A First Look at the Network Turbulence for Google Stadia Cloud-based Game Streaming

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***Abstract*—While there have been network studies of traditional network games and streaming video, there is less work measuring cloud-based game streaming traffic and none on Google's Stadia. This paper presents experiments that provide a first look – measuring Stadia game traffic for several games, analyzing the bitrates, packet sizes and inter-packet times, and comparing the results to other applications. Results indicate Stadia, unlike traditional network game systems, rapidly sends large packets downstream and small packets upstream, similar to but still significantly different than video and at much higher rates than previous cloud-based game systems or video.**

I. INTRODUCTION

The growth in cloud computing coupled with high-capacity networks has brought the potential for cloud-based game systems. These game systems seek to provide the growing ranks of gamers and their wide variety of networked devices with an alternative way to have a high quality gaming experience. Companies like Sony, Microsoft, Amazon and Google are pushing this market to triple in revenue from last year to USD $585 million this year and $4.8 billion by 2023 [1].

Cloud-based game streaming differs from traditional games in that game clients do not run full versions of the game engine. Instead, only the cloud-based server handles the game engine logic – applying physics to game objects, resolving collisions, processing AI, etc. – and renders the game frames, streaming the game as video to the game client. This allows the game client to be relatively lightweight, only sending user input (e.g., key presses and mouse movements) and receiving and playing game output as streaming audio and video.

The cloud-based game architecture offers advantages over traditional games since the server unifies developer targets and players only need lightweight clients without a game install, which also helps prevent piracy. The disadvantages are the increased traffic required for the game frame streaming and the added round-trip latency for all player actions.

In order to provision networks that can provide cloud-based games with good quality, it is important for engineers to understand the network load for cloud-based game services. For traditional network games, many popular games [2], [3], [4] have been characterized and modeled, as has traditional streaming video [5], [6]. Studies of early cloud-based game systems, such as OnLive [7], can be used to compare the networking in today's systems. This paper provides a first look at the network traffic for Google Stadia, with comparisons to traditional games and video and earlier services. Doing this early in the growth phase of cloud-based games can provide critical information needed for proper future network support.

Using two custom measurement testbeds, we investigate Stadia's network characteristics (the size and frequency of data sent and the overall bitrate), or *turbulence*.[1] To the best of our knowledge, this is the first published analysis of Stadia network traffic. In addition, we compare Stadia turbulence to traditional network games, previous game streaming services, and streaming video.

Analysis of the results shows Stadia requires significantly more network capacity than traditional network games, early cloud-based game systems and streaming video, regardless of the game being played. Stadia traffic is resilient to loss and added delay, but the service appears to detect even small degradation's in the network quality and stops the player's game session to avoid a poor experience. The results should be a useful beginning to providing networks and end-host systems that can support this emerging generation of computer game systems.

Section II provides background and related work; Section III describes our measurement methodology; Section IV analyzes the experiments results; and Section V summarizes our conclusions and possible future work.

II. BACKGROUND AND RELATED WORK

Early research in game streaming proposed a thin-client system that streamed games as video [8] and detailed measurements of the motion and scene complexity for a variety of games that would be streamed as video [9].

An early commercial effort in game streaming was the Finnish company G-Cluster which demonstrated cloud-based game technology in 2000 [10], but typical residential Internet connections could not support the bitrates required at that time.

GamingAnywhere [11] provided an open source system for research, and was used to study bitrates versus game types [12]. Notable commercial services were provided by Gaikai[2] that supported cloud-based games running inside Web browsers and OnLive[3] that had distributed cloud-based game servers and a micro-console game client for the home. Researchers studied both Gaikai [13] and OnLive [14], providing

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[1] The term "footprint" typically refers to the memory size of a software process. In a network, the size and distribution of packets over time is important, hence our word "turbulence."

[2] https://en.wikipedia.org/wiki/Gaikai

[3] https://en.wikipedia.org/wiki/OnLive

data and traffic models. Sony Corporation acquired Gaikai and purchased OnLive's patents.

