The Effects of Latency, Bandwidth, and Packet Loss on Cloud-Based Gaming Services

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Abstract

Network bandwidth increases make the concept of cloud-based gaming services a promising alternative to traditional gaming platforms. Cloud-based gaming services do this by processing and rendering the game in a cloud server, receiving control input from the client and streaming the rendered game back to the client akin to video streaming. Network latency presents a challenge cloud-based gaming services must overcome to provide a comparable experience to traditional gaming. Measuring the effects of latency on key factors, such as quality of experience and player performance, can help understand the capabilities of the current generation of cloud-based gaming services. We conduct a cloud-based gaming service user study, surveying user's subjective quality of experience and measuring their in-game performance and conduct experiments that measure cloud-based gaming services' network characteristics. Analysis of results shows a significant decrease in both quality of experience and player performance as latency increases, but latency has little effect on the frame rate or average throughput of cloud-based gaming services.

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1. Introduction

Traditionally, games could be played on a gaming console or a powerful gaming personal computer (PC). On a gaming console, the user can either buy games as a hard copy (disk) or, more commonly now, download games straight to their consoles in a digital form. On a gaming PC, however, games are only downloaded digitally. When running games, the console or PC does all of the processing and then displays the game frames on the screen. When playing a multiplayer game, the hardware has a connection to game servers and relays game information between each player's computer to create the multiplayer environment. Regardless, this requires the initial purchase of several hundred dollars of equipment and games in order to play, and online services have additional yearly or monthly fees as well.

Modern cloud gaming services fundamentally reinvent the delivery of video games to consumers. These services provide large libraries of games that can be played without having to download the game. Some services provide free licenses to games while other services may require users to own the license to the game from other parties, such as Steam or Blizzard. Many companies, such as Sony, Nvidia, and Valve, have created cloud gaming services. Sony owns PlayStation Now which offers a gaming library of over six-hundred games, including many PlayStation exclusives [1]. Similarly, the graphics card manufacturer, Nvidia, is developing GeForce Now which is another cloud gaming service that is currently in the beta stage [2]. Even Valve, the owner of the gaming platform Steam, has created Steam Link for streaming games from a desktop computer to a couch gaming setup [3]. Other services, such as Vortex, allow for the streaming of games similar to PlayStation Now, but with PC games [4].

There are two main types of cloud (over the network) gaming: desktop-to-couch and server-to-client [23][24]. Desktop-to-couch services include Steam Link, Nvidia Shield, and various open sources alternatives. These services work by utilizing the player's gaming PC and a dedicated piece of hardware located in the place where the games are to be played. The dedicated hardware receives the input from the controller, sends it to the gaming computer which then returns the video stream of the games. Thus, the dedicated hardware is thin, since it does not handle any of the processing of the game. Such desktop-to-couch services only require a one-time hardware investment.

Server-to-client services include PlayStation Now, GeForce Now, and Vortex [1][2][4]. These services utilize a thin client to input the controls and sends them to a server where the processing is handled. These servers then return the video which is streamed from the thin client. server-to-client services only need a small investment for a device to run as the thin client and a recurring expense for the cost of streaming games.

The methods of delivering games to consumers offered by cloud gaming hold many advantages compared to traditional gaming solutions. The initial cost of the hardware is much lower, since the processing required of the hardware is minimal. Since the hardware only needs to run a thin client, it does not need to be upgraded as games improve in technology. Depending on what service the user chooses, users may only need to pay a low monthly fee to have access to hundreds of popular games; in a traditional setup, games would have to be purchased individually. There is also no need to download or have physical copies of games which makes accessing these games easier for the user. Games can be streamed to different devices, such as laptops, desktops, cell phones or tablets, depending on how the user wants to experience the selected game.

Cloud gaming introduces new problems not found with traditional gaming systems. Cloud gaming services rely on a low latency network connection and high bitrates to provide a smooth video stream [22]. Most cloud gaming services have minimum bandwidth requirements as well. The required bandwidth may not be available in all locations. If these requirements are not met, the quality of the service can be significantly reduced. Purchasing an Internet connection with the required bandwidth can also be expensive.

Another challenge that cloud gaming services need to overcome is network latency. When using cloud systems, there will always be latency because of the round trip time from the user's input to the servers and the rendered frames from the servers back to the client. Latency is more of an issue when the client is farther from the data centers. Latency, in any real-time game, negatively impacts the players quality of experience (QoE) and performance in the game [11].

Previous work examining the effects of bandwidth and latency focus on non-commercial systems and explore the problem in an academic environment. These previous studies use older services, such as OnLive and GamingAnywhere, and examine the effects of latency on players' experiences and their performance [5][6][7][8]. These studies found that the players' QoE and performance declined as the latency increased. Some of these previous works also study the effects of bandwidth on the system's performance as well. They found that with less bandwidth, On-Live's streaming quality of graphics decreased as well as player performance. The games used in these studies (Crazy Taxi and Neverball) are older games and are not available on modern cloud gaming systems. The cloud gaming systems, OnLive and GamingAnywhere, are no longer in operation as well.

The goal of this project is to explore user experiences when using commercial cloud gaming systems rather than traditional gaming systems. We study modern commercial cloud-based game systems, concentrating on network characteristics and playability under latency. Hence, the subjective user experience and gaming performance in two commercial cloud gaming services are compared in a modern gaming environment. To do this, controlled experiments are carried out in which overall game performance, frame rate and connectivity are measured on different modern cloud gaming services. Data is also collected from the user describing their overall gaming experience and performance with different levels of controlled input latency into the game. This input latency is measured by the traffic over the Internet that the games are being streamed on.

During this project we studied studied 26 participants, each of whom played the same level on PayDay2, with different levels of injected latencies by using a software called Clumsy [16]. We tested two different cloud gaming services, PlayStation Now and Vortex. Fourteen participants played on PlayStation Now and twelve played on Vortex. We examined the participants QoE and performance when playing on four different latencies (50ms, 150ms, 250ms and 350ms).

Summarizing our results, the player's QoE and performance both decreased as the latency increased in both cloud gaming services. The player's average performance was greater at lower latencies and it experienced a sharp decrease between 150ms and 350ms of latency. At these latencies, the players' performance was almost 50% worse than at 50ms. Similarly, the player's QoE decreased fairly linearly as the latency values increased.

When observing the services' performances individually, PlayStation Now's performance decreased significantly when higher packet loss and lower bandwidth restrictions were implemented. PlayStation Now's frames per second and throughput dropped almost 50% at higher packet loss and lower bandwidth restrictions. On the other hand, Vortex's performance stayed consistent across all network implementations.

The rest of this report is organized as follows: Chapter 2 examines the previous works in this area of study. Chapter 3 goes into depth of the methodology of our study. In Chapter 4 we analyze the data acquired during our experiments.Chapter 5 summarizes our findings and finally, Chapter 6 suggests ideas for future work about this topic.

2. Related Work

Prior research on cloud gaming services have provided a general understanding of the mechanics of cloud gaming and expectations of our own experiments. The majority of research done examines the most popular services at the time, such as GamingAnywhere and OnLive [5][6]. Previous research also focuses on different aspects of the systems performance including frames per second, latency and bandwidth. Research has also been conducted on the players quality of experience and their gaming performance. These previous reports provide overall context in which our study is being conducted and a good base for comparison of our results.

2.1 Delays in Cloud Gaming

As described briefly in the previous chapter, the user needs a “thin” client to connect and communicate with a cloud gaming service. Figure 1 depicts components of delay in cloud gaming. This client will collect the player’s actions and transmit them to the cloud server. The server will then process the action, render the results, encode and compress the resulting changes to the game world and stream the video back to the player [8]. This “interaction delay” must be kept as short as possible to provide the best experience to the player.

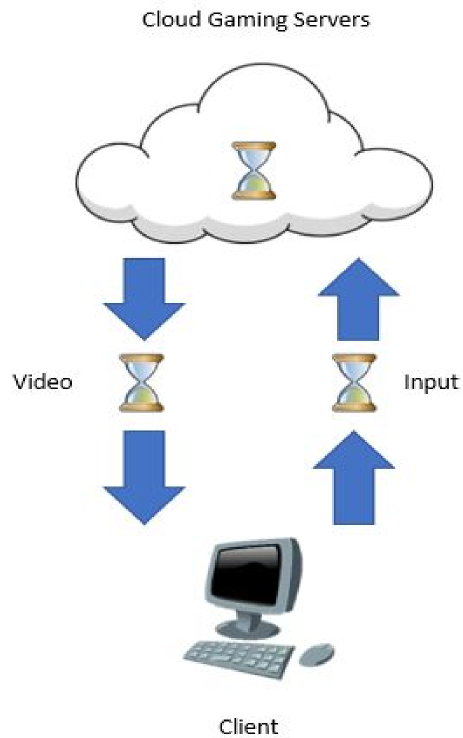

Figure 1. Diagram of how a cloud gaming system works. The client (Desktop Computer in this case) sends input to the cloud server. During this sending there is a delay for the data to reach the cloud server (represented by the hourglass). In the cloud, there is delay when the server is processing the given input and compressing video files. Finally, there is delay when the server is sending the video data back to the client.

