosen CCA and switch between them as needed for our experiments.

[1] This work does not raise any ethical issues

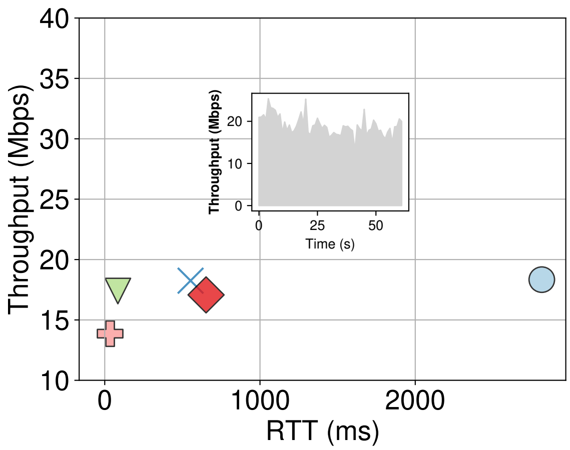
4 EVALUATION

4.1 Current VR Streaming Evaluation

Figures 1, 2, and 3 illustrate scatter plots that display the performance of five SotA CCAs over 3G, 4G, and 5G network channel traces, respectively. Each data point represents the average throughput (y-axis) and delay (x-axis) performance of a CCA. We conducted three separate runs per channel trace for each CCA to ensure the stability of the algorithms' performance and their ability to efficiently transmit the data. The figures show the results for one of the videos; however, the remaining experiment results illustrate the same trends. Each algorithm is indicated by a different color. The figures also include an inset subplot of the channel capacity over time.



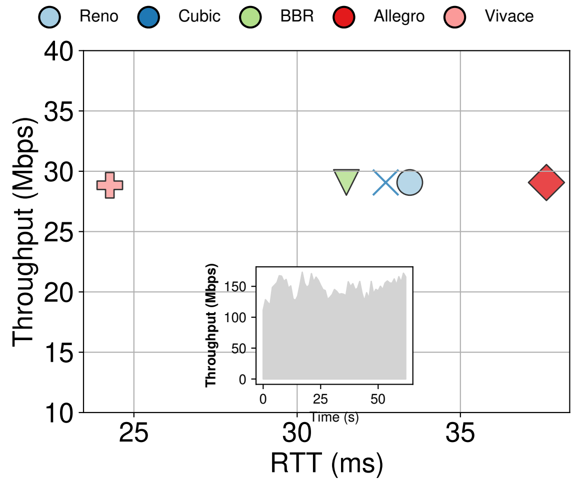
(a) 3G Stationary



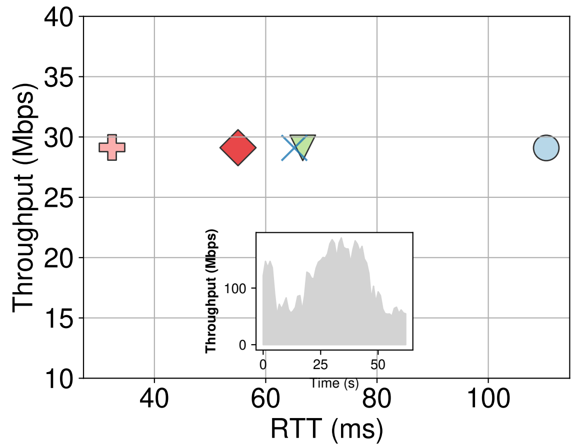
(b) 3G Walking

Figure 1: CCAs under 3G channels

Legacy CCA's performance (TCP Cubic & TCP Reno): based on our observations across all traces, we found that TCP Reno consistently had the highest delays in all network environments for VR streaming traffic. In 3G environments, TCP Cubic also experienced



