United States Broadband

Household Bandwidth Demand Study

July 2021

Cartesian®

Rising Bandwidth Demand

A look at the changing landscape *of household internet usage in the United States.*

The COVID-19 pandemic accelerated the already rapid growth of bandwidth demand across US households, driving unprecedented use of streaming video and video conferencing applications.

In this report, we review current bandwidth usage trends across the US, summarize typical broadband use cases and associated applications, and estimate the downstream and upstream bandwidth needs of the most common applications, informed by a series of real-world tests.

Cartesian®

INTRODUCTION

Home broadband is critical to many parts of modern life. We use it to work and learn, communicate with friends and family, and to entertain ourselves. Following the onset of the COVID-19 pandemic and resulting changes to the way we live and work, our reliance on home broadband has never been greater.

It is foundational that all Americans have access to quality broadband that allows them to conduct their daily activities without experiencing issues. Providing broadband access to US households that do not currently have it is a key policy focus.

Ensuring that available connections meet the downstream and upstream usage needs for US households warrants specific investigation, particularly given the changes to typical usage patterns that occurred following the onset of the COVID-19 pandemic.

In this report, we review current bandwidth usage trends across the US, summarize typical broadband use cases and associated applications, and estimate the downstream and upstream bandwidth needs of households using the most common applications, as informed by a series of real-world tests.

ABOUT CARTESIAN

Cartesian is a specialist consulting firm of industry experts focused on the global telecommunications, media, and technology industries. For 30 years, we have helped clients worldwide build and execute strategies that transform the products, services, and organizations that shape the industries in which they operate.

ABOUT NCTA

The Internet & Television Association represents innovators and creators, and aims to bring together diverse perspectives to forge and promote consensus so all our members can continue to drive the industry forward: from policy, to content creation, to delivering compelling consumer experiences.

This report was sponsored by the NCTA – all findings, analyses, and interpretations are those of Cartesian.

EXECUTIVE SUMMARY

We conducted research and a series of real-world tests to understand the bandwidth needed by U.S. households to make use of common connectivity applications, both individually and across a range of multi-device usage scenarios.

The single-application tests examined downstream and upstream bandwidth consumption for a sample of common internet applications operating in isolation, while the multi-device usage scenarios examined the downstream and upstream bandwidth consumption on a home network with multiple internet-connected devices operating simultaneously. These multi-device usage scenarios focused on mixed entertainment and simultaneous video conference call use cases, and most were designed to represent demand for four-member households, as 90% of US households are comprised of 1-4 members[1].

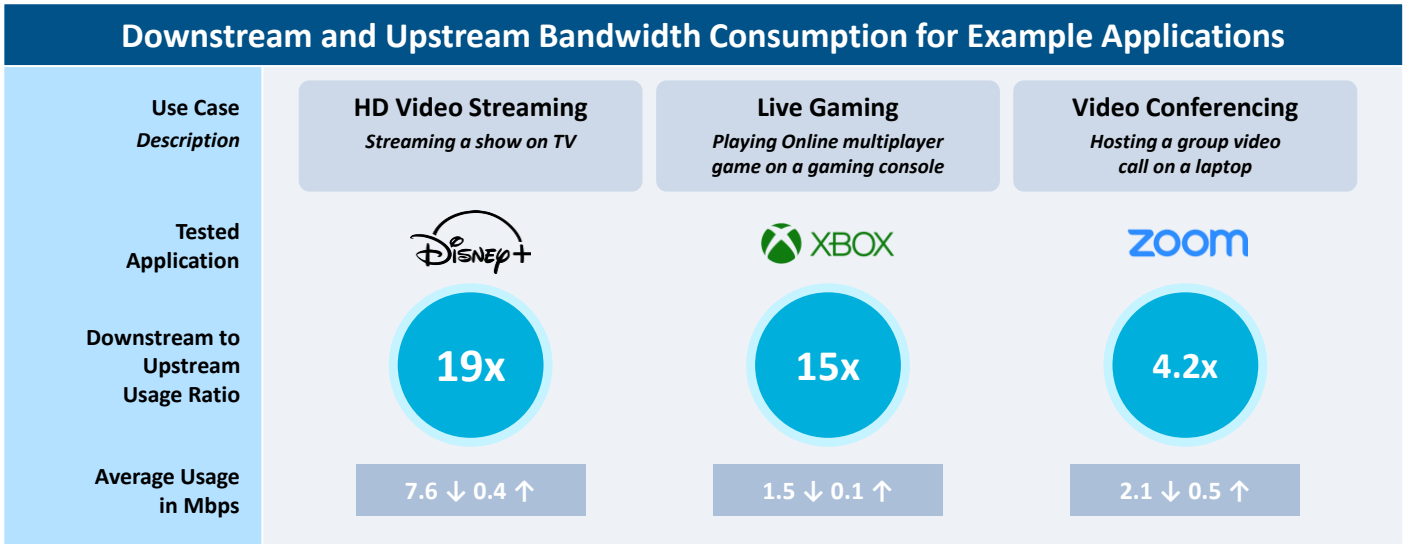
Based on our research and tests, we found:

Bandwidth Asymmetry

Most common household applications use much more downstream than upstream bandwidth

Our single-application tests demonstrated that commonly used video streaming, online gaming, and video conferencing applications, which are estimated to collectively comprise two-thirds of household bandwidth demand, typically use much more downstream bandwidth than upstream bandwidth.

The results below show examples of bandwidth consumption for a representative sample of tested applications:



Video streaming applications, such as Disney+ and Netflix, almost exclusively rely on downstream bandwidth, with the higher quality streaming options (e.g., UHD, 4k) consuming the most bandwidth.

Live games also require much more downstream than upstream bandwidth. We found downstream consumption for online live gaming is variable with occasional high peaks occurring when portions of the game are downloaded and cached, while upstream consumption typically remains low.

Video conferencing applications use more upstream bandwidth than most other applications, but actual traffic ratios vary by application (e.g., Zoom, Microsoft Teams, Google Meets), number of participants, and several other influencing factors (e.g., camera resolution). Our tests of group video conferencing calls of three to ten participants – which is consistent with typical remote learning and remote working scenarios – found that that on average more downstream

[1] According to the US Census Bureau, 63% of US households are 1-2 persons, and over 75% of US households are 3 or fewer persons.

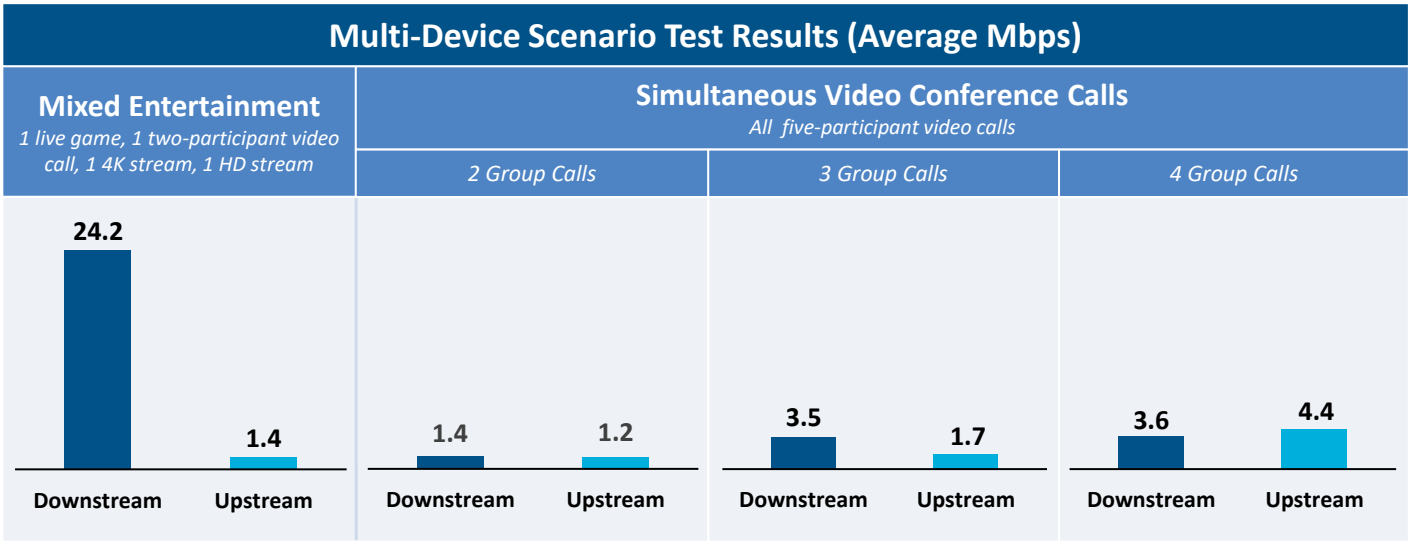
bandwidth is needed than upstream bandwidth. While, this was not consistent across all test variations in all cases, the amount of downstream and upstream bandwidth required to participate in typical and even very active video conference calls was modest and well within the range of all current commercial broadband service tier offerings.