Current established cloud-based game services of note include Sony PlayStation Now[4], NVidia GeForce Now[5] and Shadow.[6] GeForce Now has been studied by researchers [15]. These services are fairly mature, but not yet mainstream for gamers. But large tech companies may push cloud-based games into the mainstream with services such as Microsoft xCloud[7] and Google Stadia.[8]

Google Stadia was released in November 2019, advertised to support cloud-based streaming of games at up to 4K resolution and 60 frames per second. Stadia games can be played through the Google Chrome Web browser, Google Chrome OS (notebooks or tablets), Google Pixel smartphones, and Google Chromecast [16]. Stadia's network requirements specify a minimum Internet connection capacity of 10 Mb/s, with 35 Mb/s needed to stream at a 4K resolution (if accompanied by a Stadia Pro subscription) [17]. Mobile/cellular Internet connections are not supported.

III. METHODOLOGY

To measure the network turbulence of Stadia, we selected Stadia games (Section III-A), setup measurement testbeds (Section III-B), gathered network traces (Section III-C), and analyzed the data (Section IV).

A. Game Selection

In order to ascertain if turbulence for Stadia varies by game, we selected a sample of ten games. The selection of games was limited to those available via Stadia in September 2020, and we further restricted our choices to those that were freely available with the *Stadia Pro* subscription. The selected games are: 1) *Destiny 2* (Bungie, 2019) – a first person, story-based shooter, 2) *Rise of the Tomb Raider* (Crystal Dynamics, 2015) – a third person action/exploration game, 3) *Samurai Shodown*[9] (SNK, 2019) – a side-view fighting game, 4) *Farming Simulator* (Astragon, 2019), a simulation game, 5) *Thumper* (Drool, 2019) a rhythm game, 6) *Orcs Must Die 3* (Robot Entertainment, 2020) – a first person, tower-defense game, 7) *Lara Croft and the Temple of Osiris* (Square Enix, 2014) – a third person action/exploration game, 8) *Power Rangers: Battle for the Grid* (Lionsgate Games, 2019) – a side-view fighting game, 9) *Hello Neighbor* (tinyBuild, 2018) – a survival horror game, and 10) Darksiders Genesis (THQ Nordic, 2019) – a top-down combat game.

B. Measurement Testbeds

Figure 1 depicts the general setup for our measurement testbeds.

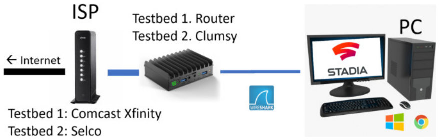

Fig. 1: Measurement testbed

Testbed 1 has a PC running Windows 10 Pro build 18363.592, launching Stadia via Chrome version 79.0.3945.117 (64-bit). The PC hardware is an Intel i7 eight-core CPU @ 2.0 GHz with 64 GB RAM with a Gb/s Ethernet NIC. The PC connects to an LED monitor with 3240x2160 pixels running at 59 Hz.

The PC connects via a Gb/s switch to a mini-PC running Linux v4.15 configured to act as a router. The router hardware is a Celeron J3455 quad-core CPU @ 1.5 GHz with 8 GB RAM and dual 1 Gb/s Ethernet NICs. The router uses `tc` [18] to constraint the network capacity, add latency or drop packets during our experiments. The router also runs Wireshark[10] to gather Stadia network traces.

The router connects to the Internet via the Internet Service Provider (ISP) Comcast, using their Xfinity modem.[11] The router connects to the modem via a Gb/s wired Ethernet connection. As a baseline measure of throughput, Google's M-Lab[12] Internet speed test consistently shows downstream bitrates from the ISP, through the router and to the client PC of over 200 Mb/s and upstream bitrates over 10 Mb/s.

