Analysis of VR Remote Gaming Utilising 5G and Edge Computing

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Acknowledgements

I would like to thank my supervisor, Laith Al-Jobouri; my family for their support throughout the years; and my friends — The Fishbowl Crew. I wouldn’t have been able to do this without all of you.

Abstract

Context

VR HMDs (Head Mounted Displays) that are standalone headsets are bulky and heavy on the face of the user. This reduces its usability, reduces the potential user base, and makes usability in active places very difficult, like VR Arenas.

Aim

The project aims to evaluate the viability of offloading VR HMD computation over 5G to an external edge server, in relation to user motion sickness, ease of use, and testing the viability of using thin clients like mobile phones.

Method

A network was developed over Wi-Fi as a proof of concept, then a second over 5G using a PC as a server, connected to a 5G CPE on both ends, with a 5G RAN in the middle and a Meta Quest 3 as the client. NVIDIA CloudXR, along with SteamVR, was used for the network software on both ends.

Results

The network showed promise on throughput, FPS, and jitter but showed high latencies on motion to photon delivery at around 80 – 95ms where recommendations suggested an ideal of 15 – 20ms and a maximum of 50ms. The Samsung Galaxy S24 Ultra showed very high latencies of 300ms or more.

Conclusion

The project demonstrated that this setup was successful at offloading VR to a separate server over 5G. But latency is too high to be usable at this stage. The Samsung Galaxy S24 Ultra is not capable of calculating the spatial data needed for VR without adding large amounts of internal latency for streaming in this way, and future work is needed to continue development on true thin clients.

Abbreviations, Symbols and Notation

VR – Virtual Reality

HMD – Head Mounted Display

CPU – Central Processing Unit

GPU – Graphics Processing Unit

UL – Up Link

DL – Down Link

IoT – Internet of Things

AI – Artificial Intelligence

SIM – Subscriber Identity Module

LED – Light Emitting Diode

HUD – Heads-up Display

FOV – Field of View

AR – Augmented Reality

MR – Mixed Reality

XR – A general term for VR, AR, MR, etc.

OLED – Organic Light Emitting Diode

ALVR – Air Light Virtual Reality

LAN – Local Area Network

WAN – Wide Area Network

WebRTC – Web Real-Time Communication

CPE – Customer Premises Equipment

QoE – Quality of Experience

QoS – Quality of Service

ITU-T - International Telecommunication Union's Telecommunication Standardization Sector

RAN – Radio Access Network

SDK – Standard Development Kit

IP – Internet Protocol

TCP – Transmission Control Protocol

UDP – User Datagram Protocol

L4S – Low Latency, Low Loss and scalable throughput

Chapter 1 Introduction

Virtual Reality (VR) used with Head Mounted Displays (HMD) is the most immersive form of gaming and general tech accessible to the public. VR is gradually becoming more and more accessible and in turn slowly being adopted by more people around the world and as the technology improves it is being adopted to more fields like product development, remote working and new industries are emerging from the technology best described as VR Arenas, facilities designed for walking around in VR for gaming and other immersive entertainment. The current roadblock for VR arenas and general VR technology is the bulky, fragile, and front-heavy HMDs from the adoption of standalone VR technology. The reason for this is that the standalone technology requires heavy and expensive CPU (Central Processing Unit) and GPU (Graphics Processing Unit) computation, sensor processing, controller tracking, and heavy batteries to provide the high framerates required to meet the industry standards of motion sickness avoidance. One potential solution is to offload the computation to a separate device, be it a PC, an internal server, or an external server. This requires a high speed and reliable connection, both UpLink (UL) and DownLink (DL), which is usually a tethered connection, although wireless connections are gradually becoming more viable.

This dissertation will evaluate the viability of offloading VR computation using 5G and edge computing compared to other solutions such as WIFI, cloud, tethered, and Standalone. This is to reduce the need for heavy hardware on the user's face, to reduce the weight and size on the user and increase the potential audience of XR. To achieve this, a solution was developed over Wi-Fi and then over 5G to a local edge server, developing a system of testing different latencies to stress the bandwidth and testing different solutions, like using dedicated head-mounted displays and using 5G native mobile phones to show the power of offloaded VR.

Chapter 2 Literature Review

Edge and cloud

Edge computing is a distributed networking framework that places servers with computation capabilities at the 'Edge' of a network, bringing the servers and compute geographically closer to the clients and compute consumption. This reduces network latency for the client, reduces network congestion by reducing the distances, reducing the amount of network data that needs to travel and in turn reduces running costs. Edge has a few different use cases from private solutions for local enterprise spaces, public solutions for distributed edge computation for clients and consumers, and solutions within the network and Internet of Things (IoT) designed for use by service providers (Ericsson, no date a).

Edge computing is related to cloud computing; the application of edge computing is to be used when real-time processing is required, along with reducing network congestion only transmitting necessary data. This enables communities with slower and older network systems to use IoT technology when only needed at a local scale. Edge can also be used with minimal computation and act as traditional servers, connecting people and serving light applications such as web pages and local communication.

Edge computing encourages decentralised networks, which improves security, data privacy, and reduces unnecessary network congestion. Cloud is designed to be contained in a small number of central hubs, which means it is cheaper to deploy and maintain. Cloud is seen as less secure with large amounts of secure data being stored in one location from a large area and longer latencies if users are far away from the cloud services (Smith, 2024) (Ericsson, no date a). Some may see cloud centralisation as an advantage as it is more easily controlled and manipulated.

Edge services are easily scaled and deployed to new places since it is optimised for frequent small footprint deployments; they can continue to run with intermittent and no internet connection if the use case allows, for example, remote gaming and local networking such as weather cams.

Internet of Things

IoT (Internet of Things) is a concept of a highly complex network derived from many things, from household appliances to industrial applications. The main goal of IoT is to gather data, increase efficiency, and automate processes.

IoT has many interesting applications, including applications in healthcare in medical centres and at home, on things like pacemakers and other monitoring systems. This lets data analysis and AI (Artificial Intelligence) developers use this data to save lives through AI and automation. Applications in smart cities, gathering data for traffic management, waste collection, and environmental monitoring. This can reduce traffic and waste. Increasing recycling, increasing efficiency for waste collection routes, and waste pickup. (*What is IoT (Internet of Things)?*, no date)

With massive data collection includes massive data sensitivity. Security is an incredibly important focus for IoT, as hackers and malicious groups will view these systems as high-reward targets. If these groups gain access to these systems, it could mean manipulation of medical devices down to the individual patient. Manipulation of traffic logic can cause mass panic within communities. Manipulation of individual vehicles that are connected to IoT. IoT may be one of the most important and sensitive systems created within technology, alongside military and government data systems. Continued research is needed to understand if systems like these are worth the risk to people, communities, and national security. (*What is IoT (Internet of Things)?*, no date)

Edge computing can aid in the security of these systems, decentralising systems so that instead of one large data centre, many separate servers are needed to enter. Social engineering will be more monotonous as one person will have access to less data. Encryption will have increased separation. If an attack is found, it will be much faster and simpler to pull data plugs and remove these servers from the extended internet. For physical attacks and physical entry, police forces will have an easier time entering and locking down these premises from their reduced size.

5G, WI-FI, and LI-FI

WI-FI is a wireless networking technology that allows devices to connect to the internet without a physical connection and was the first widely adopted wireless standard by consumers. It operates on the IEEE 802.11 wireless standard in 2.4, 5, and 6 GHz frequency bands. Some believe WI-FI is an acronym for "wireless fidelity". This is incorrect with the name WI-FI coined by the brand consultancy firm Interbrand in 1999 to be catchy with the popular at the time name HI-FI (High Fidelity) audio systems to make the technology more interesting and understandable to consumers compared to the name IEEE 802.11b.