2.2 Latency and Quality of Experience, Player Performance and Frames per second

Previous research has been conducted on network latency and how it affects overall performance in cloud gaming services. These reports tend to focus on singular data results such as frames per second (fps), quality of experience (QoE) or user performance. These experiments observe the changes in data versus network latency in the cloud gaming services, a similar approach to our project.

2.2.1 Frames per second

The number of frames displayed per second (or fps) impacts the user's QoE and performance. With a lower fps, the game will not have a smooth gameplay, becoming choppy and stuttering as the frame rate decreases [9]. However, Zadtootaghaj, Schmidt and Moller have shown that the ranges of playable fps rates in cloud gaming is large with good bandwidth. The report explains that with a higher bandwidth (10 Mbps), the playable fps ranges from 25 up to 60 fps. However, when bandwidth drops below 5 Mbps, the range of playable fps drops significantly [12]. When conducting our study on the cloud services, fps is measured with respect to latency and bandwidth constraints.

Grant and Solano evaluated the effects of bandwidth and latency on the fps on a cloud gaming service, OnLive [6]. During this study, they observed the variations in frame rate across different network conditions such as bandwidths, latencies and packet loss. When evaluating their results, they concluded that bandwidth has a great effect on the fps of the OnLive stream. When using an unrestricted bandwidth, the fps averaged around a high of 50 fps. However, when the bandwidth was tested using 10 Mbps and 5 Mbps connections, the fps dropped to an average of around 30 fps and 25 fps respectively. Figure 2 shows some of their results.

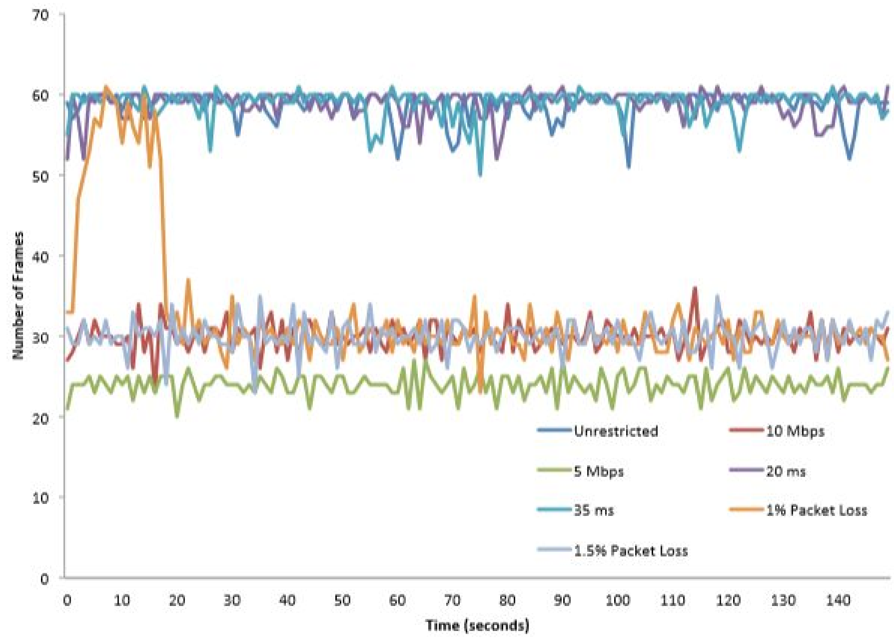

Figure 2. OnLive fps captures with varying latencies, packet loss and bandwidth [6]. The y-axis represents the fps values of the game, while the x-axis represents the current in game time of the capture. The different lines show different outcomes of fps values depending on latency, packet loss and bandwidth. It is noticeable that when bandwidth decreases, the fps value also decreases. However, latency does not seem to have a large effect on the fps value.

2.2.2 QoE and Player Performance

The Quality of Experience (QoE) and performance of the player is a focus in our project. The quality of experience can be inferred by various measures of the game's behavior, including the network's performance when using a cloud service. A large portion of prior research on cloud gaming services has measured the QoE of players through testing.

Chen, Huang and Lei focused on the player's overall playing time with respect to latency [10]. They discovered that the more significant the network impairment players experienced, the sooner they were likely to leave the game session. Gamers who experienced 150ms latency played for an average of four hours, but those experiencing 250ms latency played for only an average of one hour. Since the game being tested was a MMORPG (Shen Zhou Online), latency did not have a significant effect at values below 150ms. This allows for a playable game at higher latencies. Although we did not observe overall playing time when testing the cloud systems, when using test subjects, we did not have any participants quit during the trial because the latency caused the game to be unplayable.

Dabrowski, Manuel and Smieja observed the effects of latency on the players QoE and the player's performance when playing the game Crazy Taxi [5]. They observed the test subject's QoE and player performance with different levels of latency injected into the network. After compiling data, they concluded that an average latency of +/- 50ms is needed for a significant effect on the participants performance when playing the selected game. However, they also observed the player's QoE and performance when playing on the same latency multiple times. They collected data showing that over 50% of the participants had an improved score across all the repeated latency trials. When conducting our user study, it will be important to ensure that the players only experience the specific latency once to ensure accurate player performance results. If the players experience the same latency more than once when testing the same game level, their player performance could increase causing a skew in data.

Claypool and Finkel found that performance decayed exponentially with increasing latency and the subjective user rating for QoE reduced linearly with increases in latency [7]. It does this by drawing conclusions from the data of two similar studies. The first study explores about fifty players' performance in the game Crazy Taxi, using the commercial cloud-based service OnLive. Data points were created using latency versus performance, where latency was artificially increased. The results found that performance decayed exponentially with increasing latency. Similar results were found in the second study, which measured the performance of ~40 players in the game Neverball, as affected by increasing latency. The second study used the academic cloud-based service GamingAnywhere.

Shea, Liu, Ngai and Cui focused on the QoE of the players with respect to latency when playing a fast paced, first person shooter game (Borderlands) [8]. First person shooters rely on accuracy and a good network connection to compete with opponents, thus latency needs to be kept at a minimum to avoid misfired shots and unintended game movements. This specific study focused on the effects of latency and packet loss of OnLive servers. They concluded that the quality of experience is significantly affected by dropped packets regardless of the round-trip time. They observed that a lossless connections with round-trip times less than 120ms is desirable for fast-paced first-person shooters.

Finally, Lee, Chen, Su and Lei included the documentation of the user's QoE with increasing latency by examining the player's facial expressions [11]. When testing three different genres with added latency using the gaming service OnLive, data was collected from the user's facial expressions using electromyography to determine the player's quality of experience. After experimenting with different latencies and genres, they concluded that on average the player's negative emotion was aroused approximately in proportional to the magnitude of latency. Also, when examining the QoE differences across genres, they observed that generally FPS games have the highest real-time strictness (RS), followed by role-playing games (RPG), while action games (ACT) have the lowest RS. Figure 3 shows a graph that was extracted from the report showing the QoE results across three different genres of games with respect to increasing latency. Although our study does not go as in depth when calculating the user's QoE, it provides a general understanding of the possible outcome of the quality of experience when playing different genres under varying network latencies.

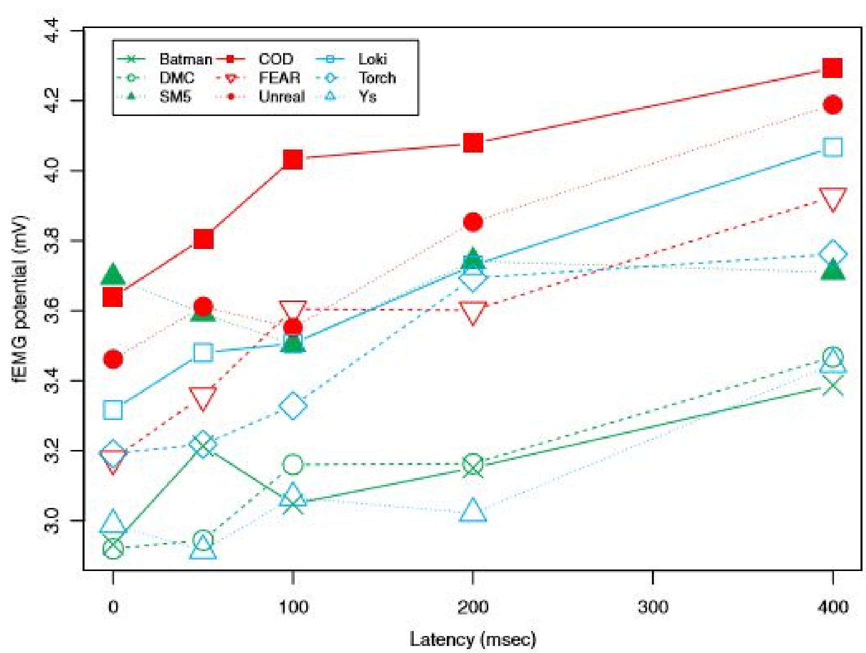

Figure 3. Users QoE observed over a range of games using electromyography [11]. The y-axis represents the fEMG potential which is the player's QoE (the lower the fEMG the better QoE). The x-axis represents the increasing values of latency in the network. There is a trend that when the latency value increases, the fEMG values also increase (QoE decreases).