Testbed 1 is located Sunnyvale, CA, USA. ICMP ping times (twice a second) run from our PC client to Stadia servers over all game sessions had no packet loss, a mean and median of 11 ms and a min-max range of [8 ms, 25 ms]. All measurements on Testbed 1 were done in March 2020.

Testbed 2 has a PC running Windows 10 Education build 17134.1726, launching Stadia via Chrome version 85.0.4183.121 (64-bit). The PC hardware is an Intel i5 four-core CPU @ 3.0GHz with 8 GB RAM with a Gb/s Ethernet NIC. The PC connects to an LED monitor with 2560x1080 pixels running at 60 Hz.

The PC connects to a TP-link AC1750 router with 450 Mb/s bandwidth. The PC uses Clumsy v0.2 (64-bit) to constrain the network capacity, add latency or drop packets during the experiments. The PC also runs Wireshark to gather Stadia network traces.

The router connects to the Internet via ISP SELCO, using an ARRIS modem. The router connects to the modem via a Gb/s wired Ethernet connection. The M-Lab Internet speed test consistently shows downstream bitrates of 80 Mb/s and upstream bitrates over 7 Mb/s.

Testbed 2 is located Shrewsbury, MA, USA. ICMP ping times (twice a second) run from the PC client to Stadia Server over all game sessions had no packet loss, a mean of 28 ms and a min-max range of [16 ms, 32 ms].

The use of two testbeds provides some confidence that the results generalize - one is on the U.S. east coast and the

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[4] https://www.playstation.com/en-us/explore/playstation-now/

[5] https://www.nvidia.com/en-us/data-center/rtx-server-gaming/

[6] https://shadow.tech/usen/

[7] https://tinyurl.com/y4jshreo

[8] https://stadia.google.com/

[9] Note, Shodown is the correct spelling – not Showdown.

[10] https://www.wireshark.org/

[11] https://www.xfinity.com/

[12] https://www.measurementlab.net/about/

other the U.S. west coast. Based on IP address, testbed 1 connected to Stadia servers in Henderson, Nevada, and testbed 2 connected to Stadia servers in Loudoun County, Virginia.

C. Experiments

Pilot studies determined 3 minutes of gameplay provided for the full range of observed network behaviors. For each game, a scenario was selected to represent core game play:

D2	Destiny 2: After obtaining the first weapon, the player in first person fights through several indoor skirmishes against bots.
DS	Darksiders: After the tutorial, the player uses different weapons and abilities to fight minions and several elite monsters.
FS	Farm Simulator: The player in first person plows rows in a field with a cultivator in the Tutorial's Arable Farming level.
HN	Hello Neighbor: In the first mission, the player in first person tries to sneak into a neighbor's house and avoid being captured.
LC	Lara Croft: The player as Lara Croft uses a staff, pistol, and rifle to fight and traverse traps by jumping and climbing.
OD	Orcs Must Die: After entering in the first mission, the player as Kelsey sets traps and defends 4 waves of orcs with a shotgun.
PR	Power Rangers: The player uses three characters to fight with AI players in versus mode.
SS	Samurai Shodown: The player as Haohmaru fights Charlotte Christine de Colde through three skirmishes in story mode.
Th	Thumper: The player guides the beetle through the twists and turns of levels 1-1 through 1-10.
TR	Tomb Raider: The player as Laura Croft jumps and climbs across collapsing, outdoor terrain to enter the Prophet's Tomb.

The Wireshark traces are trimmed to 3 minutes of the core gameplay (i.e., loading, menus, etc. are not included – just gameplay).

Table I provides the full list of experimental parameters. At higher sustained latencies, Stadia would shut down the client.

TABLE I: Parameters

Game	D2, DS, FS, HN, LC, OD, PR, SS, Th, or TR
Capacity	10, 20, 30 Mb/s, or no restriction
Added Latency	0, 10, 20 or 30 milliseconds
Induced Packet Loss	0, 1, 2 or 20 percent
Iterations	3 runs per game session, per condition

Network performance measures were extracted from the traces, including: packet sizes (bytes), inter packet times (milliseconds), and bitrates (Mb/s).