5G is the fifth-generation technology of cellular networks, in ideal scenarios, up to 20 Gbps download and 10 Gbps upload. This is much faster than 4G at a peak download of 1Mbps and upload of 0.2Mbps. Another solution is to use WI-FI; WI-FI 6 has a maximum throughput of 9.6 Gbps (Intel, No date). Private 5G is an emerging technology intended to be deployed in offices and commercial buildings as a high-speed replacement for WI-FI. 5G offers higher reliability to WI-FI with a higher tolerance to a large number of connected devices. This enables a stronger adoption of IoT (Internet of Things) devices. 5G uses a SIM-based authentication (Subscriber Identity Module) and gives networks a physical security system that eliminates credential-based attacks (*Ericsson Private 5G*, no date). Dual sim is a common feature on modern mobile phones, which enables the use of private 5G for office spaces alongside the user's personal sim. As private 5G continues to be adopted, it may be in the manufacturer's interest to increase the number of SIMs, or more likely eSIMs, that a phone can hold.

LI-FI is a technology of wireless transmission where instead of using radio waves as cellular networks and WI-FI (Intel, no date) (Vodafone, no date) LI-FI transfers data over visible light at high frequencies, pared with the wavelength of visible light being higher than radio LI-FI can reach speeds of up to 224 Gbps. This is achieved using LEDs (Light Emitting Diodes) using Visible Light Communication, and the spectrum is 1000 times larger than the radio frequency (LIFI Group, no date). The main downside of LI-FI is the limited range, where LI-FI is only accessible beneath the bulbs and as it is visible light does not penetrate anything that causes a shadow (LIFI Group, no date b). LI-FI is also a niche product usually used in industrial applications such as manufacturing, healthcare, and military applications, incentivised by the security features. This in turn brings up the price of the technology, making it more specialist and less accessible to the consumer. 5G, with its ability to connect many devices at once, its high bandwidth capabilities, and the long-range capabilities reaching 100km (Ericsson, 2023) 5G is an ideal candidate for XR offloading, private and public, to computation servers.

Head Mounted Displays

HMDs (Head Mounted Displays) are the displays needed to use VR (virtual reality) and play VR games. HMDs are a wide variety of different technologies with a few distinct categories.

Heads-up Displays

HUDs, (Heads-up Displays) add semi-transparent text or images to a user's FOV (Field of View). This category includes different technologies that use HMDs and other techniques. A common use of HUDs are light aircraft and military applications (Matt Thurber, no date). Google Glass is the most well-known use of HUD technology in an HMD use case, where it has a small screen in the top left corner of the user's FOV to display information connected to a mobile phone. Google intended for it to be used as Google Maps navigation while driving, a general work aid, and promoted it as a lifestyle product. Google developed a platform for third-party apps to be developed and it showed promise in places like medicine and healthcare (McClatchy, 2015). The product is mostly remembered for its famous flop when announced and released to consumers in 2014 with its radical ideas and high price point (*Why Google Glass Failed*, no date).

Augmented Reality

AR (Augmented Reality), a technology that can either add things like three-dimensional objects in an additive way similar to HUDs (*VITURE Pro XR: Experience Next-Gen Clarity*, no date) or use cameras to display the world through screens and add objects to that world. The Apple Vision Pro (*Apple Vision Pro*, no date) is a cutting-edge AR HMD that is designed for workspaces with high-performance spatial computing and retina displays. HMDs that replace the outside world with a view of the user's view on a screen are also commonly referred to as MR (Mixed Reality) for their versatility to range from pure passthrough to pure Virtual reality.

Virtual Reality

VR (Virtual Reality) is an HMD technology where the HMD fully covers the user’s eyes and brings the user into a virtual world. VR may use cameras to track itself in space for “inside out” tracking headsets, but it is not intended for the user to see the cameras. Other VR HMDs use outside-in tracking, where they use external tracking devices separate from the HMD placed around the room and send the data to the headset or external computer for computation. HMD gaming is mostly used in VR for its creative freedom, AR gaming also has a market, and the most common VR headset, the Meta Quest 3, has just released the ability for 3rd party developers to develop AR games and applications (Williams, no date).

Thin Clients

Thin Client is a term that ranges from devices designed to be used alongside computational servers for services like running applications and storing data. Extending to devices that purely send off input data and display a video stream while acting as a separate device. Traditionally, thin clients are an office and enterprise technology to reduce the cost and increase security of individual workstations by using servers and virtual machines (*Thin Client: What It Is, How It Works & Use Cases*, no date). The future of thin clients includes mobile phone thin clients and game consoles. This reduces the cost of devices to the consumer while increasing security, surveillance, and reducing the ability to use unauthorised software. Client devices also increase the workload on the network. This is what Edge servers can aid (Sharwood, no date).

Offloading VR Approaches

There are many different headsets that would be possible to use for offloading and remote VR. The Bigscreen Beyond is the cutting-edge HMD and currently the world's smallest and lightest VR HMD, weighing in at 127 grams. This is the type of headset that is ideal for offloading and is designed to be connected to a separate computer. It achieves the minimum specs of a general HMD with 90Hz refresh rate, 102 degrees FOV and an ultra-high resolution micro-OLED display it does sacrifice some features to achieve the size is has with no wireless connectivity, dim screens and the need for custom cushions for the user and custom lenses for users that need prescription glasses. It is also less accessible to consumers with a high price point that does not include controllers or audio (Bigscreen Beyond, no date) (Linus Tech Tips, 2023). The meta quest 3 is designed as a standalone headset that also includes offloading capabilities over tethered USB Type C Link cables and WIFI, it is one of the most common consumer headsets due to its price point, adaptability to what the user needs and compatibility with a wide range of other software (*Meta Quest 3: Mixed reality VR headset*, no date).

ALVR, FOV Optix, and NVIDIA CloudXR

To achieve XR offloading, there needs to be software that connects the HMD to the computer/server. ALVR (Air Light VR) is generally the most well-known and most compatible software to achieve PC-based VR computation over WIFI. Even though it has been around for over 8 years, it has kept up to date recently supporting the Apple Vision Pro (*alvr-org/ALVR*, 2025). ALVR uses standard video compression techniques, and with the software being around for a long time can include bloat and legacy computation that newer software will not have.

FovOptix is a software developed alongside a journal article (Alhilal, Ahmad, et al., 2024) (WuZemyp, 2024) and is built on top of the ALVR codebase. It is a software that introduces Fixed-Foveated Video Encoding. Fixed-Foveated Video Encoding is a technique that gives different parts of the frame different amounts of quality based on the field of view. Generally, this is not possible without eye tracking, but with the Foveated Video Encoding being fixed to the centre of the screen, eye tracking is no longer needed. For the purposes of offloading and HMD size reduction, this is a good option, but both ALVR and FovOptix are only developed for local LAN setups.

NVIDIA CloudXR is a software currently being developed by NVIDIA designed to stream XR over any network, including LAN, WAN, WIFI, and 5G from server to what's called a thin client device, any device that has minimal components, a monitor, and high bandwidth to upload data and download video streams. This also includes thick client devices like standalone headsets like the Meta Quest and other HMD devices. This may also be compatible with 5G enabled mobile phones, which are thin devices compared to the computation needed for many uses of VR. Currently, Bigscreen Beyond is not supported by NVIDIA CloudXR, whereas the Meta Quest 3 is supported.

Offloaded VR over WI-FI has been achieved before (Casasnovas, M. et al. 2024) using Unity Render streaming and WebRTC. They use a testbed of a client pc to control the HMD, a WI-FI 6 access point, and a powerful PC with VR gaming capabilities to act as the server. They tested Quality of Service (QoS) and used ITU-T Y.3109 recommendations as Quality of Experience (QoE) standards to follow and compare to. During testing, the article achieved the ITU-T Y.3109 service quality recommendations for motion sickness prevention. They did not stress test the system by adding latencies to simulate a true server rather than a PC and a WI-FI router. This would only be an accurate setup for a local area network.

Using 5G with VR will most likely stay as a professional application in commercial and industrial applications due to 5G being professional hardware, private 5G is a promising solution to high speed, wireless, long distance and multi connection for VR arenas, large facilities designed for VR experiences like shooters and other immersive entertainment. Ericsson develops private 5G solutions that are ideal for this type of application (Ericsson, no date d) that would pair well with future 5G enabled HMDs and thin client HMDs. Peñaherrera-Pulla, O. *et al.* (2024) focuses on offloaded VR over 5G focusing on industrial scenarios, they use a SIMCom 8202G M.2 5G modem. They concluded that WI-FI 6 was slightly faster than 5G. It is important to note that the paper was using a WI-FI CPE to convert 5G into a compatible WI-FI connection for the HMD, as there are currently no HMDs with 5G compatibility or any cellular connection ability. Another solution may be some ability to connect the HMD with a wired ethernet connection to avoid the WI-FI bottleneck. It is also very difficult to compare 5G to WI-FI when WI-FI is an unavoidable step in the network.