(a) 4G Stationary



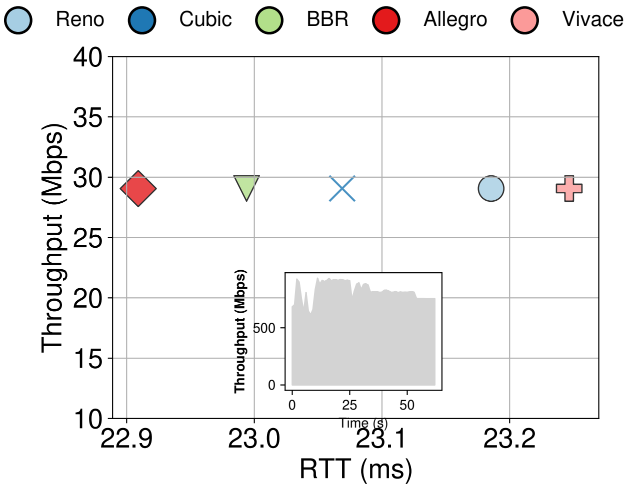
(b) 4G Walking

Figure 2: CCAs under 4G channels

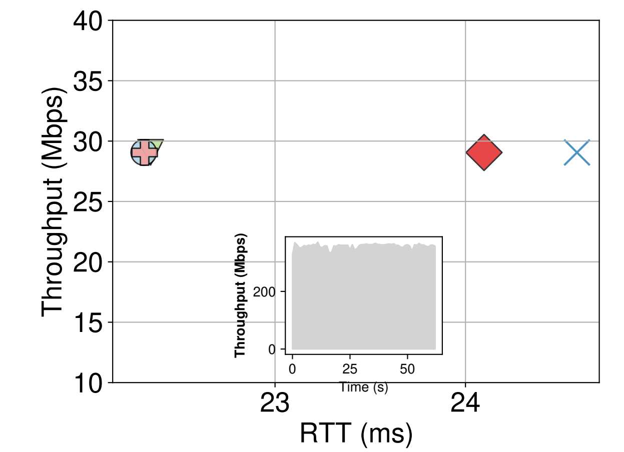
very high delays due to bufferbloat issues in the low-bandwidth environment. In 4G environments, Cubic was able to maintain the required throughput while staying relatively competitive with other CCAs in delay performance.

Google's BBR performance: BBR exhibits consistent performance across all experiments. It is able to maintain the required throughput when the bandwidth is available in 4G and 5G environments while also being able to avoid incurring excessive buffering and maintaining reasonable delays in 3G environments. It beats Vivace in delay performance in some cases, however, for most cases Vivace is able to maintain lower delays.

Allegro and Vivace: Allegro consistently incurs high delays, close to Reno in all environments. On the other hand, Vivace consistently performs the best out of all CCA in terms of delay performance. In some cases, it sacrifices some throughput performance to achieve this whereas it's closest competitor, BBR, undertakes a more throughput-oriented approach.



(a) 5G Stationary



(b) 5G Walking

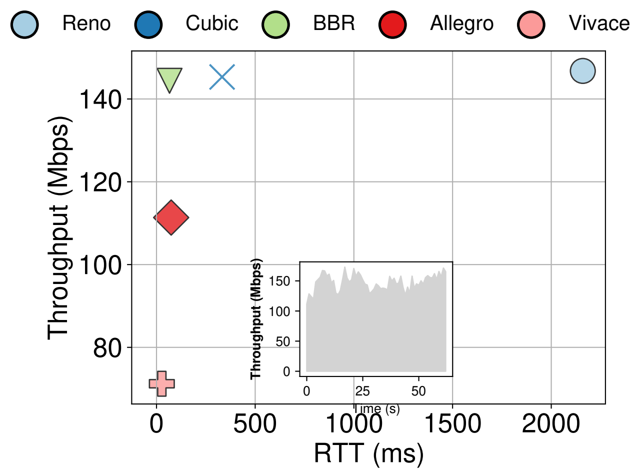
Figure 3: CCAs under high-BW 5G channels

Based on our observations across all traces, we observe that due to the 5G channel traces having ample excess bandwidth capacity, all CCA have a negligible difference in throughput and delay performance amongst each other. This can be attributed to the fact that there are minimal queuing delays when the data rate of the video stream is sufficiently lower than the available bandwidth. Due to this, we do not gain much information about the CCAs performance in the 5G experiments.

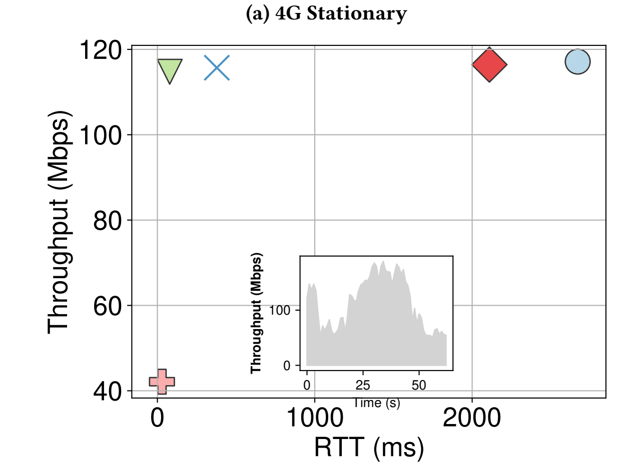
On the other side of the spectrum, the 3G results show extreme differences in latency between the CCA due to the fact that the required data rate is higher than the available capacity, which causes excess delays and bufferbloat in the case of legacy CCA. It is important to note that BBR and Vivace are the best protocols at maintaining low delays in these environments, while legacy CCA incur extremely high delays. In 3G environments, Vivace sometimes performs worse than BBR in terms of throughput in order to maintain lower delays. In 4G environments, Vivace consistently performs better than all the other CCA that were tested while also maintaining good throughput performance.