Finally, we found that the bandwidth consumption does not scale linearly with the number of participants on a single video conferencing call. For example, when we tested increasing the number of video conferencing call participants 8x from one to eight, the increase in bandwidth needed to accommodate the additional video feeds was less than 2x.

Moderate Bandwidth Intensity

Multi-device scenarios consume a moderate amount of bandwidth

Our multi-device test scenarios demonstrated that bandwidth demand for common household internet use cases is moderate relative to internet speeds commercially available to most US households.



In our mixed entertainment scenario – which tested four typical applications running on a network simultaneously – we observed significantly higher rates of downstream vs. upstream bandwidth consumption with a ratio of 17x. The absolute bandwidth consumption remained moderate throughout the test.

All of our simultaneous video conference call scenarios – which tested two, three, and four simultaneous group calls occurring on a network – required less than 5 Mbps downstream or upstream. The bandwidth consumption did not scale linearly as more simultaneous group video calls were added, suggesting factors beyond the number of applications running influence bandwidth usage. However, the variation remained low on an absolute basis.

The average tested bandwidth for multi-device scenarios was typically lower than what would be implied by adding together the standalone recommended bandwidth for each individual application used. Collectively, these scenarios indicate that households can simultaneously run several applications while only consuming moderate bandwidth.

Growing Bandwidth Demand

Downstream bandwidth demand is expected to continue growing faster than upstream

Demand for bandwidth has increased over time, driven by a greater number of connected household devices and increased adoption of bandwidth-intensive applications. The growth in demand is likely to continue, particularly following the recent increase in remote work and remote learning adoption, as well as a projected increase in household dependence on connected devices for in-home entertainment.

However, downstream and upstream bandwidth consumption are not rising in tandem. Our findings show that most common applications today use much more downstream bandwidth than upstream bandwidth. This is consistent with peak bandwidth demand patterns reported by several internet service providers, which indicate the current downstream to upstream consumption ratio is 14x, up from 4.5x in 2010.[1] Even as internet traffic has greatly increased, downstream demand has grown faster than upstream, and we expect this pattern to continue as households increase the amount of time spent using downstream-intensive applications such as video streaming.