Testing is a crucial part of this research. Ideally, Quality of Service (QoS) and Quality of Experience (QoE) should both be tested. Varela, M., Skorin-Kapov, L. and Ebrahimi, T. (2014), in their paper “Quality of Service Versus Quality of Experience” describe the difference between QoS and QoE, misconceptions, and ambiguities. QoS is used generally in telecommunications to describe different aspects of the service quality, latency, jitter, packet loss, etc. QoE is a much broader term that focuses on the experience of the user rather than focusing on the network itself and assuming that if the network is fast, the user experience is positive. QoE is used by most specialities in software alongside User Experience (UX) research and development. QoE is more complex to test as it requires user testing, feedback etc. whereas QoS can use predetermined standards like ITU-T to standardise minimums and ideal network conditions.

To conclude that this paper and research have successfully achieved a usable VR experience, the researcher will need to accurately measure if the setup is compatible with the majority of people. The International Telecommunications Union (ITU-T) Y.3109 recommended a round-trip delay of less than 20ms with an ideal of less than 8ms. A recommended bandwidth of 80Mbps with an ideal of 1Gbps (ITU-T Y.3109, no date). Ericsson states that 5G is capable of bandwidths up to 20Gbps (Ericsson, no date c). Round trip delay is generally attributed to the network infrastructure, distance between client and server, and in this case, computation capability. Casasnovas, M. et al. (2024) achieved this in their article “Experimental evaluation of interactive Edge/Cloud Virtual Reality gaming over Wi-Fi using Unity render streaming” to ITU-T standards.

Lee, K.-Y. *et al.* in the paper “Adaptive Cloud VR Gaming Optimized by Gamer QoE Models” developed QoE models with VR Cloud Gaming, they used local servers and tested different games and different network conditions. They found that cyber sickness is highly dependent on the user and thought their research found this can be greatly reduced, but say that this also requires future work.

Chapter 3 Methodology

Preliminary Setup

Prior to gaining access to the university's private 5G infrastructure, a preliminary setup was made to begin research towards using 5G to offload VR computation to a server. The setup contained a Windows 11 PC acting as the server, a WRT1900ACS WI-FI 5 router, and a Meta Quest 2 HMD. The PC acts as the server running ALVR (Air Light VR) with SteamVR. The PC is connected to the router via ethernet, and the router is connected to the Meta Quest 2 HMD via WI-FI.

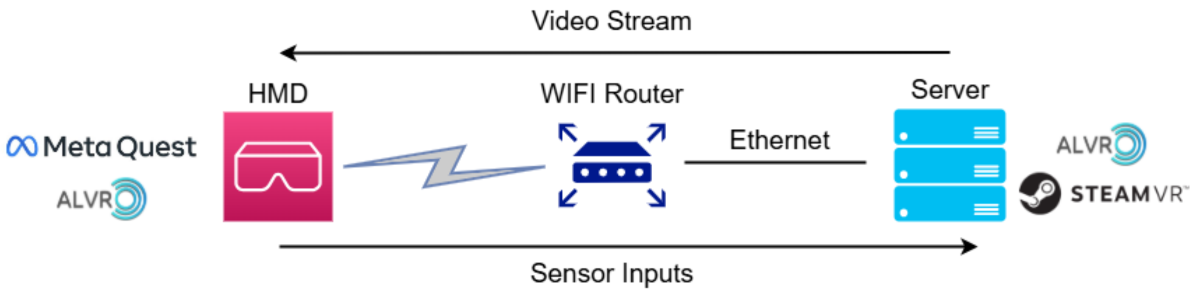

Figure 1 - Diagram showing the WI-FI and ALVR setup prior to creating the 5G setup

After consideration of a few options, FovOptix was the first choice. During development, Rust compile errors occurred with FovOptix that ended up unsolvable. An issue was opened on the FovOptix GitHub repository and remains open and unanswered at the time of writing. FovOptix was developed on top of ALVR, so it was quick to pivot to ALVR.

During brief observational testing of the system, latency seemed good, but the throughput and visual fidelity were poor. This may have been due to the slightly older WI-FI version at WI-FI 5. During testing, there were unpredictable dropouts, this seemed to be related to the distance to the router; a close proximity caused problems, and a minimum approximate 3-metre distance seemed to smooth out the transmission. Modern wireless VR most commonly used by consumers is Steam Air Link, and they recommend Wi-Fi 6 (Rakver, no date). A Meta Quest 2 was used, the Meta Quest 3 is capable of WI-FI 6E. Generally, to achieve WI-FI 6E, the consumer is required to purchase a third-party router, which is a premium commodity. Future developments to WI-FI 7 will continue to increase the throughput and reduce latency.

5G Setup

Overview

To carry out this research, a prototype client-server network was developed using cutting-edge network architecture and software. A testing game was developed to aid in consistent network data transmission for testing. The system utilises the NVIDIA CloudXR SDK to control the network transmission between the server and client as it is developed with 5G in mind, it can operate in a WAN (Wide area network) configuration, and the development kit is capable of streaming to many HMDs and mobile phones. This lets the research test both dedicated standalone HMDs and thin clients.

Network design

The network consisted of a PC acting as the server, connected to a 5G CPE via Ethernet. This connects to the universities 5G RAN, which connects to the second 5G CPE, this is connected to the HMD via ethernet with a ethernet to usbc NVIDIA CloudXR SDK is used for the network software as it has been developed to be used over a wide variety of network types including WI-FI and 5G. NVIDIA CloudXR SDK has software for a Windows server, VR Client software that supports the Oculus VR SDK, and an AR Core client for Android tablets and phones. The SDK also includes an ARKit client for IOS devices. IOS is understood to be slightly more capable of XR due to the spatial computing features. Development for the CloudXR IOS ARKit Client would have required access to a MAC to run and compile Xcode, which was not accessible at the time. The server is connected to the CPE through ethernet, and the client's CPE is connected to the client through ethernet and an ethernet to USB C converter capable of 1000 Mbps to best emulate a 5G enabled HMD device. The CPEs are also capable of WI-FI 6, where 5G converted to WI-FI will also be tested.

Server PC			
Windows 11	12th Gen Intel(R) Core(TM) i7-12700	RAM : 64GB	GPU : NVIDIA GeForce RTX 3070

Teltonoka RUTX50 5G CPE Router	
5G up to 3.3Gbps	SA & NSA

Meta Quest 3		
Android	Qualcomm Snapdragon XR2 Gen 2	RAM: 8 GB

Samsung Galaxy S24 Ultra		
Android	Qualcomm SM8650-AC Snapdragon 8 Gen 3	12GB RAM