IV. ANALYSIS

This section analyzes: 1) bitrates and turbulence (Section IV-A), 2) the effects of capacity constraints, packet losses and added delays (Section IV-B), and 3) comparisons with other game and video systems (Section IV-C).

A. Turbulence

Our traces show Stadia uses UDP for both downstream and upstream game traffic. To assess network turbulence, we analyze bitrates (computed every second), packet sizes and inter-packet times. All analysis includes IP and UDP headers (20 and 8 bytes, respectively).

Figure 2 shows downstream bitrate distributions on the y-axis (computed every second) for each game under test with no added loss, latency or capacity restrictions. Each box depicts quartiles and median for the distribution. Points higher or lower than 1.4 × the inter-quartile range are outliers, depicted by the circles. The whiskers span from the minimum to the maximum non-outlier. Visually, there is considerable variance in bitrates both within and across games, with medians varying about 13 Mb/s across games and inter-quartile ranges low (less than 1 Mb/s for Farm Simulator) to high (15 Mb/s for Tomb Raider). The maximum bitrates are similar for most games, with the exception of Darksiders. The below 5 Mb/s bitrates generally occur when the game screen is monochrome (e.g., after a player death in Tomb Raider).

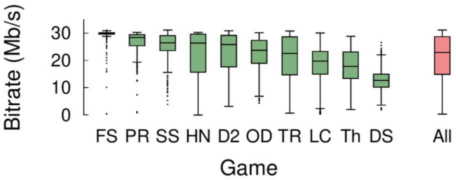


Fig. 2: Downstream game bitrates.

Figure 3 shows Stadia turbulence for the same data.

Figure 3a shows cumulative distribution functions (CDFs) of the downstream and upstream bitrates. The median downstream bitrate is about 25 Mb/s and the median upstream bitrate is about 0.5 Mb/s, about 50x lower. The downstream bitrate is skewed to higher bitrates approaching 30 Mb/s, but about 10% are below 10 Mb/s.

Figure 3b shows CDFs of the downstream and upstream packet sizes. The downstream packet sizes are consistently large, with most either 1232 bytes (71% of all packets) or 1228 bytes (24% of all packets). Note, these packet sizes are smaller than the typical MTU of 1460 bytes that could be used. Nearly all (99.4%) of the upstream packets are 100 bytes, probably small due to being either acks or user input information.

Figure 3c depicts a comparison of the inter-packet time CDFs. In general, downstream inter-packet times are quite small, with a median less than 0.2 ms, and 85% less than 0.3 ms. Upstream inter-packet times are much higher, with most fairly evenly distributed between 0.01 and 2 ms.

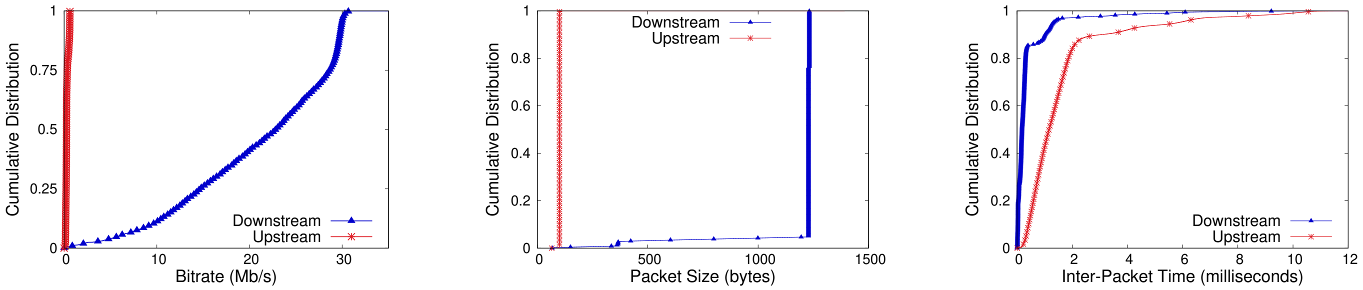
Given that downstream bitrates are about 50x higher than the upstream bitrates, we subsequently only analyze the downstream, unless noted otherwise.