CONTENTS

US Broadband Evolution & Context

Cartesian®

BROADBAND SPEEDS RISE IN RESPONSE TO GROWING BANDWIDTH DEMAND

1.1 Recent US Broadband Trends

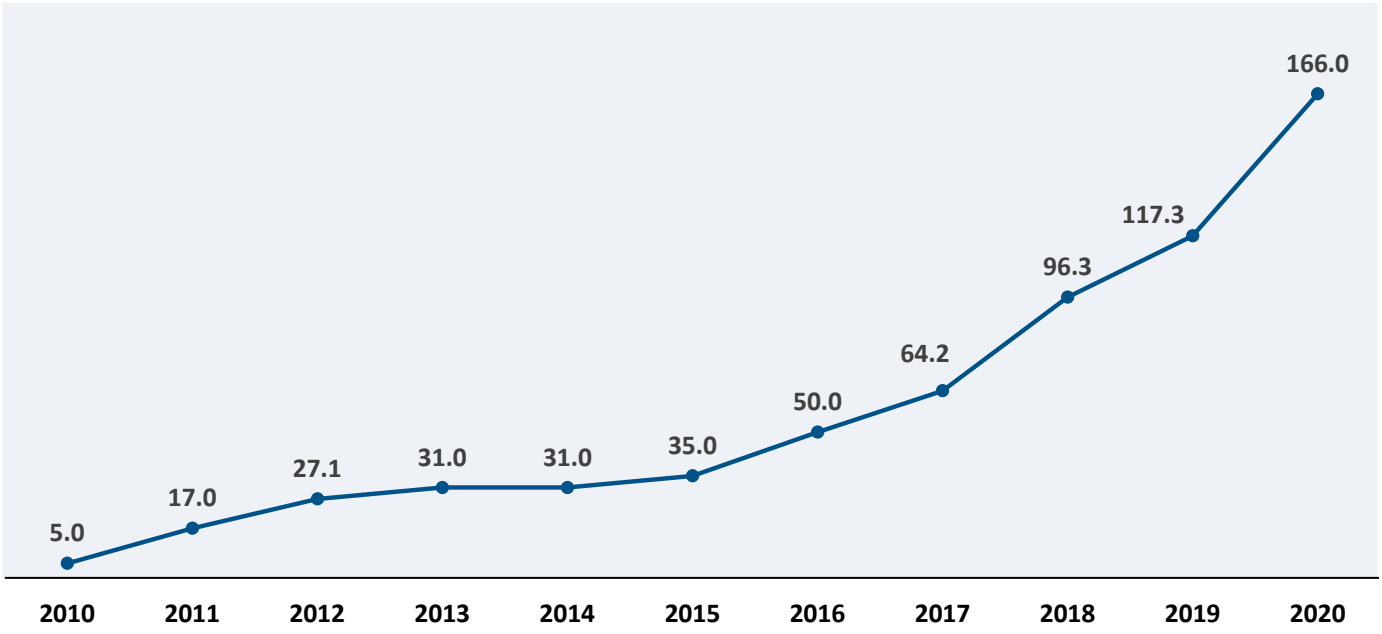
Over the last two decades, the consumer broadband market has seen rapid evolution across multiple fronts, including rising speeds, wider adoption, and a growing number of connected devices in the typical home. This evolution coincided with increased demand for bandwidth-intensive activities such as video streaming, video conferencing, online gaming, cloud storage, smart home devices, rich media web browsing, and photo sharing.

As the US adjusted to lockdowns and social-distancing measures put in place to reduce the spread of COVID-19 in 2020, we have seen an acceleration of these trends, as well as widespread adoption of many bandwidth-intensive use cases – such as remote work, remote school, and telemedicine – that tend to rely heavily on video conferencing to substitute for previously in-person interactions. Household bandwidth demand has spiked to record levels since the onset of the pandemic and is expected to continue to grow in the coming years.[2]

Internet speeds have rapidly increased

By the end of 2020, the average consumer downstream internet speed reached 166 Mbps, approximately 30x the 2010 average.[3] This trend has been driven by substantial internet service provider (ISP) investments in network capacity, widespread fiber rollouts, and the implementation of transport technologies such as DOCSIS 3.1, to meet growing consumer demand for high-speed connectivity.