Table 1 - Hardware Specifications

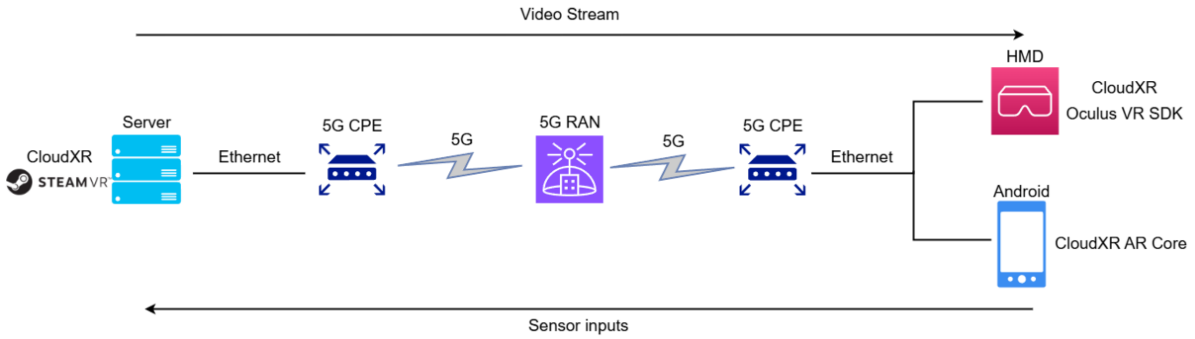

Figure 2 - 5G testing setup

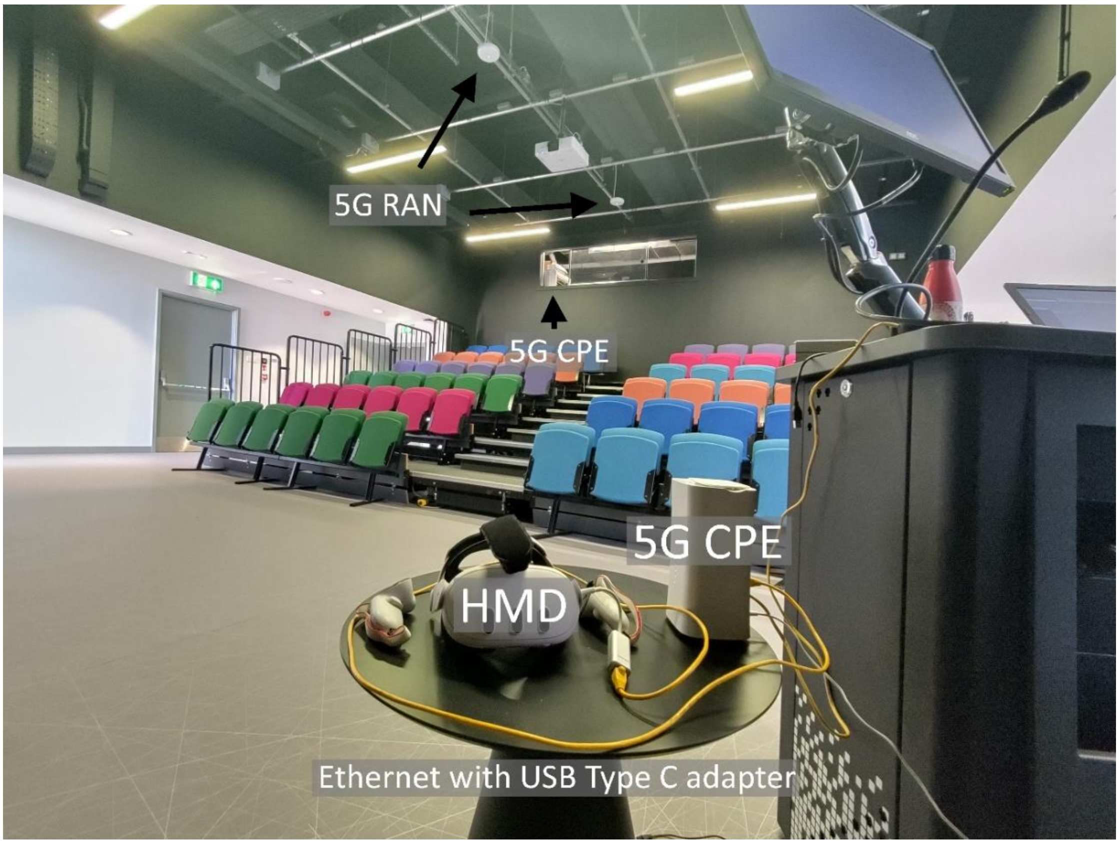

Figure 3 - Photo of setup from the client's perspective showing the server in the background

Figure 4 - Photo of setup from the server's perspective showing the client in the background

The server runs NVIDIA CloudXR, which is run on top of Steam VR. CloudXR is a driver that is activated and waits for a connection while Steam VR runs. CloudXR does not run if an HMD is physically connected to the server. The network that was used for this project acts as a WAN network, so port forwarding was used on both CPEs to pass WAN IP to LAN IP.

- Open TCP ports required:

Server		Client	
Connect	48010	Connect	49007

- Open UDP ports required:

Server		Client	
Control	47999	Control	49006
Audio	48000	Audio	49003
Video	47998, 48005	Video	49005, 50000-55000
Microphone	48002	Microphone	49004

Table 2 - Port forwards to open for CloudXR

The CPEs have standalone 5G sims and standalone capability on band n77 and are connected to the university's private 5G network. The Teltonika RUTX50 5G CPE is capable of both transmitting WI-FI and Ethernet. Currently, no HMDs are capable of 5G, so to mimic a 5G enabled HMD, an Ethernet to USB-C adapter capable of 1000 Mbps has been utilised to reduce the bottleneck of a lower bandwidth connection. In previous works, researchers have used HMDs connected to CPEs over WI-FI. Comparing this to direct WI-FI transmission would be more convoluted to understand the comparison between WI-FI and 5G. 5G to WI-FI will also be tested to observe the impact of WI-FI on this network in comparison to 5G to Ethernet.

The HMD that has been used is the Meta Quest 3, as it was the HMD accessible for the project. The Oculus VR Client was built and installed on the Quest 3 HMD, and an IP address of the server needs to be added to the headset in a text file called CloudXRLaunchOptions.txt. Due to the WAN configuration of this setup the necessary ports were forwarded, and the IP of the server-side CPE was added.

Other command line options were added, network topology was set to WAN, client network interface was tested with 5G, and L4S was enabled. L4S (Low Latency, Low Loss, and Scalable Throughput) is a new technology focused on reducing latency and congestion loss while having very little impact on classic performance, primarily for real-time applications. Side Quest was used for debugging and changing settings on the HMD. The launch options configurations were tested for the optimal configuration for latency and visual fidelity.

Client-side port forwarding was found to be unnecessary in this network, as the server will already have the information to send data back to the client.

The Android phone used to test thin client devices was the Samsung S24 Ultra. The phone is capable of 5G, but not standalone 5G, so an Ethernet to USB-C adapter was used. The AR Core Client was built and installed, it is important to mention that to build the client, the project directory needed to be on the pc root to not extend past Windows file length limitations. The AR Core client has fewer command line options than the Oculus, and the IP of the server is inputted at launch.

Unreal Engine testing game

A small testing application was developed in Unreal Engine to test different scenarios in a game environment and in a reproducible manner. The application consists of a VR environment with 3 situations, a static or near-static scene, some confetti on the screen, and random static to simulate as much data transfer as possible.

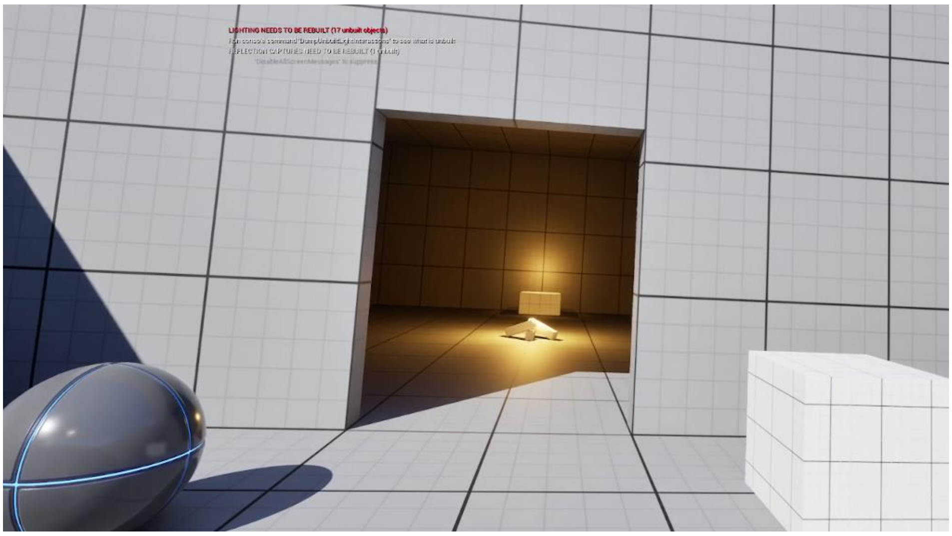

Figure 5 - Screen capture in game for low throughput scenario

A tutorial by YouTuber Cleverlike was used to create a confetti effect for the testing game. It used the Unreal Engine 5 Niagara system (Cleverlike, 2023).

The confetti was developed through Niagara with the confetti emitter. A blueprint sets the VR camera to a preset location for the ability of repeated tests and activates the confetti emitter on a timer. Widgets are added to the VR controller menu to start the test.