2.3 Summary

The multiple experiments conducted on OnLive's services allow for an ideal comparison with our overall project. In these previous experiments, researchers examine the player's QoE and performance with increasing latencies. In all of these experiments it was noted that the player's QoE and performance both decrease as the latency increases. Since our project theme is based on the same concept of studying the player's QoE and game performance with respect to latency, it allows us to make some assumptions about the possible outcomes of our project.

These previous reports have shown that the effects of latency on players' QoE varies with game genre being tested. A high latency can create an unplayable environment in certain genres such as FPSes, but in other genres like ACT it will only degrade the player's experience slightly. When observing game performance through the cloud gaming service, independant variables that need to be considered include bandwidth, latency and packet loss.

3. Methodology

In order to observe the underlying effects of latency, bandwidth, and packet loss on different aspects of game performance and user experience with cloud gaming services, we developed an evaluation methodology to collect the necessary data from each gaming service. This chapter explains the process of choosing the two different cloud gaming services and the game chosen to be tested. It also goes into depth with regards to the hardware used to conduct these experiments, the software needed to measure data in the gaming environment, and key parameters in cloud gaming services. Finally, this chapter discusses the process designed for the user study.

3.1 Cloud Services

As there is an upwards of ten cloud gaming services on the market today, we chose two cloud gaming services to evaluate. The selection criteria included the variety in available games, popularity, price, and hardware requirements. Our choices were PlayStation Now and Vortex [1][4]. These two services provided similar games and hardware requirements, which is helpful for doing a direct comparison. As far as we know, there are few to no other studies on these two systems.

3.1.1 PlayStation Now

The first gaming service we selected for research was PlayStation Now [1]. PS Now is one of the most popular and well-known cloud gaming services out on the market today, yet it is still a relatively unstudied cloud gaming service [13]. PlayStation Now includes over 600 accessible games, primarily PlayStation exclusives. The primary servers for PlayStation services are in Europe, but they do provide multiple servers inside the U.S. as well. However, the number and specific data center locations are not open to the public.

3.1.2 Vortex

The second cloud gaming service we selected for research was Vortex [4]. Vortex provides a small library of free games, but more games can be played if the user has the licensed copy on STEAM. Vortex has slightly over 100 games available to play on their servers. Previous research on Vortex is minimal because of its lack of notoriety.

3.2 Game Chosen

When selecting the game to test, we wanted both platforms to run the same game. Finding multiple games that were common across both services was a challenge because PlayStation Now has primarily PlayStation exclusive games, and Vortex has a smaller library of games to choose from. We also wanted users to be able to learn how to play the game quickly.

Lastly, the game needed objective performance, such as an overall score of a level, that allowed us to observe the user's performance.

The type of game genre we chose to evaluate was the First Person Shooter. First Person Shooters rely heavily on shooting accuracy and quick reaction times for good performance in-game. Previous research has reported that a lossless connection with round-trip times of less than 120ms is desirable for First Person Shooters [14]. We chose PayDay2 (505 Games, 2013) as our first-person shooter, primarily because it was present in both the cloud gaming service libraries. PayDay2 offers a wide range of missions, including robbing banks, kidnappings and other heists [15]. The player's score is based on how fast the mission is completed and if the mission is completed in full. Figure 4a and Figure 4b show two examples of gameplay from PayDay2 captured while running our tests. The first screenshot displays one of the objectives in action, which is to open a secured room. The second screenshot shows regular game mechanics of the player reloading a weapon.

Figure 4a. PayDay2 player is drilling a locked door to get inside.

Figure 4b: PayDay2 player is reloading the weapon during a mission.

3.3 Software Used

Four applications were used to measure and control network performance for each of the cloud gaming services. First, we used Clumsy (Version 0.2) to artificially add network latency and other network defects during gameplay [16]. Clumsy is a simple application that filters packets being sent or received by the user's network. These packets can then be subjected to: loss, throttle, latency, duplication, out of order, and tampered data. Second, we used Fraps (Version 3.5.99) to record the frames per second of the game being displayed in a text file, allowing for observation of average and minimum frames per second [17]. Third, we used a network sniffer called Wireshark (Version 2.6.4) to observe and extract data from the network when testing each cloud gaming service [18]. With Wireshark, the user can capture and evaluate network data and protocols in the current session. Wireshark is used to examine bandwidth variance with added latency on each service, the protocol type of the messages being sent, the IP address of the servers in use and network errors. Finally, we used NetLimiter 4 (Version 4.0.13) to restrict network bandwidth [19].

3.4 Hardware Used

Since each cloud gaming service has its own hardware requirements, we needed hardware that satisfies the minimum hardware requirements for each service. A chart of the recommended hardware is shown in Figure 5, as well as the recommended bandwidth needed to run the games. Vortex has the highest bandwidth requirement (10 Mbps). However, PlayStation Now has the highest processor requirement (Intel Core i3 3.5 GHz), storage requirement (300MB) and RAM requirement (2GB). The recommended hardware does not include a specific graphics card recommendation.

Recommended Hardware/Network Requirements		
	PlayStation Now	**Vortex**
Processor	Intel Core i3 3.5 GHz	*Not Specified*
Storage	300 MB	*Not Specified*
RAM	2 GB	*Not Specified*
Bandwidth	5 Mbps	10 Mbps
FPS	60	60
Resolution	720p	720p

Figure 5. Recommended hardware requirements for each gaming service.

The hardware used in the testing had the following specifications:

- Intel(R) Core(™) i7-4790K CPU @ 4.00GHz, 4 Cores, 8 Logical Processors
- 16GB RAM
- Monitor: 1920x1080p, 60Hz
- 1.8TB Storage

Also, since a higher bandwidth connection may provide better game performance and streaming, when conducting the tests on each service, a wired Ethernet connection is used on the WPI network.

3.5 Parameters of Study

The network variables we controlled included: latency, bandwidth and packet loss. We examined the different effects they have on the frames per second, quality of experience (QoE), and player performance for each cloud gaming system described earlier in this chapter.

3.5.1 Latency

The first parameter of study is latency. Round-trip is the time between sending data to the server and receiving a response back from the server. Although we add latency into the network when testing each service, this is an addition of base level latency between the client and the server. To find the base latency, we used the utility ping to get the time it takes for a packet to be sent and received from the client to the given IP address. The effects that latency has on these systems was our primary focus throughout these tests.

3.5.2 Bandwidth

The next parameter being studied is bandwidth. Since cloud gaming performance relies heavily on bandwidth, we observed how bandwidth restrictions affect the overall performance of the cloud service. Bandwidth is the amount of data sent and received over a network during a specified period. Wireshark is used to capture and examine the total bits/second over the entire gameplay. This bandwidth data can then be compared across each platform.

3.5.3 Packet Loss

The final parameter being studied is packet loss. Packet loss is when data fails to reach its destination point, mainly caused by errors in the network or a packet being dropped due to congestion. These errors cause the packet to be lost in transmission and need to be resent from the original sender.

3.5.4 Frames per second

The first game performance data that is measured is frames per second (fps). Fps is the rate at which the display images of the game are being refreshed. A fps of around 60 is typical for a gaming display and provides a smooth gaming performance. However, as fps drops, the visual display becomes choppy. We used Fraps to measure and document the frames per second throughout each gaming session.

3.5.5 QoE and User Performance

Besides the fps performance data, we also recorded the user's quality of experience (QoE) and the user's game performance. The users QoE is determined by user enjoyment and the overall experience of the game. This data was extracted by asking the player questions after each gaming session. The user's game performance was determined by their final score. These variables will be explained in more detail in sections 3.7.1, 3.7.2, and 3.7.3.

3.6 Experimental Studies

We conducted experimental studies to assess the network behavior of the cloud gaming systems. We used the same hardware and network connection as we did with the user study and tested the game under different latencies, bandwidths, and packet losses.

3.6.1 Process

The testing environment was on the WPI campus in a reserved computer lab, kept the same across test sessions. The values of the network modifications stay the same in each category (latency, bandwidth, and packet loss). However, to ensure that tested services have an equal starting latency, we determined the initial latency values to each cloud service, using 'ping' to measure the latency from our host computer to each cloud gaming service. Vortex had an initial ping value of 20ms and PlayStation Now had a ping value of around 45ms. We provided uniform base ping values of 50ms by adding 30ms latency to Vortex and 5ms latency to PlayStation Now.

We began to conduct experiments with the three different network parameters. For each test, we first opened the PayDay2 game on each cloud gaming service. We then selected the Offline portion of the game, which disables multiplayer functionality. Next, we selected the "Jewelry Store" mission on normal difficulty. After the main mission was selected, we enabled Clumsy for latency and packet loss, and NetLimiter 4 for bandwidth restriction and input the desired network values associated with the current test case. Next, we opened Wireshark and Fraps to record the network traffic and the fps of the game. Finally, we played the chosen level for a five minute session and recorded our data. After the session was over, we saved the Wireshark and fps CSV files to a common file drive for future analysis. At the end of each gaming session, we filled out a QoE survey that details our experiences during each gaming session. This survey will be explained in more detail later in section 3.6.3.

3.6.2 Data Examined

We examined the game performance of each cloud gaming system under three different types of network parameters; latency, bandwidth and packet loss. When testing latency, we used four different values; 50ms, 100ms, 150ms and 200ms of latency. For bandwidth, we used values at 10 MB/s, 5 MB/s and 2.5 MB/s. For packet loss we used 1%, 5% and 10%.