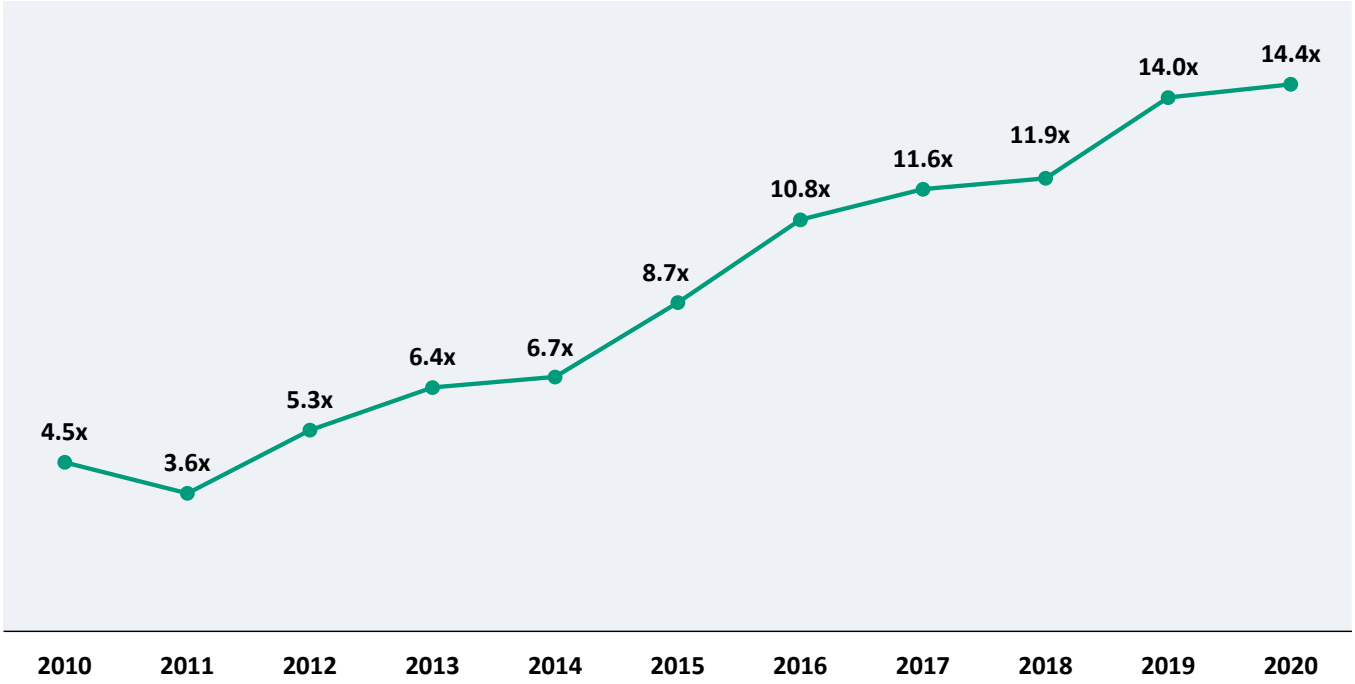
FIGURE 1. AVERAGE US MEASURED INTERNET DOWNSTREAM SPEEDS (MBPS): 2010-2020



Sources: Akamai, FCC, Ookla

As available speeds to consumers have increased, downstream bandwidth usage has consistently surpassed upstream bandwidth usage, both in absolute terms and growth rates. The current downstream to upstream bandwidth consumption ratio is estimated to be 14:1, as measured