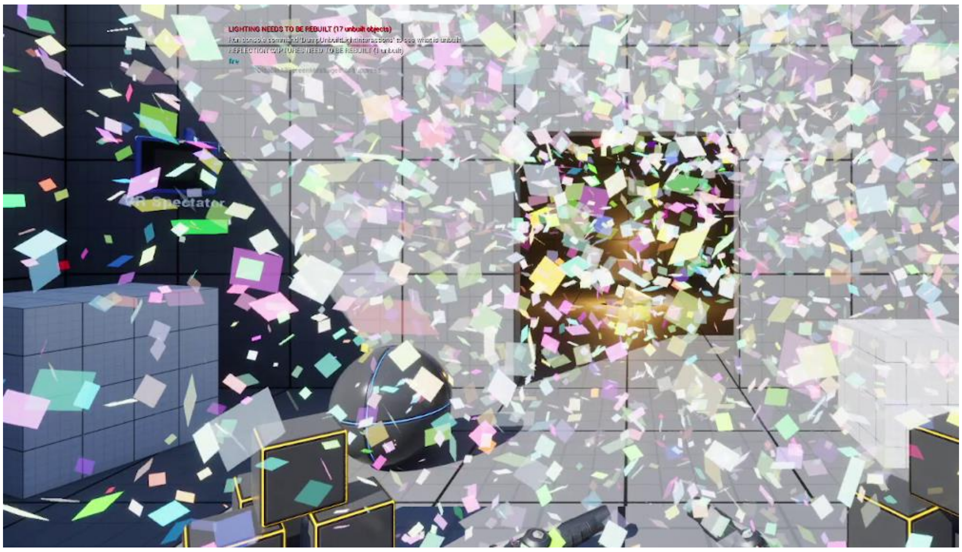

Figure 6 - Screen capture in game of medium throughput scenario – confetti falling from the top of the screen

The random static was created with a tutorial by YouTuber Coreb Games (Coreb Games, 2024). Using an Unreal Engine material, noise nodes are used separately for the X and Y directions, and a parameter that is multiplied by the input and set to the floor of the float. This means every unit is set to the specific colour. This is added to delta time (X) and reversed for the other coordinate (Y), which is then fed into a 'min' node, which determines the smallest of the two, giving a static effect. This effect is not perfect due to Unreal Engine's temporal anti-aliasing, which smoothest out transitions and removes the "snappiness" of the effect.

Figure 7 - Screen capture on game of high throughput scenario – random static

Testing

The project has been developed to test the viability and current state of using 5G to offload VR computation to a separate server on premises. CloudXR includes developer launch options -tqs or -trace-qos-stats to save detailed QoS statistics that are saved in CSV format on the HMD. These consist of –

- Frames Per Second
- Frame Time (ms)
- Client Queue Time (ms)
- Late Awaiting Latch (ms)
- Average Video Rate (kbps)
- Estimated Available Bandwidth (kbps)
- Bandwidth Utilization (%)
- Packet Loss (cumulative)
- Jitter (us)
- Round Trip Delay (ms)
- Received Packets (cumulative)
- Received Packets Dropped (cumulative)

For this research, 6 significant parameters were observed: Frames Per Second, Frame Delivery Time (Motion To Photon), Bandwidth Utilisation, Round Trip Delay, and Jitter. These values will be cross-referenced with the ITU-U Y.3109 Virtual Reality Quality of Service Recommendations to prevent motion sickness. Testing also included physical tests through gameplay, observing the visual fidelity and responsiveness of the game under certain network conditions and configurations. Most of the observational tests were conducted in parallel with the QoS testing mentioned previously by observing the fidelity of the lines on the floor of the SteamVR empty environment, the responsiveness of the hand tracking, and head tracking by moving around and observing the ground moving accordingly.

During testing, the bitrate seemed slower than it should be. It was found another hidden client launch option was found for setting the maximum bitrate; if no value was set, the maximum bitrate seemed to be around 10,000 kbps measured through the bandwidth utilisation. Setting the bitrate noticeably increased the bitrate, so this is considered during testing.

After gathering and processing the QoS data, a test is conducted in-game using the optimal configuration to observe the network conditions in a game scenario. This is to observe the network in a direct games QoE perspective and to analyse the viability of using this system on a VR Arena scenario. The data from this test will also be cross-referenced with the ITU-U Y.3109 Virtual Reality Quality of Service Recommendations.

The observational tests are intended to be supplemental insight to accompany the main QoS data.

A previous network and test were created to prepare for the use of 5G. A network was developed to test over WI-FI using a server, router, and Meta Quest 3 HMD. The server was connected to the router over Ethernet, and the HMD was connected to the router over WI-FI. This was to compare the capabilities and limitations, as it is another option for the use cases that are being focused on in this research. ALVR (*alvr-org/ALVR*, 2025) was used for the Wi-Fi connection, other options were considered - FovOptix (WuZemyp, 2024) for the cutting-edge technology. Unfortunately, the repository failed to compile due to Rust compiler errors. Efforts were made to resolve the errors, but progress was limited due to a lack of familiarity with the Rust programming language. Another option was using WebRTC (*WebRTC*, no date) from research conducted in the journal article “Experimental evaluation of interactive Edge/Cloud Virtual Reality gaming over Wi-Fi using unity render streaming” (Casasnovas *et al.*, 2024) that used WebRTC to develop their system of streaming Unity VR over Wi-Fi using WebRTC and Unity render streaming. The research achieved jitter at 60 and 90 FPS (Frames Per Second). For the initial test, this research ALVR was decided to be used for its maturity, development community, and documentation. ALVR was chosen after the failure of using FovOptix.

Chapter 4 Results

Performance was conducted over 10 separate tests, testing each combination of different launch option parameters.

- Lan, ethernet, l4s
- Lan, ethernet
- Lan, mobile5g,l4s
- Lan, mobile5g
- Wan, ethernet, l4s
- Wan, ethernet
- Wan, mobile5g, l4s
- Wan, mobile5g

Once the optimum configuration is found, a second test is conducted with an added parameter, -b (maximum bitrate), a value that is multiplied by 1000 in the client software.

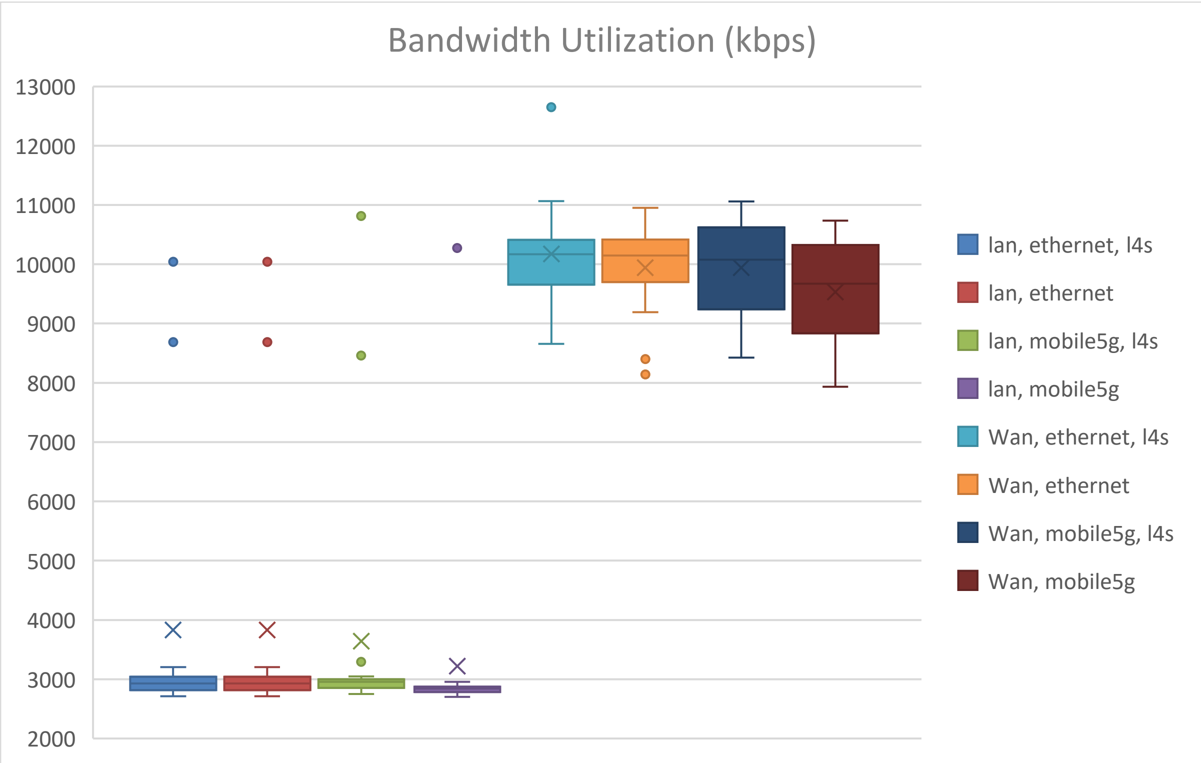

Figure 8 - Results of bandwidth utilisation data over a period of time from CloudXR -trace-qos-stats