3.6.3 Questions Asked

At the end of each test, we filled out a survey about our experience with the game and its performance. These questions mainly focused on the visual quality of the game and the responsiveness of the controls. This documented our thoughts on the gaming experience. The questions that were asked in this survey can be found in Appendix A.

3.7 User Study

We focused exclusively on the effects of latency on each cloud gaming service and how it affected the user's performance and experience. We used the same gaming environment and equipment in the experimental studies. Our goal was to have a user study with 30 test subjects from the WPI community.

3.7.1 Process

Students arrive at the testing area and they read and sign a consent form that allows them to participate in our user study. After the consent form is signed, we have them fill out a short Qualtrics survey to learn more about their gaming experience. We then introduce them to the gaming setup. We then open up the cloud gaming service application and start PayDay2, using the same mission selection process in the experimental studies. We give them five minutes to get familiar with the game controls and mechanics. After the test mission, we open up Clumsy and set the latency value to one of the previously specified testing values. The user is not allowed to look at the screen when we are changing the latency values. After the latency values are set, we instruct the user to play the mission for 2 minutes and tell them to accumulate as much currency as possible within that period. After the time has elapsed, we stop the mission and record the amount of currency they accumulated, which is used to determine their game performance. We then give the user a survey about their gaming experience. After the survey is completed, the latency value is changed and the user repeats the process two more times. After the final test, the user is offered to participate in a raffle to earn a $25 gift card.

3.7.2 Data Examined

After each PayDay2 session, the user's overall gaming experience is recorded.The user study primarily focuses on how latency affects the user's gaming experience and game performance. We use latency values of 50ms, 150ms, 250ms, and 350ms to examine the user's experience on each cloud gaming service. The QoE data is extracted from the surveys that the users answer after each test for the specific cloud gaming system.

3.7.3 Questions Asked

After each test session, the user fills out a survey to help us quantify their experience of the gaming service under that specific latency condition. These questions focus on the user's opinions of the responsiveness of the controls, how the latency affected their performance, and their overall enjoyment of the gaming session. Questions are on a scale from one to five, 1 being the worst and 5 being the best. These questions are in Appendix A.

4. Analysis

This chapter analyzes the data collected during our experimental study and the user study. Section 4.1 details the analysis of the performance of PlayStation Now and Vortex individually. Section 4.3 analyzes the user study in three different categories: overall results, PlayStation Now results and Vortex results.

4.1 Experiment Results

We analyzed how each service responded to changes in network latency, packet loss, and bandwidth restrictions. For each network modification, we observed the effects on the services' frames per second (fps) and throughput. We used three different latencies to test the cloud services: 50ms, 100ms, 150ms and 200ms. When observing the effects of packet loss, we used values of 1%, 5% and 10%. Finally, we used values of 2.5 Mbps, 5 Mbps and 10 Mbps when restricting bandwidth. The resulting fps and throughput values of each test are displayed in Figures 6 through 10.

4.1.1 Vortex Results

With regards to Vortex, bandwidth restriction had no statistically significant effect on frame rate as seen in Figure 6. Additionally, latency had no statistically significant effect on frame rate or throughput, as seen in Figures 7 and 8 respectively. The same can be said for packet loss, which also had no statistically significant effect on either frame rate or throughput, even at percentages of loss as high as 10%, as seen in Figure 9 and 10 respectively. On the x-axis of each graph is the network restriction present in each test. These can be either packet loss, bandwidth restrictions or latency. On the y-axis of each graph is the performance variable we are observing. This will be either frames per second or throughput. Overall, Vortex has unvarying frame rate and throughput despite varied network conditions.

4.1.2 PlayStation Now Results

Unlike Vortex, PlayStation Now’s frame rates degraded significantly with bandwidth restrictions, as seen in Figure 6. Having the bandwidth restricted to 5 Mbps dropped the average frame rate down to 35 frames per second from its usual 60 frames per second. However, ping appeared to have no statistically significant effect on the average frames per second, as seen in Figure 7. The throughput stayed stable under both high and low latency conditions, as seen in Figure 8. Once again, as with bandwidth restriction, PlayStation Now suffered when it came to packet loss. Values exceeding 5% saw a slight drop in average frame rate, as seen in Figure 9. The throughput also degrades as well with loss, as seen in Figure 10, with values over 2% causing the throughput to decrease to half from 10 Mbps down under 5 Mbps, and a value of 10% causing the throughput to drop below 2.5 Mbps. Ultimately, PlayStation Now’s throughput and fps are affected by bandwidth restrictions and packet loss, but not latency.

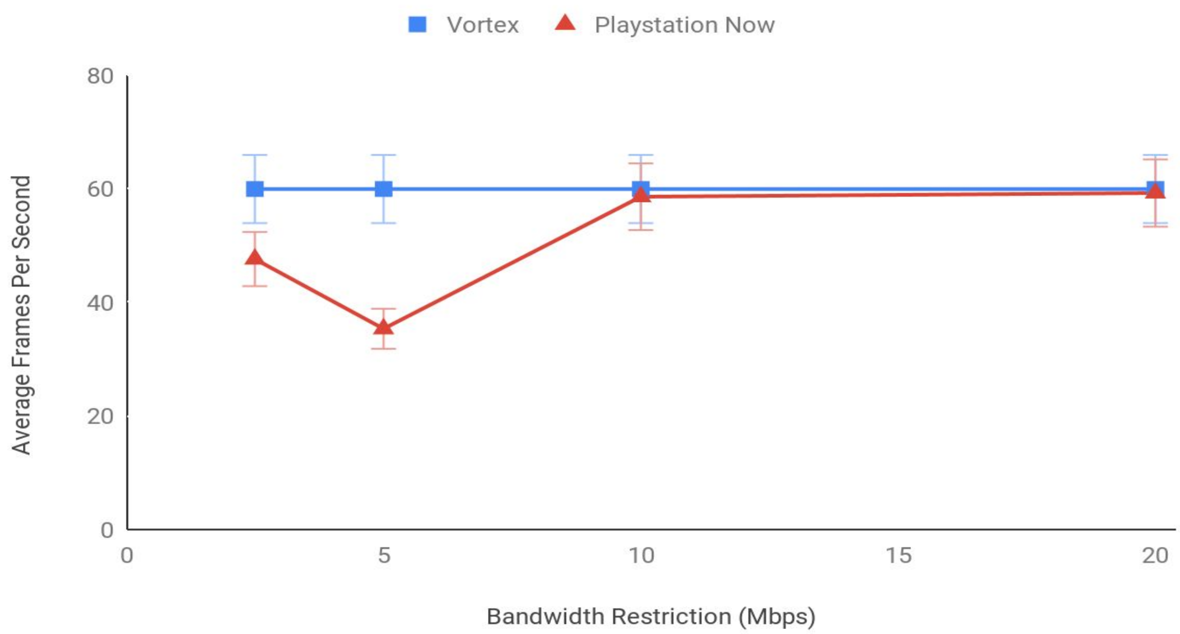

Figure 6: Average Frames Per Second vs. Bandwidth Restriction
Vortex has a stable fps of 60 for bandwidth restrictions while PlayStation Now's fps drops below 60 when subject to below 10 Mbps bandwidth restrictions

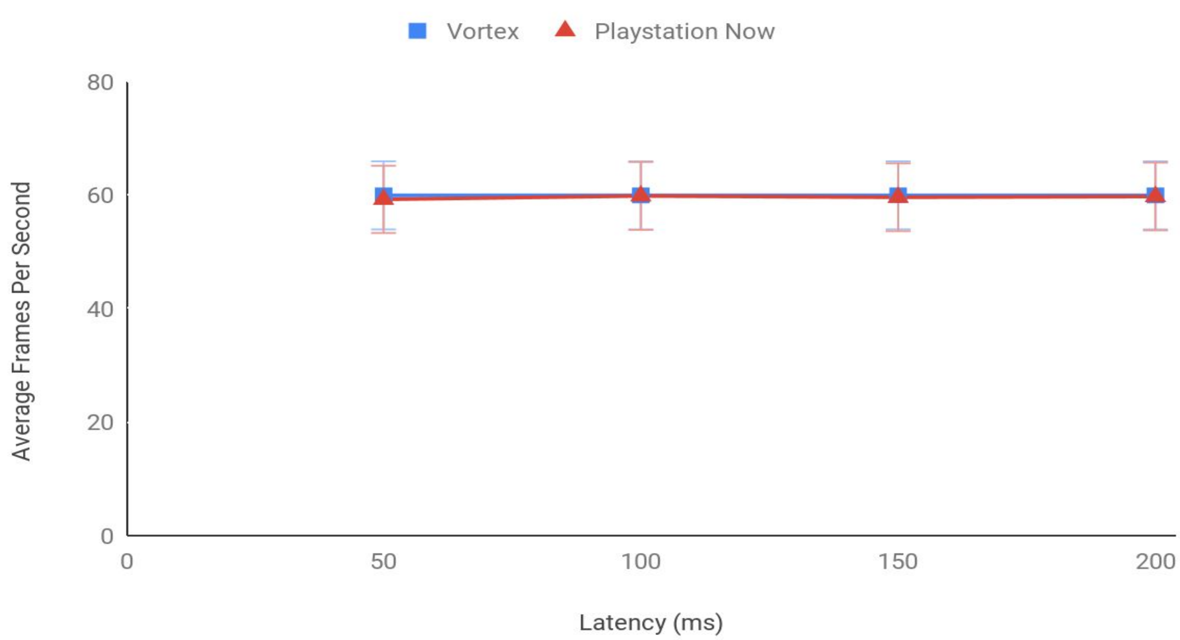

Figure 7: Average Frames Per Second vs. Latency
Vortex and PlayStation Now have similar performance with regards to fps as latency increases