by several major broadband operators during peak consumption hours and depicted in Figure 2. This notable difference is driven by shifts towards using home internet for more downstream-heavy activities.

FIGURE 2. AVERAGE US PEAK HOUR DOWNSTREAM TO UPSTREAM BANDWIDTH TRAFFIC RATIO: 2010-2020[4]



Source: CommScope

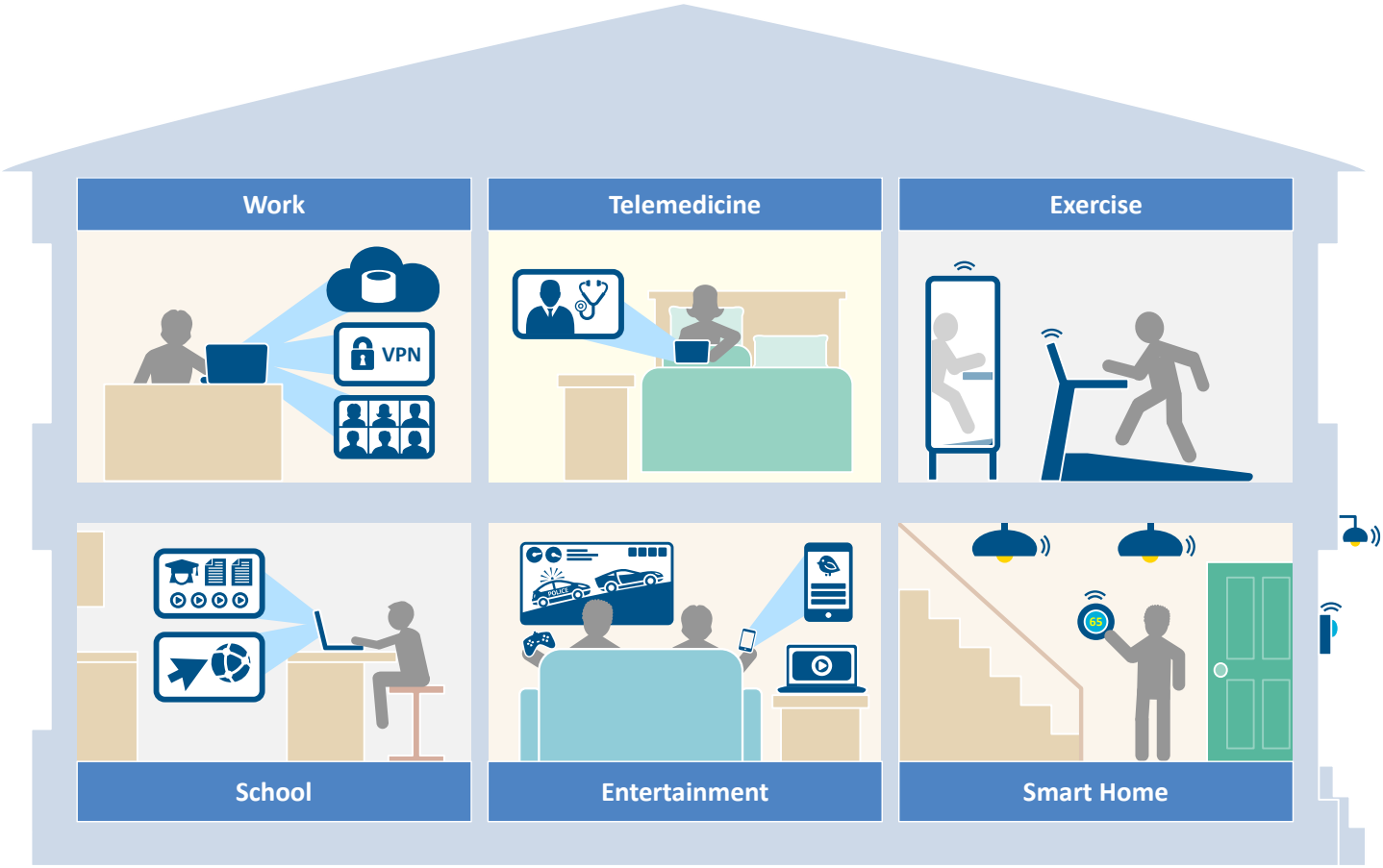
84% of US households now have broadband internet connections