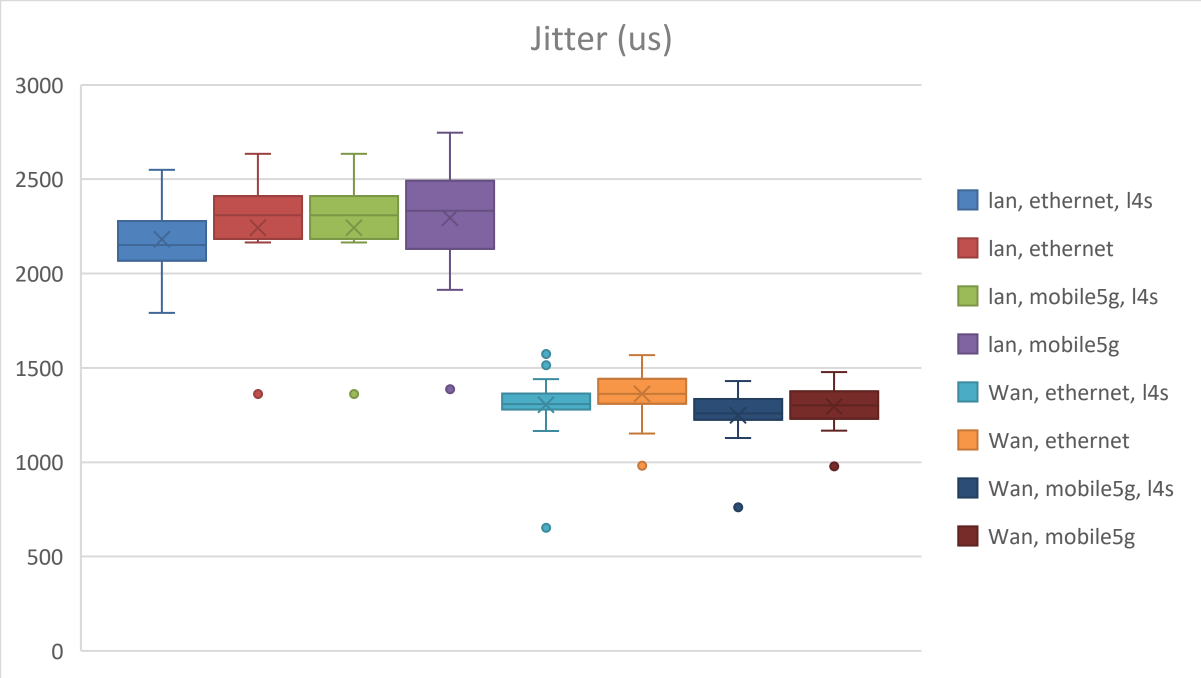

Figure 9 - Results of Jitter data over time from CloudXR -trace-qos-stats

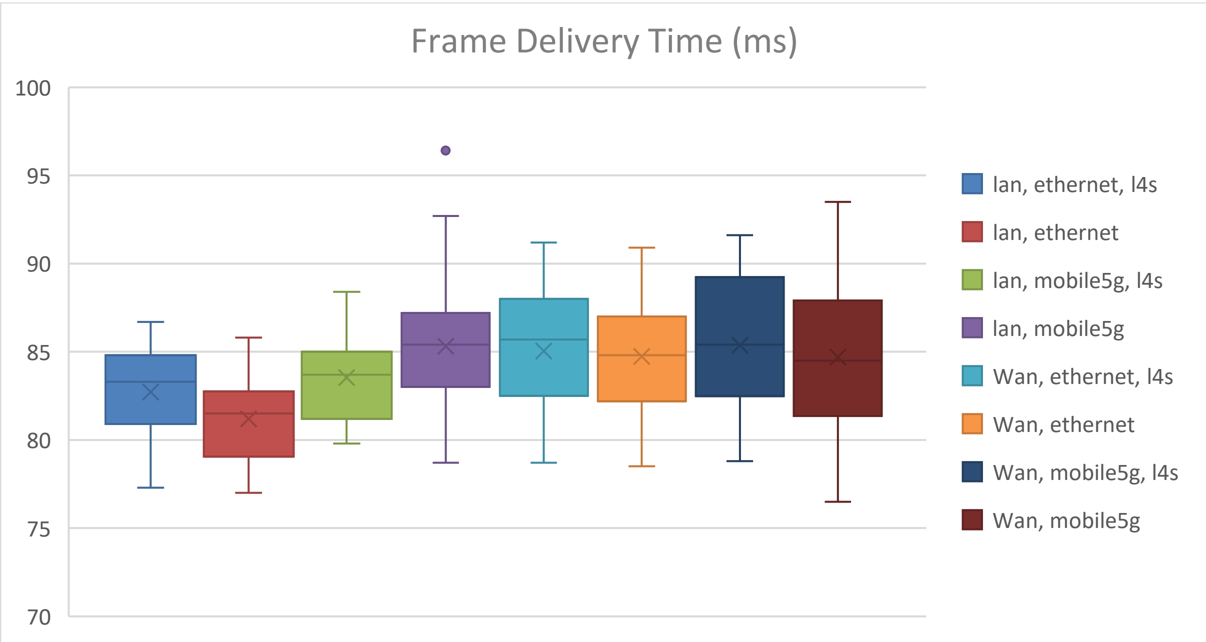

Figure 10 - frame delivery time in milliseconds (motion to photon delay) from CloudXR -trace-qos-stats

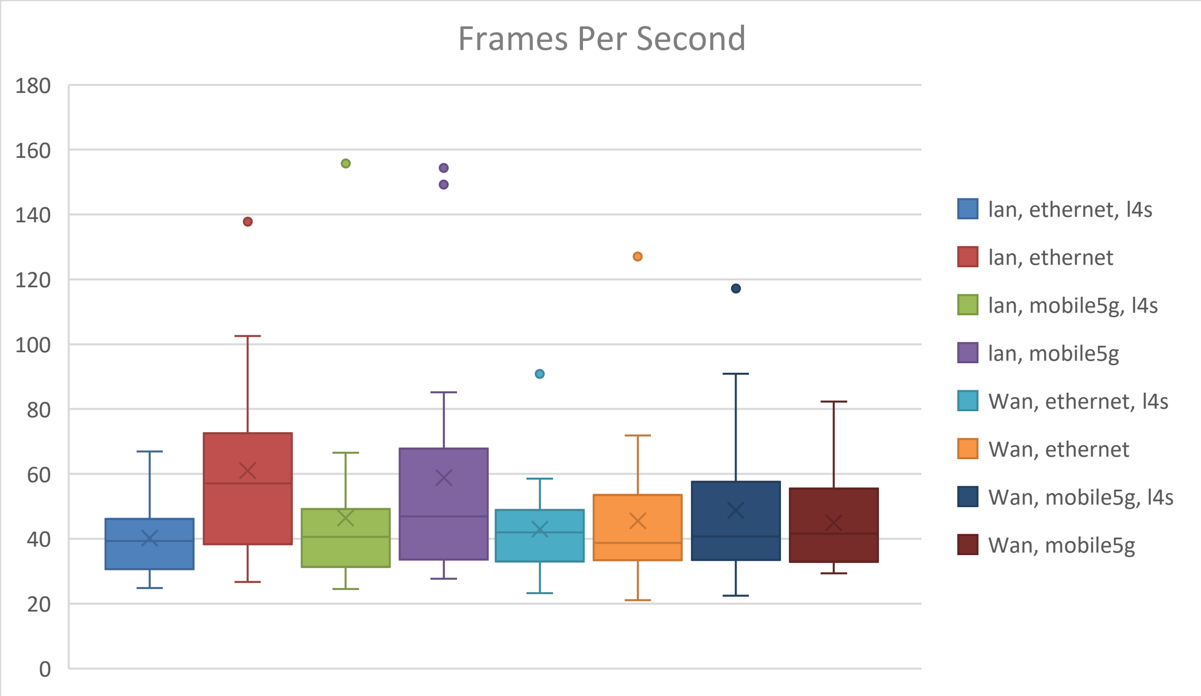

Figure 11 - Frames Per Second from CloudXR -trace-qos-stats

These findings show that Wan is the main significant variable. Continued tests were conducted with Wan to test the significance of changing the max bitrate.