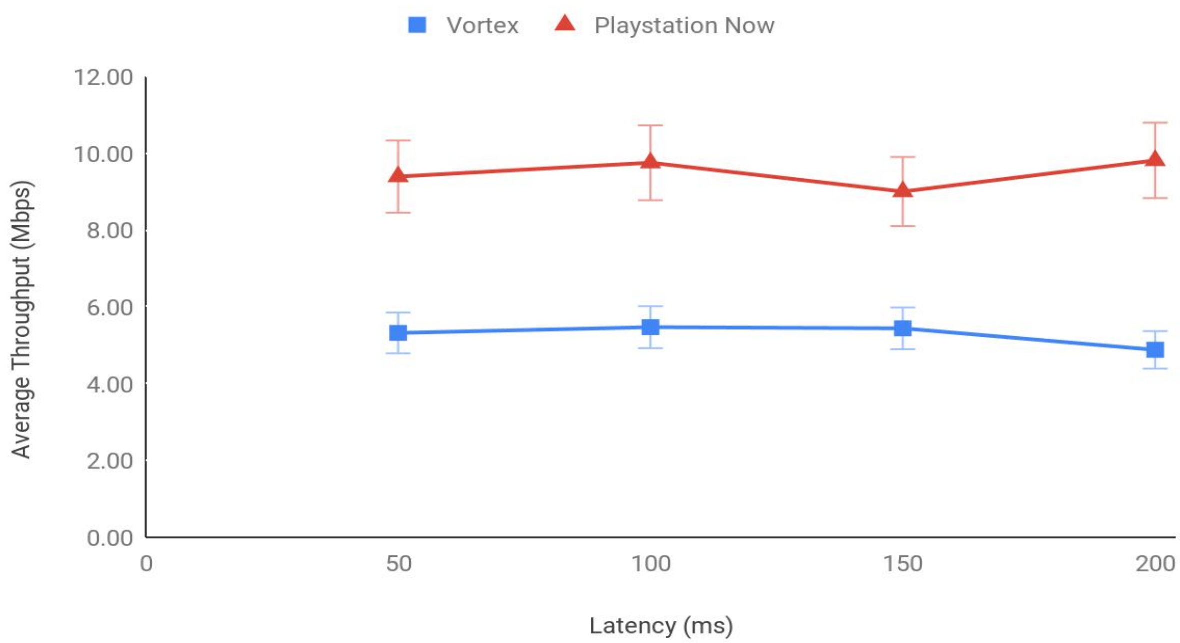

Figure 8: Average Throughput vs. Latency
PlayStation Now holds a significantly higher throughput than Vortex across all latency values

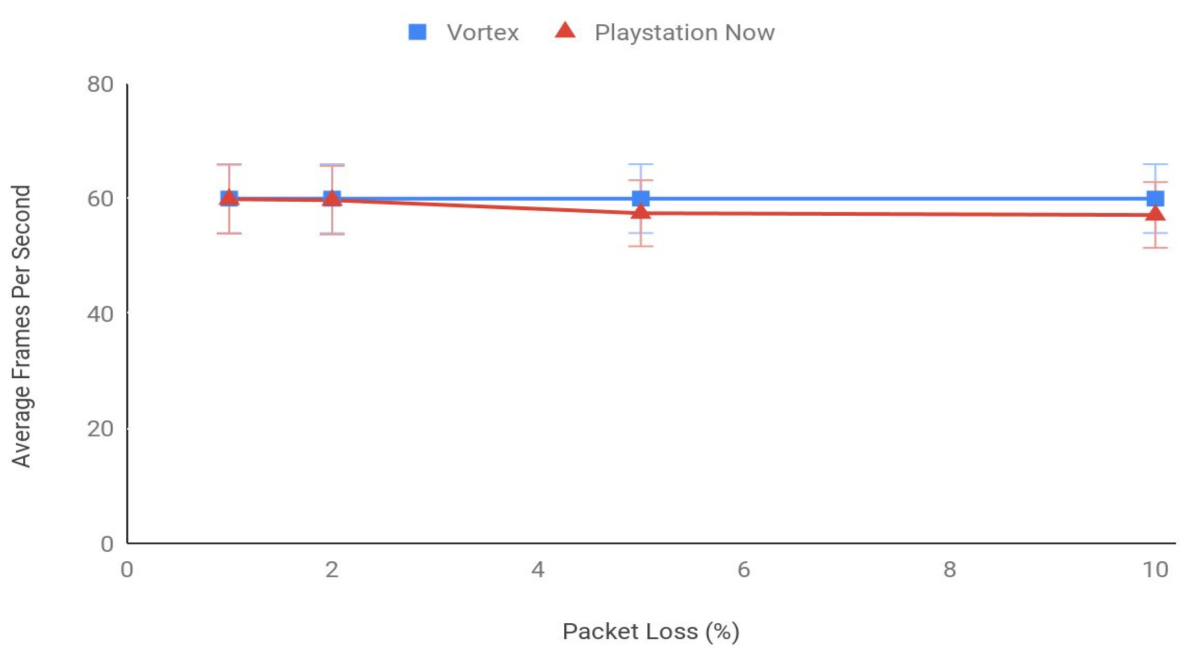

Figure 9: Average Frames Per Second vs. Packet Loss
Vortex maintains a steady fps when subject to increasing packet loss values, while PlayStation Now's fps decreases slightly as packet loss increases

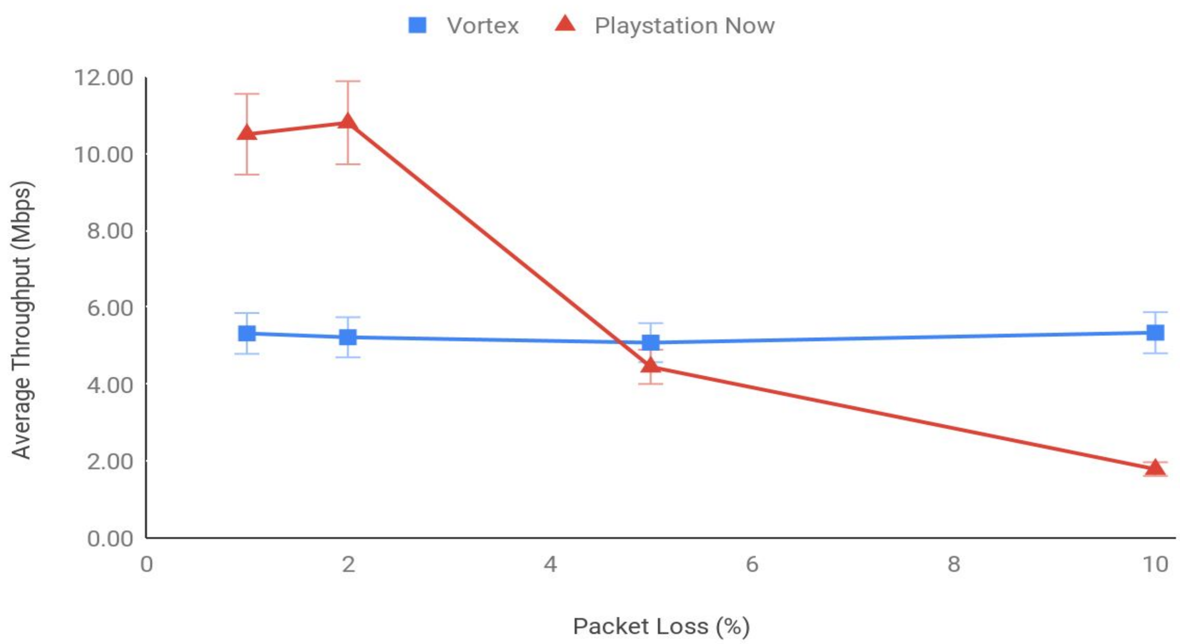

Figure 10: Average Throughput vs. Packet Loss
Vortex maintains a steady throughput as packet loss increases, while PlayStation Now's throughput decreases significantly as packet loss increases

4.2 User Study Results

In this section, we provide the user study data collected from our 26 user subjects. The data is separated into three sections: overall results, PlayStation Now results, and Vortex results. Within each of these sections, we observe the users' quality of experience, performance and how much latency affected their performances. We conducted paired t-tests for all of these observations for both PlayStation Now and Vortex individually. We did not conduct a t-test on the overall results because the results from the individual t-tests provided us with conclusive data. The results of each section are also quantified in graph form for each metric being observed.

4.2.1 Demographics

We gathered subjective data from the twenty-six Worcester Polytechnic Institute (WPI) students that participated in our user study. WPI undergraduates have a gender distribution of 66% male and 34% female [21]. The ethnicity diversity of undergraduates is primarily white (61%) followed by smaller percentages of Hispanic/Latino, Asian and African American, together consisting of 15.6% of the population. Of these twenty-six participants, fourteen used PlayStation Now and twelve used Vortex. We analyzed the data with charted paired t-tests[20].