Internet connectivity has become a basic need for most US households. Broadband adoption has rapidly increased over the past two decades, reaching an estimated 84% of households today.[5] The telecommunications industry has spent more than $1.5 trillion over this period to build high-speed network infrastructure to all but the most rural communities across the US, as 95% of US households are now estimated to be passed with 25/3 Mbps broadband.[6] The FCC has committed significant funding to closing that gap, awarding $9.2B in December 2020 to 180 ISPs that committed to bring high-speed broadband to over 5.2M locations over the next 10 years.[7] Given the ever-increasing demand for broadband use cases, we expect government funding to support broadband deployments and consumer adoption to remain a policy focus.

The number of internet-connected devices in a typical household continues to grow

The average US household today has more than 11 internet-connected devices, each requiring varying levels of bandwidth to fulfill its purpose in the home.[8] The development of new types of internet-connected hardware and the near ubiquitous household adoption of Wi-Fi have collectively enabled an explosion of personal devices – such as smartphones, tablets, and laptops – along with increased adoption of other types of "smart" devices including TVs, appliances, cameras, and sensors.

FIGURE 3. COMMON INTERNET-CONNECTED ACTIVITIES IN A HOUSEHOLD



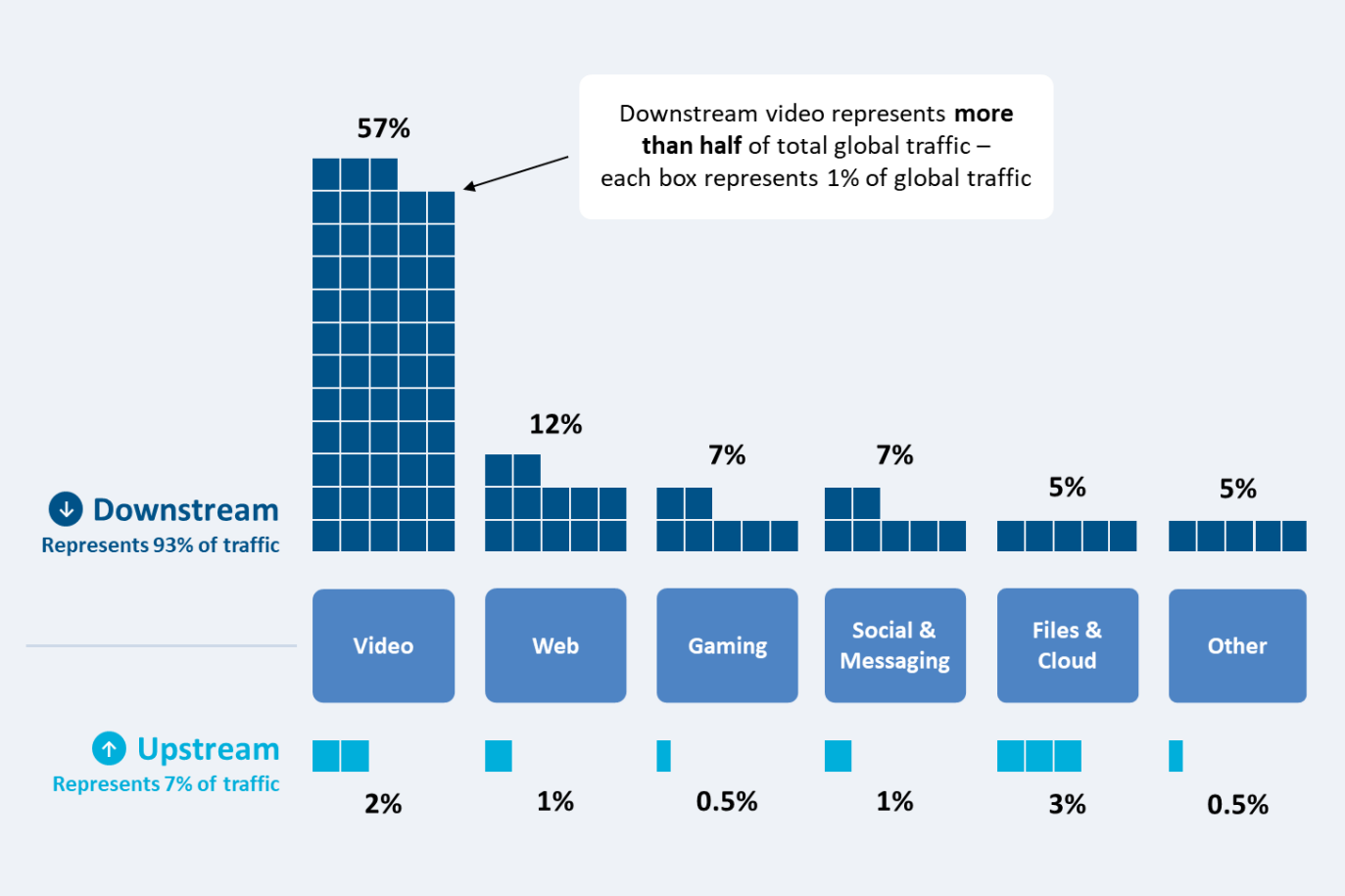
Source: Cartesian

Typical internet use cases have evolved, and require more bandwidth

As broadband speeds and adoption have increased, high bandwidth-consuming activities have grown in parallel. Most notably, high-resolution video streaming, multi-participant video conferencing, social media, messaging, file transfers, and cloud computing applications have become increasingly commonplace, and collectively comprise a substantial portion of internet bandwidth today. Video applications alone represent an estimated 61% of global downstream bandwidth, while just two videos providers – Netflix and YouTube – make up an estimated 34% of the total downstream traffic in the Americas.[9]

Additionally, gaming has become increasingly internet dependent, as gaming preferences have shifted to online, real-time gameplay. Many games now require a consistent broadband connection to play simultaneously with millions of people globally in real-time. Virtual and augmented reality, still in their nascent stages, could represent yet another use case that drives increased demand for bandwidth in the future.

FIGURE 4. SHARE OF GLOBAL BANDWIDTH CONSUMED BY DIFFERENT INTERNET TRAFFIC TYPES



Sources: Sandvine, CommScope, Cartesian

1.2 Common Home Broadband Use Cases & Applications

High speed broadband connections enable telemedicine, remote school, remote work, and home entertainment, along with a variety of other connected activities and home functions. These use cases have become especially important and widely adopted during the COVID-19 pandemic. It is apparent now more than ever that internet connectivity is critical, enabling millions of Americans to conduct remotely a range of activities that were predominantly in-person at the beginning of 2020. As Americans consider what life looks like after the pandemic, it's possible that many of these forced remote use cases will continue to be virtual by choice.

FIGURE 5. HOME BROADBAND USE CASES

Remote Work

Video conferencing, email, VPNs to access corporate networks, cloud storage, and other SaaS applications

WIDESPREAD REMOTE WORK ADOPTION

Stay at home orders across the US forced millions of Americans to work from home. By June 2020, 42% of the US labor force was working remotely.[10] Many companies are signaling they will implement flexible work from home policies as stay-at-home orders are beginning to be lifted across the country.