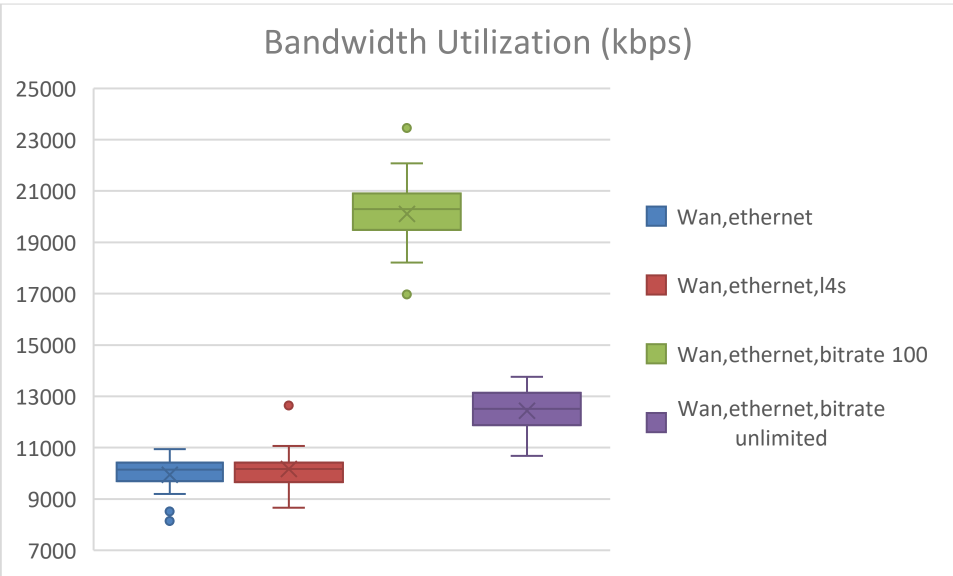

Figure 12 - Bandwidth Utilization testing bitrate options from CloudXR -trace-qos-stats

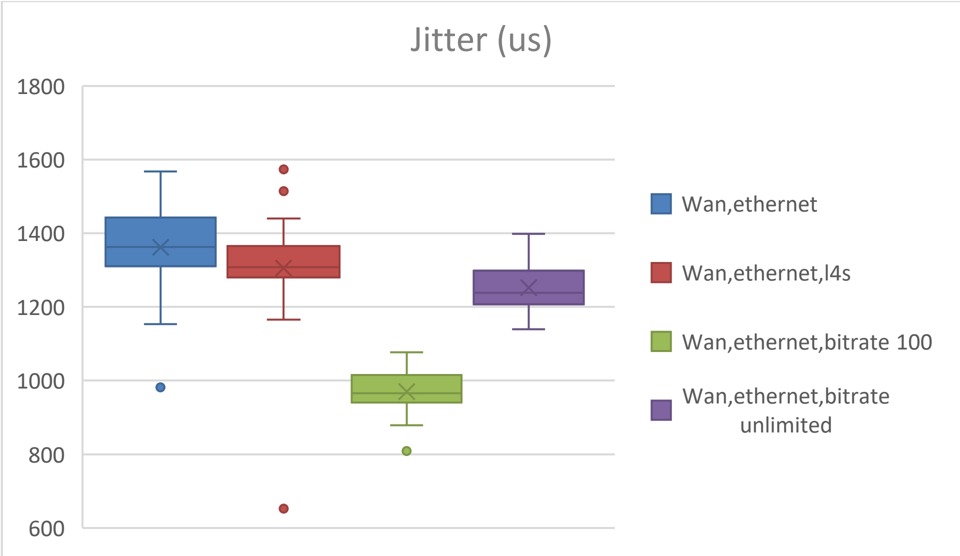

Figure 13 - Jitter in microseconds testing bitrate options from CloudXR -trace-qos-stats

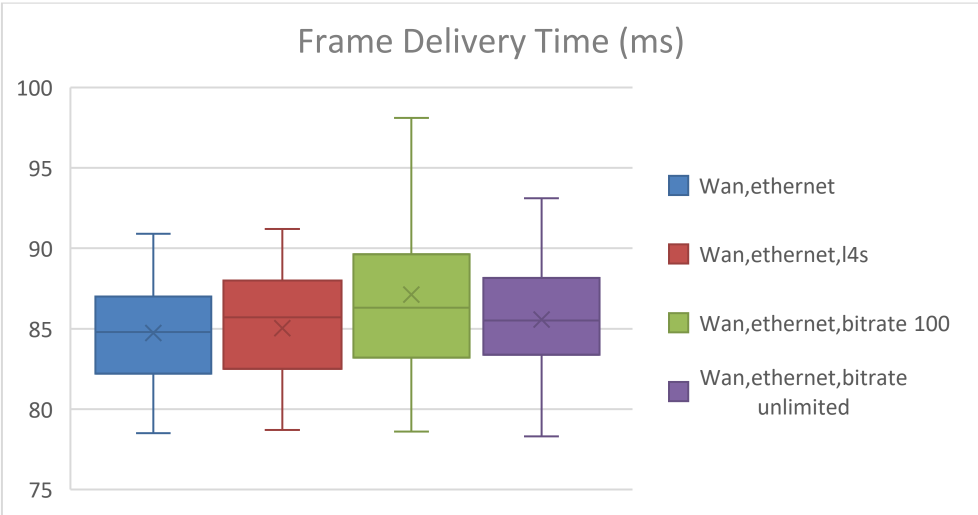

Figure 14 - Frame delivery time (Motion to Photon Latency) testing bitrate options from CloudXR -trace-qos-stats

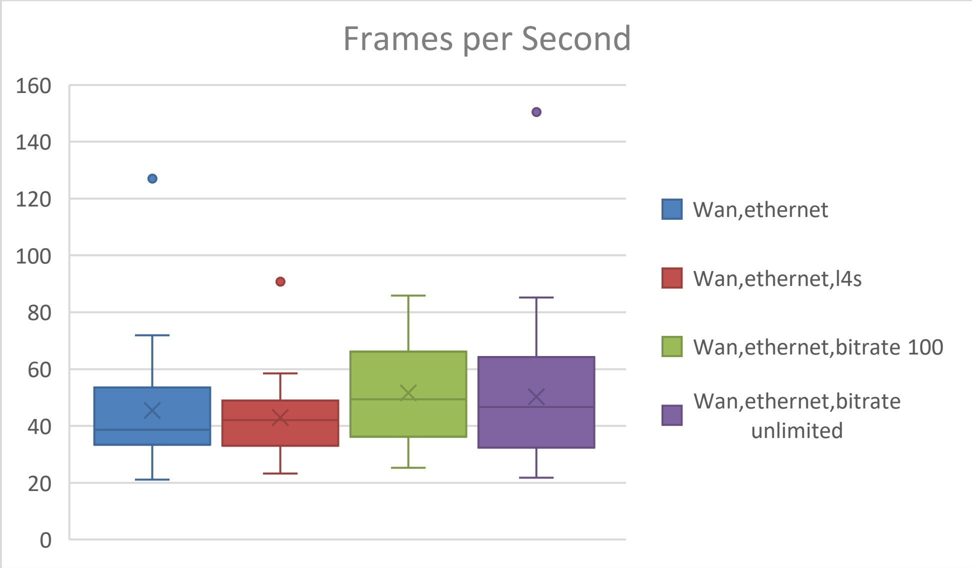

Figure 15 - Frames per Second testing bitrate options from CloudXR -trace-qos-stats

An isolated network performance test was done to review the latency of the network itself in comparison to the latency within the NVIDIA CloudXR framework and network. This is to understand the added latency of server compute times, the impact of SteamVR, and NVIDIA CloudXR network.