4.2.2 Overall Results

The testing yielded data which conformed to our expectations developed during the experimental testing and review of related works. Each graph displays the average of all of the responses at 50ms, 150ms, 250ms, and 350ms latency. Figure 11 shows the average of the users' overall enjoyment when playing across the four latencies, with the y-axis being users' rated experience. Figure 12 shows how much the latency affected the users' game performance, with the y-axis being how much the latency affected the users' performance. Finally, Figure 13 shows users' performance when playing on each of the four latencies, with the y-axis being the users' performance. In each of these graphs, the x-axis represents the amount of latency added into the network. The points in each graph represents the average rating or performance of both services, while the bars represent the standard error. The statistical significance of these results and the paired t-test are discussed in the next sections.

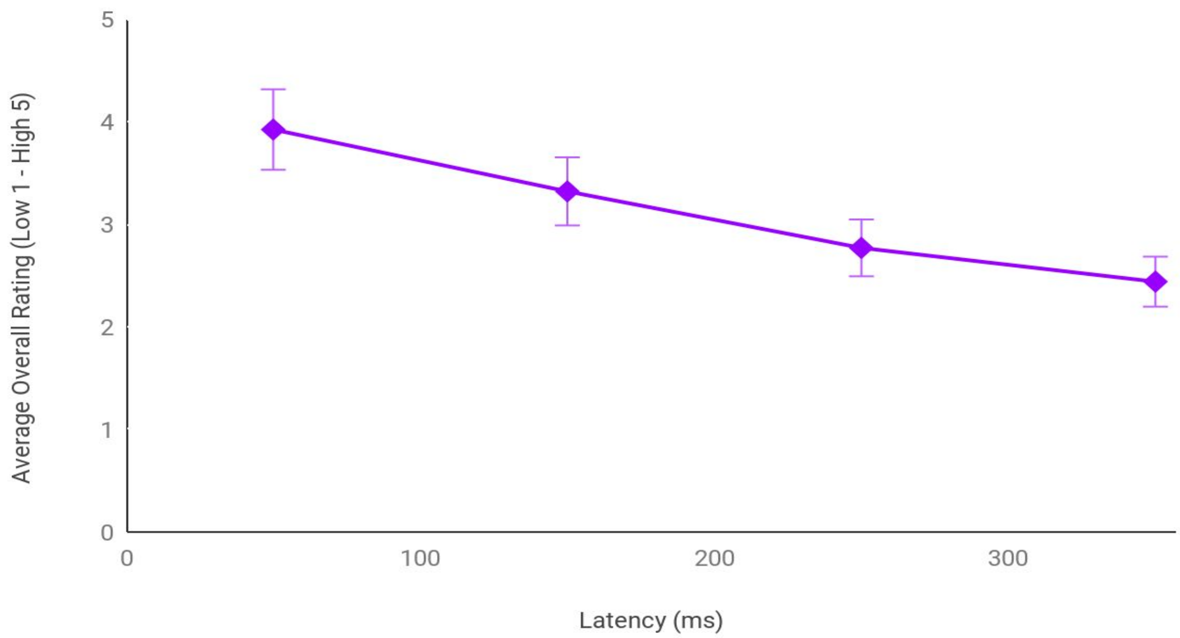

Figure 11: "How fun was the test?" Rating vs. Latency
The players' overall experience decreases as the latency increases

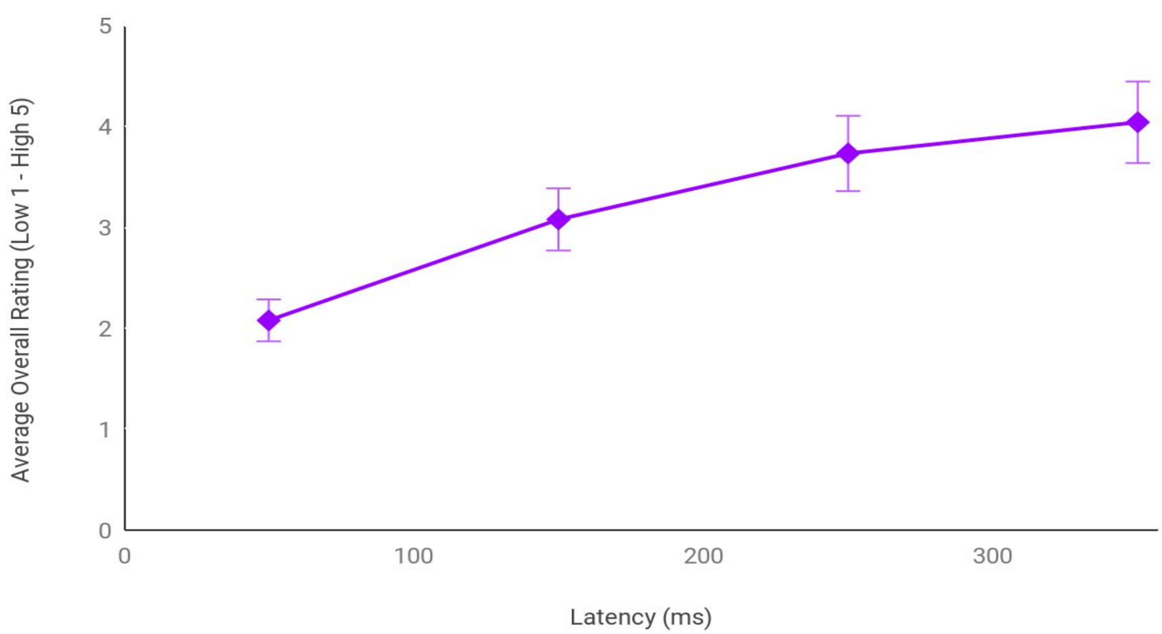

Figure 12: "How much did the lag affect your performance?" Rating vs. Latency
As latency increases, the greater effect it has on the players' performance

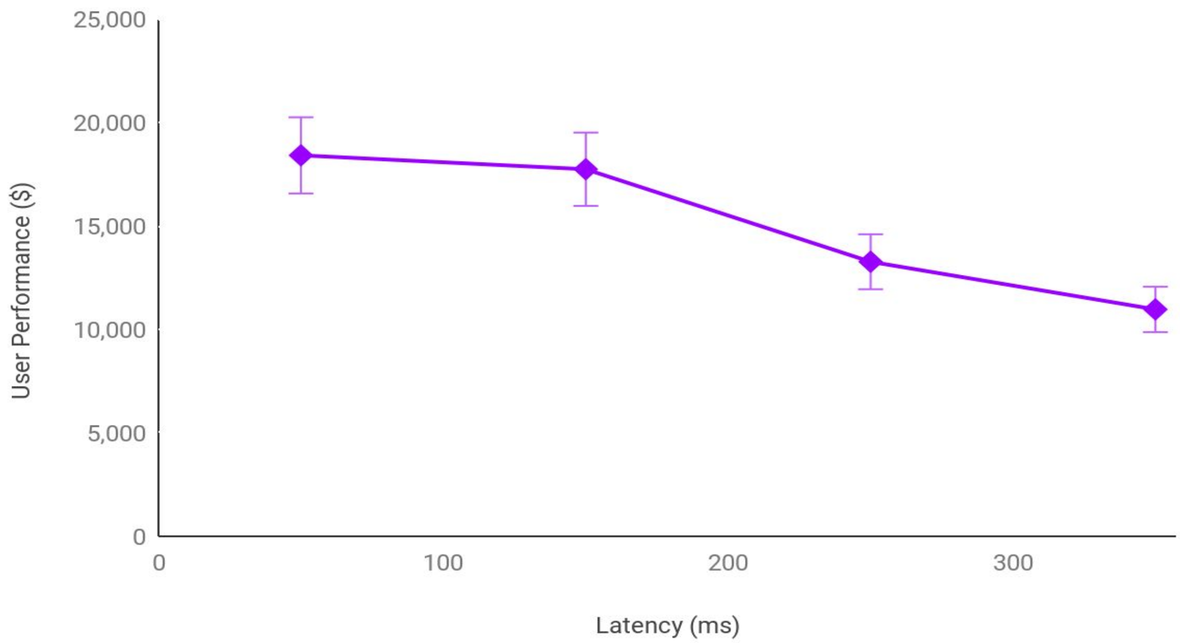

Figure 13: User Performance vs. Latency
As the latency increases, the players' performance decreases

4.2.3 PlayStation Now Results

A paired t-test was performed for each of the three metrics: self-rated enjoyment, self-rated performance, and recorded performance (money collected). The degrees of freedom for these tests is thirteen (one less than the total number of participants). The t-test results are displayed in Figure 14. Since all of the tests indicated p-values at or below the selected significance level (5%), these results are statistically significant. This is evidence that the mean at 50ms is different than the mean at 350ms.

4.2.4 Vortex Results

The same procedure was performed for the Vortex results. A paired t-test was performed for each of the three metrics: self-rated enjoyment, self-rated performance, and recorded performance (money collected). The degrees of freedom for these tests is ten (one less than the total number of participants, with one incomplete test being discarded). The t-test results are displayed in Figure 14. The t-test results were the same as PlayStation Now, thus they are statistically significant. Figure 15 shows the users' overall enjoyment when playing on PlayStation Now and Vortex with the four different latencies, and the axes for Figure 15 are the same as Figure 11. Figure 16 shows how much the latency affected the users' performance and Figure 17 shows the users' game performance when playing on PlayStation Now and Vortex. Figure 16 has the same axes as Figure 12, and Figure 17 has the same axes as Figure 13.