4.2 Future VR Applications

Figures 4 and 5 illustrate scatter plots that display the performance of the five SotA CCAs over four different types of mobile network channel traces while simulating a 250 Mbps real-time video stream. We remove the 3G channels from these experiments as their available capacity compared to the required bandwidth is too small. The results indicate a similar trend where Vivace consistently performs the best in delay. However, in 4G environments, Vivace has significantly worse throughput performance, while BBR has similar delay performance to Vivace while maintaining high throughput. These experiments assume a fixed target bitrate which achieves the desired video quality.



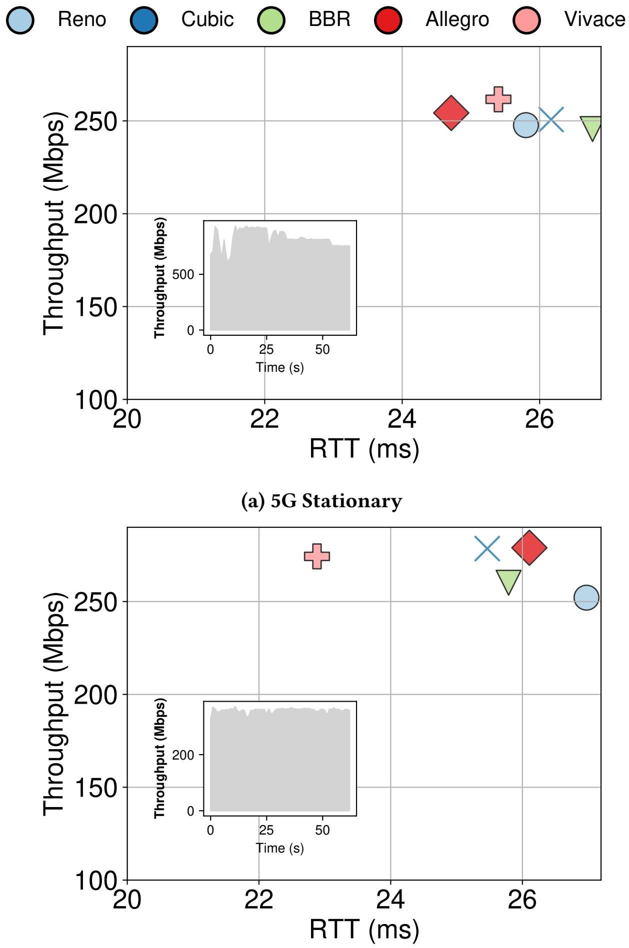
(a) 4G Stationary



(b) 4G Walking

Figure 4: CCAs under 4G channels

The key findings from these experiments with respect to the capabilities of the CCA for supporting AR/VR streaming are: (i)



(a) 5G Stationary

(b) 5G Walking

Figure 5: CCAs under high-BW 5G channels

Vivace consistently provides low delays, although it also has poor throughput utilization so it performs the best when the available capacity is higher than the required bandwidth by a certain margin; (ii) legacy CCA is not suitable for low-latency streaming applications; (iii) BBR is suitable for applications that require a balance between high bandwidth and low latency; and (iv) from these results, it can be theorized that when the required bandwidth is lower than the available capacity, Vivace is the best choice for achieving the required throughput while maintaining low latency; However, as the required bandwidth approaches the available capacity, BBR becomes the better choice as it has better throughput utilization.

5 CONCLUSION

This paper presents a study of congestion control algorithms in mobile network environments for upcoming AR/VR streaming applications. We observe that although current state-of-the-art CCAs are able to support a smooth streaming experience up to a certain extent, further work still needs to be done to improve them further to support real-time immersive streaming. Furthermore, we believe that improvements to CCA for VR streaming could enable 4G networks to provide a smooth experience, which would overcome the problems caused by the current lack of 5G infrastructure and the poor transmission distance and coverage radius of 5G base stations. If a smooth AR/VR streaming experience can be achieved under 4G/LTE conditions, then not only would it significantly increase the number of people that could use these applications, but it would also accelerate the development and deployment of these new applications.

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