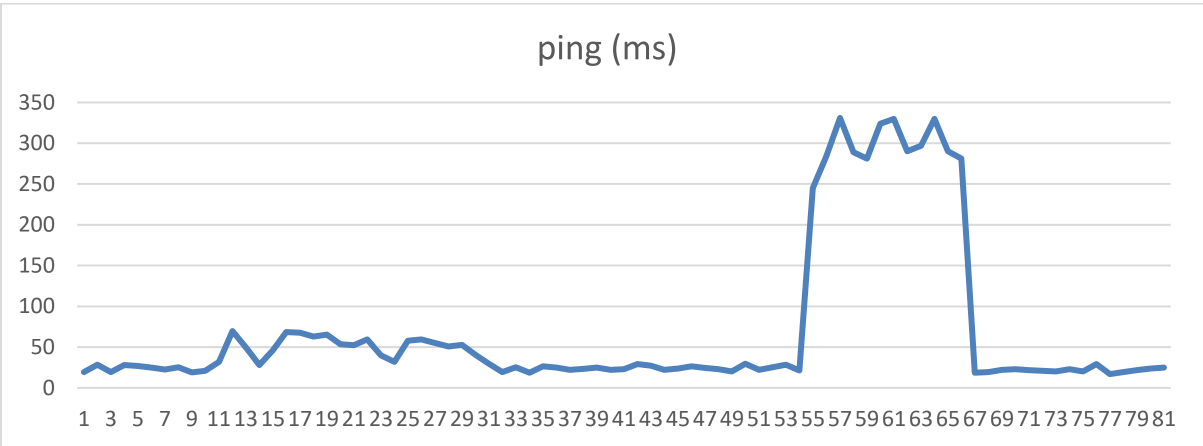

Figure 16 - Ping reaction to high throughput from iperf3, 13 – 29 is under a requested load of 100Mbps, 55 – 67 is under a requested load of 200Mbps with 75% packet loss and an average saturated received bitrate of 125Mbps.

Chapter 5 Discussion

This section evaluates the extent to which the aims and objectives were achieved by examining the network setup, analyzing the test results alongside observations, and cross-referencing with the ITU-T Y.3109 recommendations. It also outlines potential directions for future work.

Aims and objectives

This project aimed to analyse the viability of using 5G with edge servers to offload VR computation. To compare the needed latencies, throughputs, and FPS to the observed.

General observations

Throughout testing, a significant performance improvement was seen from approximately 3000kbps (Figure 8) to 21,000kbps (Figure 12). During observation, the video stream fidelity was high, but it still had noticeable drops during fast-paced gameplay. Jitter remained low, 1000us or 1ms on average (Figure 13). Frames per Second remained adequate at 30 – 60 FPS (Figure 15). This is lower than ideal, where the ideal is around 90FPS.

Latency

The frame delivery times or motion to photon remained around 80 – 97ms (Figure 14). This is inadequately long. Below 50ms is understood to be acceptable for a VR experience (*A Survey on Virtual Reality over Wireless Networks*, no date), and 15- 20ms is recommended to prevent motion sickness during VR gameplay (*Novel Approach to Measure Motion-To-Photon and Mouth-To-Ear Latency in Distributed Virtual Reality Systems*, no date). During gameplay observation, the motion prediction was constantly over-correcting and shaking because of the long latency times.

Latency in the network with no load was around 20ms. This may have been due to the need for two wireless 5G connections, connecting the server to the 5G network through 5G and another 5G connection down to the HMD. The amount of hops the data needs to make may be causing an impact. The server being connected through the 5G network via a 5G CPE is unnecessary in this application and can be reduced by being connected to the network physically, as the servers are static and unchanging.

NVIDIA CloudXR uses 11 specific ports and a 5000 range of video ports on the client side (50,000 – 55,000). NVIDIA CloudXR has continuous bidirectional traffic using both UDP and TCP protocols and will have application-layer logic. These required systems add overhead to both latency and throughput compared to a clean iperf3 test.

Edge server

It may not be useful to apply these findings to using an edge server, as an edge server will be connected to the network physically. An edge server is designed to interact with multiple users at once, send high-throughput compute data over the network, and only have one wireless 5G connection to the client. The NVIDIA CloudXR Documentation states that “There should be only one wireless hop in the path” (*NVIDIA CloudXR SDK — NVIDIA CloudXR SDK documentation*, no date) due to the network accessibility in the university, two wireless 5G hops were required to be used.

Throughput

The network is capable of transferring around 100Mbps before overloading the network (Figure 16). NVIDIA CloudXR at maximum throughput reached 21Mbps (Figure 12). During the same test of WAN, Ethernet, Bitrate 100, the frame delivery time increased slightly on average, with outliers 5ms higher than the others. This may indicate that it is reaching the maximum throughput.

FPS

The system produced approximately 30 – 60FPS (Figure 15) for all tests. This shows that the server itself is capable of producing an adequate FPS, and the network was transmitting the adequate FPS to the client. This, in relation to the high Motion to Photon latency observed, demonstrates that the bottleneck is in the network itself.

Android ARCore Client

The Android ARCore Client was developed and started with an observational test. The latencies observed were around 300 - 500ms. This may be due to the phone's low computation ability rather than the network. After a short amount of time, the phone became noticeably hotter. Potentially, a more powerful Android phone could perform better.

The results from the test seem contradictory due to the Samsung Galaxy S24 Ultra containing a CPU that is more powerful compared to the Meta Quest 3 (Table 1). QoS data collection was unsuccessful due to development time constraints. For these reasons, thin client testing requires further research.

Chapter 6 Conclusion

This project aimed to evaluate the viability of using 5G and edge computing to offload VR HMD processing to an external server. Unfortunately, the edge servers were unable to be utilised, so a Windows 11 pc was used in place of the edge server. A setup was developed using a PC as the server connected to a Meta Quest 3 VR HMD via 5G – a 5G CPE connected to a 5G RAN connected to another 5G CPE connected to the HMD via ethernet with an ethernet to USB C adapter. NVIDIA CloudXR was used as the network software to enable 5G transmission.

Testing the network and observing the findings, the network successfully transmitted VR gaming over 5G to the client HMD, but the setup was unsuccessful at meeting user QoE standards. The latency of the setup was approximately an unsatisfactory 80 – 90ms, where 50ms is understood to be usable, and 15 – 20ms is ideal.

FPS was around 40 – 80 FPS, which demonstrates the server itself was capable of VR rendering and the bottleneck was the network setup itself.

Future Work

The edge server was unable to be used, so a stand-in PC acting as the server was substituted. This setup required two wireless 5G connections where an edge server would be connected directly with high bandwidth and low latency to industry connections. Testing the same setup with a true Edge server would need to be conducted to understand the viability of using this technology with a true high-speed system.

This development is designed with multiple users in mind. Currently, NVIDIA CloudXR only supports one user in a one-to-one relationship. NVIDIA CloudXR can be used with vGPU to run with separate virtual machines to enable multi-user support with one GPU. Using virtual machines to enable multi-user support may add a large amount of overhead to the system; development towards multi-user native support would add a significant improvement to this technology. Using NVIDIA CloudXR or another networking software.

The ITU-U Y.3109 is made for locally processed VR and does not mention latency. This means that QoE tests and results within the ITU-U Y.3109 standards may not be accurate for VR gaming, where latency is the biggest factor. Human testing for latency, jitter, movement prediction, and over over-correction is essential to understanding what is required for a positive user experience.

This research did not engage with NVIDIA CloudXR ARkit for IOS due to constraints of access to a MAC for compiling Xcode. IOS is understood to have improved spatial computing and sensors compared to Android.

The findings from the thin client Android device seemed contradictory, as it has a more powerful processing unit than the Meta Quest 3 and requires further research into obtaining a successful thin client setup.

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