T-Test Results				
	Vortex		PlayStation Now	
Metric Being Observed	T-Score	P-Value	T-Score	P-Value
QoE	3.975	0.10% - 0.05%	3.975	0.10% - 0.05%
Self Rated Performance	-3.390	0.50% - 0.10%	-3.390	0.50% - 0.10%
Recorded Performance (Money Collected)	3.334	0.50% - 0.10%	3.334	0.50% - 0.10%

Figure 14. Table of T-Test results from Vortex and PlayStation Now when observing QoE, Self-Rated Performance and Recorded Performance

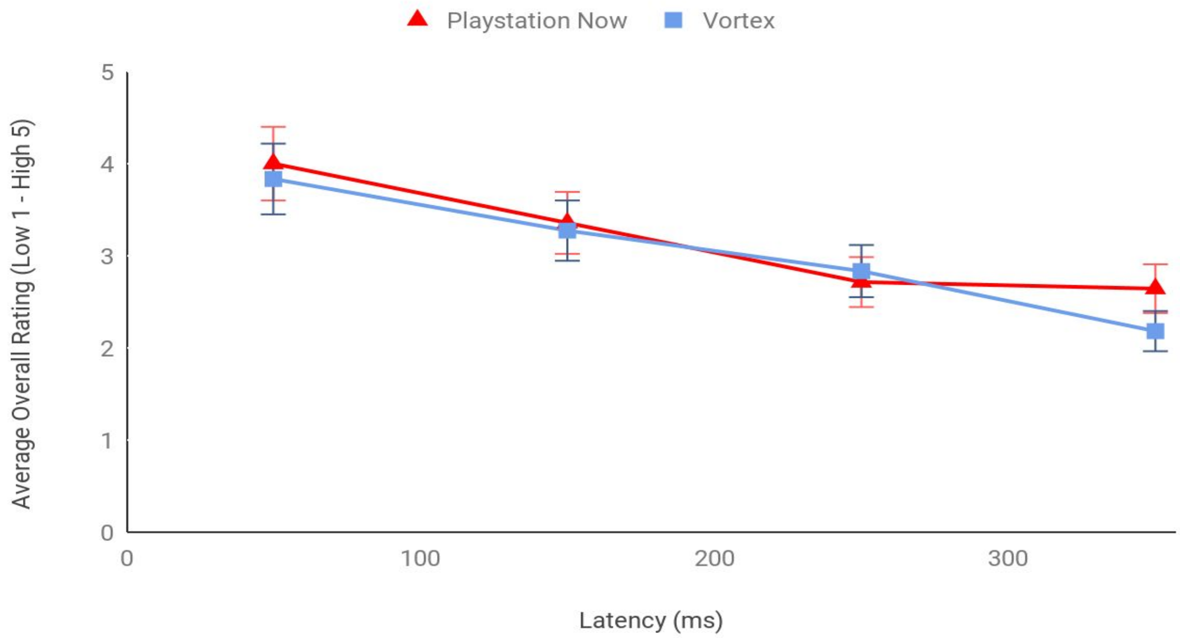

Figure 15: "How fun was the test?" Rating vs. Latency
As latency increases, the players' experience decreases. PlayStation Now has a slightly better QoE at the highest latency tested

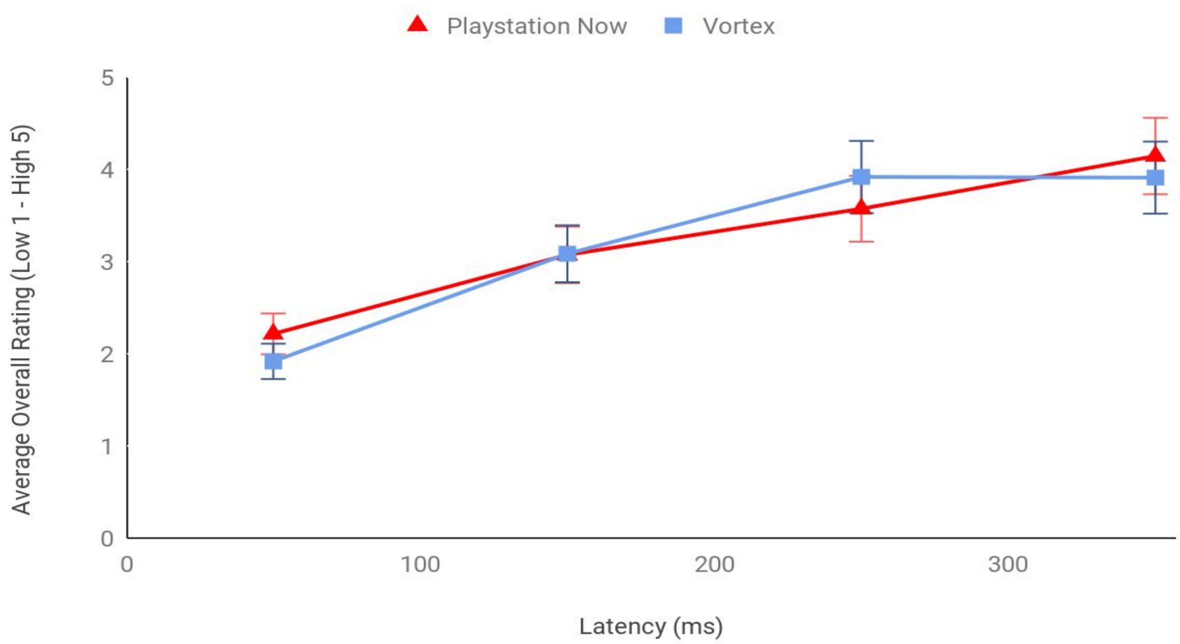

Figure 16: "How much did the lag affect your performance?" Rating vs. Latency
As latency increases, the greater effect it has on the player's performance

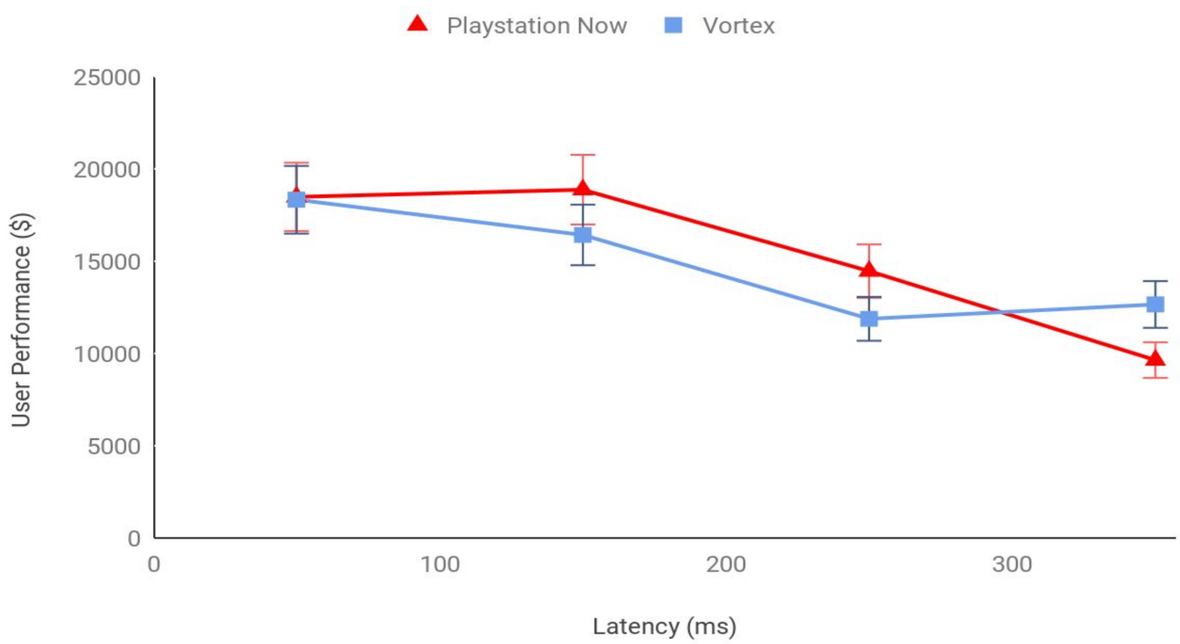

Figure 17: User Performance vs. Latency
As latency increases, the players' performance decreases. PlayStation Now players' had a steady decline in performance after 150ms while Vortex players' had slightly better performance scores at the highest latency

4.3 Summary

Experimental studies revealed that Vortex maintained a stable framerate even when bandwidth was restricted to 2.5 Mbps. Likewise, Vortex maintained a stable frame rate and throughput at any tested latency, up to a maximum of 200ms. Vortex continued this stability in both frame rate and throughput in our tests with packet loss, even at the maximum tested value of 10%. On the contrary, PlayStation Now's framerate suffered when bandwidth dropped below 5 Mbps. PlayStation Now was able to maintain a stable frame rate and throughput at any tested latency, up to a maximum of 200ms. PlayStation Now's frame rate dropped slightly and its throughput plummeted to less than half of its normal value when packet loss was at or exceeding

5%. PlayStation Now normally maintained a throughput of 10 Mbps, double that of Vortex's 5 Mbps.