B. Network Perturbations

We explore Stadia performance under degraded network conditions: reduced network capacities, packet losses and added delays.

1) Restricted Capacity: Figure 4 shows bitrates when the bottleneck capacity is restricted. From the figure, the capacity constraint lowers the maximum bitrate, but also smooths out the bitrate variance, providing an overall much smoother bitrate over time.

2) Packet Loss: Congested networks typically result in packet losses as full router queues are forced to drop packets. Figure 5 shows performance when our testbed randomly drops IP packets. In effect, Stadia network traffic is quite resilient



(a) CDFs of bitrates.

(b) CDFs of packet sizes.

(c) CDFs of inter-packet times.

Fig. 3: Stadia turbulence (network bitrates, packet sizes, and inter-packet times).

to packet loss with the bitrate mean and variance not visually correlating with loss.

3) Added Delay: As evidenced by our baseline round-trip times, our testbeds have good proximity to Google Stadia servers, but other networks may have significantly higher client-server network latency.

Figure 6 shows performance with added round-trip delay for all client-server traffic. Each trendline depicts a separate game session with a different amount of added delay (our baselines means are 11 ms and 28 ms). The delays seem to stabilize the bitrate variance; however, delays above 30 milliseconds were noticeable (see Section IV-D).

C. Comparison

In order to put cloud-based game turbulence in context, this section compares Stadia to an early commercial cloud-based game system and to related applications – traditional network games, streaming video and videoconferences.

1) Early Cloud-based Game Streaming: OnLive was a commercial cloud-based game streaming system available from 2010-2012. As such, it represents a reasonable "state of the art" about a decade ago and can provide for a longitudinal comparison. Figure 7 compares the bitrate CDFs for Unreal Tournament (UT, a first person shooter by Epic Games, 2002) in OnLive [7] with Destiny in Stadia. From the graphs, Stadia uses considerably more downstream capacity than the previous generation system OnLive; Stadia's median is about 3.5 times that of OnLive, and Stadia's peak is about 5 times that of OnLive. Upstream, the trend is similar, with Stadia having a median and peak about 4 times that of OnLive.

2) Traditional Network Games: This section compares Stadia turbulence to previously published network game turbulence. Specifically, Destiny on Stadia is compared to UT using publicly available traces [19]. For a summary comparison, median values are extracted for bitrates, packet sizes and inter-packet times. In both cases (Destiny and UT), core gameplay is used (e.g., not login and server selection).

Table II provides a comparison of network turbulence for Stadia compared with traditional games. Downstream, Stadia games have more turbulence than traditional games, with about a 350x greater bitrates, 15x larger packets, and 250x more frequent packets. This is perhaps expected given that traditional game clients receive game object updates while cloud-based game clients receive game frames. However, even upstream, Stadia has significantly greater turbulence, with 8x greater bitrates, 50% larger packets, and 45x more frequent packets. Thus, any switch to cloud-based games from traditional network games must plan for a significant increase in the network traffic both downstream and upstream.

TABLE II: Turbulence for Network Games (medians)

	Bitrate (Mb/s)		Pkt Sz (B)		Int-Pkt (ms)	
Game	Up	Down	Up	Down	Up	Down
Trad. (PC)	0.015	0.039	74	91	15	15
Cloud (OnLive)	0.12	6.2	130	1203	8.0	0.7
Cloud (Stadia)	0.53	25.8	100	1228	1	0.18

3) Video Streaming: Since cloud-based game downstream traffic has similarities to streaming video, we compare Stadia to YouTube and Zoom. The same PC client and Chrome Browser that ran our Stadia client streamed a 4k YouTube video.[13] Subsequently, the same PC client was used in a 2-person Zoom videoconference session.

Figure 8 depicts the results. Stadia clearly has the highest sustained bitrate, about 5x higher than the average YouTube bitrate of 4.1 Mb/s. Zoom clearly has the lowest bitrate, with a mostly steady mean of 1.3 Mb/s.

D. Observations

Even slight degradations caused by added delay or reduced capacity can cause Stadia to terminate the session and inform the player: "You need a better connection to play." Similarly, Stadia terminates when a bulk-download competes on our client with restricted capacity (results omitted due to space constraints). This seems a deliberate choice by Google – rather than gracefully degrade the experience during network problems, Stadia stops the session completely. i.e., the player gets a good experience or none at all.

Note, however, that Stadia is extremely resilient to loss – the game's visual quality and playability does not significantly decline even for packet loss rates as high as 20%.

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[13] ''Warriors'',https://youtu.be/0Ni4Rwm13y0

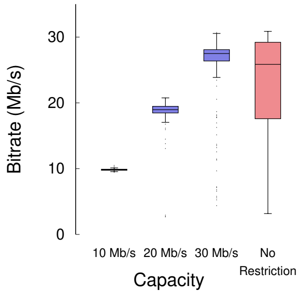


Fig. 4: Restricted capacity.

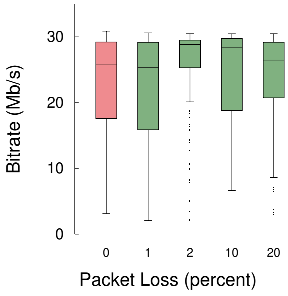


Fig. 5: Induced packet loss.

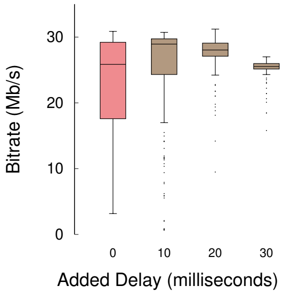
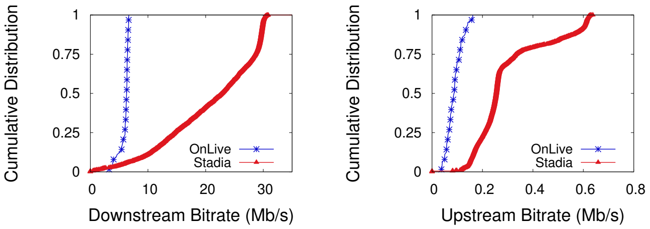


Fig. 6: Added delay.



(a) Downstream.

(b) Upstream.

Fig. 7: Bitrates for Stadia versus OnLive.

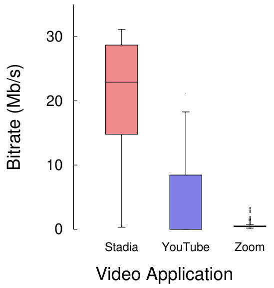


Fig. 8: Downstream bitrates for Stadia, YouTube and Zoom.

V. CONCLUSION

A detailed understanding of emerging cloud-based game system traffic can help plan and design systems and networks that support them. This paper presents a study on the network turbulence of Goggle Stadia. Testbeds with a custom router enables experiments for 10 games across a range of network conditions, and provides for a comparison with traditional network games, early cloud-based game systems and videos streaming applications.

Analysis of the results shows Stadia has far more downstream turbulence than upstream, with large, frequent packets downstream and infrequent small packets upstream. Stadia does not respond to most packet losses but does to capacity restrictions and even modest amount of added delays. Stadia's bitrates are significantly higher than other streaming video services, and are far higher than traditional network games. The results can be used to help plan for support, classification and treatment of cloud-based game traffic.

Future work can include testing additional Stadia games, or, testing Stadia in the presence of competing traffic. And with more and longer traces, models for traffic turbulence as well as protocol-level details could be derived.

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