We observed decreased performance when users played PayDay2 as the latency was increased. Increasing it too far, generally in excess of 350ms, rendered the game unplayable. In general, users enjoyed PayDay2 more when the latency was lower. Furthermore, users' performance, both self assessed and measured via money stolen, became worse as the latency increased.

5. Conclusion

Cloud gaming services are becoming more popular in the gaming industry. These services allow players to enjoy high quality games without the need of a powerful computer. The performance of cloud gaming services is often affected by the latency between the client and the servers. This latency can cause a decline in player performance and quality of experience. We conducted a study to determine how the increase of latency affects the QoE and performance across two different cloud gaming services. We also conducted experiments that tested how the performance of each service was affected by latency, bandwidth and packet loss.

In our experimental study, we played PayDay2 on two cloud gaming services, PlayStation Now and Vortex. We recorded frame rate and throughput for each service when the network was subject to different amounts of latency, bandwidth restrictions, and packet loss. We used Fraps to capture the frame rate data in each trial and Wireshark to capture the throughput under each restriction. Vortex has stable frame rates and throughputs even under conditions of high packet loss and latency or reduced bandwidth. On the contrary, PlayStation Now has reduced frame rates and throughput under comparatively milder conditions.

In our user study, we studied the effects of network latency on 26 participants playing PayDay2 on PlayStation Now and Vortex. The participants played the same PayDay2 mission on four different network latencies: 50ms, 150ms, 250ms and 350ms. We recorded each user's game performance by noting how much currency they acquired within the given time limit. We also recorded each participant’s QoE by having them fill out a survey that asked questions about their experience after each trial.

Overall, latency reduces the user’s quality of experience at any level. As for player performance, values over 150ms negatively affected the performance, although players were able to accurately report that they were experiencing latency, even if that latency was at or under 150ms. There were no significant differences between the quality of experience and performance results between PlayStation Now and Vortex.

In conclusion, usage of cloud gaming services, such as PlayStation Now and Vortex, is viable at low latencies. To ensure that the user enjoys the gaming experience and performs well, the latency of the network should be less than 150ms.

6. Future Work

There are many opportunities for future study in the area of cloud gaming services. These opportunities range from those in the short-term, such as extensions to research done in this study, to those in the long-term, which would encompass works that require either their own study or a multitude of studies to be compared.

6.1 Short Term

Future work in the short-term includes extending the study to analyze the effects of bandwidth restrictions on quality of experience and player performance. This studies' experimentation showed that having bandwidth restricted to below 10 Mbps significantly degraded the quality of experience for the game, arguably more so than latency. Analyzing the effect of bandwidth restriction more thoroughly, perhaps with a user study conducted in a similar manner as this studies', would allow for comparison between different types of network issues and their severity.

Another item of short-term future work would be to extend the study to analyze the effects of packet loss on the quality of experience and player performance. This studies' experimentation showed that packet loss or or higher than 5% significantly degraded the quality of experience for the game on a similar level of severity as with bandwidth restricted to below 10 Mbps. Analyzing packet loss would further solidify the understanding of the effects of network issues on quality of experience and player performance, and provide guidelines for selecting a network connection for cloud gaming services.

A final item with regards to short-term work would be an extension of the user study. Having a larger sample size can help with statistical significance, but one issue with our user study in particular was the lack of diversity. The primary group of participants were college students presumably aged between 18-22. This is not representative of the general population as a whole, and most of the participants reported previous first person shooter experience. Conducting a user study would more data to compare to the conclusions of this study.

6.2 Long Term

Long-term, comparing the effects of network issues on quality of experience and player performance in game genres other than first person shooters is another area for future work. Not only would this provide more data to analyze for the aforementioned effects, but studying it would provide an opportunity to see if the effects are the same across different genres. Studying if fast paced, reaction-time based games (such as first person shooters) suffer more from network issues than slower, more methodic games (such as strategy games) could be done. These studies could be conducted in a similar manner as this study, for a direct comparison. A meta-analysis could then be conducted to see how the effects of network issues on quality of experience and player performance compare between genres.

Additionally, future work could compare the effects of network issues on quality of experience and player performance in both cloud gaming services and more traditional gaming platforms. This kind of work could show whether the effects of latency experienced in cloud gaming services is identical to the latency most people with online gaming experience are familiar with. Likewise, this work would be able to find if the effects of latency in cloud gaming services are more severe than that often experienced in traditional gaming, and thus that mitigating latency should be of a higher priority than normally. One could do this by comparing user performance in a cloud based game in an 'local mode' versus a traditional multiplayer game in an 'online mode'. The same AI would be against the user in both cases, but for the cloud based game there would be no additional network latency as would be introduced if the cloud based game was also played in an online mode.

A last item of future work would be comparing latency in cloud based gaming systems to input lag in traditional gaming systems. The results of our experiments suggests that the effects of latency are similar to those of input lag. However, latency in cloud gaming services not only affects the input but also the output. Research could go into whether this 'output lag' has any special effects unique to it, or if it is merely perceived as additional input lag. A user study could be conducted where half of participants are given input lag in a traditional gaming system, and the other half are given and equivalent amount of latency in a cloud gaming service. Quality of experience and performance could be measured and compared to find if the effects of latency on cloud gaming services are identical to the effects of input lag in traditional gaming systems.

Appendix A: Surveys

Experiment Test Survey

At any point in the trial, did you experience a sudden interruption to normal play?

[ ] No.

[ ] Once.

[ ] On multiple occasions.

At any point in the trial, did you feel that your controls were unresponsive?

[ ] No.

[ ] Once.

[ ] On multiple occasions.

At any point in the trial, did you feel that your controls were delayed?

[ ] No.

[ ] Once.

[ ] On multiple occasions.

At any point in the trial, did you feel that the game was ‘choppy’?

[ ] No.

[ ] Once.

[ ] On multiple occasions.

At any point in the trial, did you notice any graphical artifacts?

[ ] No.

[ ] Once.

[ ] On multiple occasions.

If you answered yes to at least one of these questions, rate your experience, where a ten represents your experience playing a game without lag/latency.

Did you have any additional comments/concerns? If so, record them below.

User Study Survey

Q1) User Number:

Q2) How fun was the previous test:

❍ 1 (Not Fun)

❍ 2

❍ 3

❍ 4

❍ 5 (Fun)

Q3) Rate the lag in the test sequence:

❍ 1 (Low)

❍ 2

❍ 3

❍ 4

❍ 5 (High)

Q4) How much did the lag affect your performance?

❍ 1 (No affect)

❍ 2

❍ 3

❍ 4

❍ 5 (Great affect)

Q5) Please provide any other feedback below:

User Study Qualtrics

Q1) User Number:

Q2) For SONA participants only! Name:

Q3) For SONA participants only! Email:

Q4) Rate your ability as a computer/console gamer: (1 = Low Ability, 5 = High Ability)

❍ 1 (1)

❍ 2 (2)

❍ 3 (3)

❍ 4 (4)

❍ 5 (5)

Q5) Rate your ability with playing multiplayer network games: (1 = Low Ability, 5 = High Ability)

❍ 1 (1)

❍ 2 (2)

❍ 3 (3)

❍ 4 (4)

❍ 5 (5)

Q6) Select all the game types you are experienced with: (Multiple choices may be selected)

❑ First Person Shooter (FPS) (1)

❑ Real Time Strategy (RTS) (2)

❑ Massive Multiplayer Online (MMO) (3)

❑ Turn Based game (any) (4)

❑ Puzzle games (5)

❑ Point and click adventure games (6)

❑ Multiplayer Online Battle Arena (MOBA) (7)

❑ Racing games (8)

❑ Sports games (9)

❑ Mouse-based rhythm games (e.g. osu!) (10)

❑ Other (11) ____________________

Q7) How many hours a week, on average, do you spend playing video games?

❍ Less than 1 hour (1)

❍ 1 to 5 hours (2)

❍ 6 to 10 hours (3)

❍ 11 to 15 hours (4)

❍ 16 to 20 hours (5)

❍ More than 20 hours (6)

Q8) How much time today have you spent playing video games before this experiment?

❍ 0 hours (1)

❍ Less than 1 hour (2)

❍ 1 to 3 hours (3)

❍ 3 to 5 hours (4)

Q9) Have you heard of cloud gaming? ❍ No ❍ Yes

Q10) Have you used a cloud gaming service before? ❍ No ❍ Yes (Please name the cloud service below) ______________________________

Q11) What is your field of study? (Multiple choices may be selected)

❑ Mechanical Engineering (1)

❑ Biology and Biotechnology (2)

❑ Robotics Engineering (3)

❑ Biomedical Engineering (4)

❑ Electrical and Computer Engineering (5)

❑ Computer Science (6)

❑ Interactive Media and Game Development (7)

❑ Chemical Engineering (8)

❑ Civil Engineering (9)

❑ Other (10) ____________________

Q12) Are there any other factors that may affect your ability to test the video game that you would like to let us know?

Q13) Please tell the user-study facilitator and proceed with the study

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