Telemedicine

Video conferencing for virtual appointments, web portals, file storage, and email

INCREASED USE OF VIDEO APPOINTMENTS FROM HOME

The use of applications such as Doxy.me and AmWell that facilitate remote healthcare service to Americans has continued to grow. This function has become increasingly common during the COVID-19 pandemic, with 50% of America's physicians using telemedicine to treat patients, up from 18% in 2018.[11]

Education

Video conferencing, educational videos, file sharing, message boards, web browsing, and email

REMOTE LEARNING NECESSITATED BY COVID-19

Many K-12 schools and universities have implemented part- or full-time remote learning since the COVID-19 pandemic began, making it imperative that the 56.4 million school-age children across the country have adequate internet bandwidth to attend class via video conferencing applications.[12] Classrooms around the country are using applications such as Zoom, Schoology, Edmodo, and Blackboard to conduct remote learning.

Entertainment

Video streaming, social media, live gaming, and music streaming

POPULARITY OF HOME ENTERTAINMENT

Video streaming is extremely popular in the US, with 78% of households subscribing to at least one streaming service as of August 2020.[13] As movie theatres and many other forms of out of home entertainment shut down, demand for various forms of internet-based home entertainment exploded.

Fitness

Fitness sites, apps, pre-recorded or live classes, and connected workout equipment

USE OF FITNESS APPS ARE COMMON IN 2020

In 2020, 74% of Americans aged 18-56+ are estimated to use an app for their daily fitness routine[14], and over 60% expect they will continue some form of online exercise at home after the pandemic.[15] Sites and apps such as YouTube, Beachbody, and Mindbody offer pre-recorded or live streamed workouts. Even some fitness equipment is now aided by connectivity, such as Peloton and Mirror.

Smart Home

Smart appliances such as surveillance systems, lightbulbs, refrigerators, and thermostats

HOMES ARE EQUIPPED WITH SMART DEVICES

As of September 2019, 69% of homes have at least one smart home device.[16] Smart appliances are sold for almost every corner of the house, including the living room, kitchen, and bedroom. Many devices can seamlessly integrate into home Wi-Fi networks with minimal bandwidth consumption, although some devices with video features such as security cameras do have more intensive requirements.

1.3 Bandwidth Utilization Innovation

As demand for bandwidth has increased, technological innovation has enabled various applications to utilize available bandwidth more efficiently. Several representative case studies – each of which are capabilities or standards deployed by many ecosystem participants – highlight the impact innovation has had on typical consumer bandwidth use cases.

In-Home Traffic Prioritization

Home router technology has become much smarter. Traffic prioritization, which identifies which devices/applications need more bandwidth and prioritizes the access of users in the home to the internet service accordingly, is now a default feature in a growing number of routers, providing a mix of automated rules and end-user settings and customization.[17] When there are bandwidth constraints, this technology can ensure that real-time use cases such as video conferencing and online games are prioritized over less time-sensitive applications, reducing the likelihood of disruption.

Adaptive Bitrate Streaming

Adaptive bitrate streaming enables video to be delivered more efficiently. To achieve this, the video player dynamically switches between different file sizes for the same piece of content at any point during the stream in response to changing bandwidth availability. If the player detects bandwidth constraints, a smaller file size with a lower associated level of quality can be temporarily selected, eliminating the need for disruptive buffering or stream failures. This technology was first introduced in 2000 and has been improved upon by firms such as Move Networks, Adobe Systems, and Apple. A widely used streaming protocol called HLS offers adaptive bitrate streaming, was developed by Apple in 2009, and MPEG-DASH, another common protocol was first published in 2012.[16] Today this technology is foundational to nearly every streaming video service including YouTube and Netflix.

Compression and Encoding Standards

Video streaming has also benefited from encoding and compression improvements. Video encoding is the process for making video files smaller via compression, allowing them to be delivered more efficiently. H.264 was first introduced in 2003 and is the current compression standard used widely across the industry.[18] It can reduce a video size by 50% without sacrificing image quality when compared with MPEG-4 to MPEG-2, and achieves this efficiency in many ways, including: [19]

- Ignoring certain static parts of a video sequence (e.g. unmoving background)
- Estimating certain blocks of the video frame using adjacent blocks
- Optimizing across several video processing techniques[20]

A new standard, H.265, which has been released and is gaining adoption, promises further improvements on H.264's compression capabilities.[21] An estimated 43% of video developers have already adopted the new standard, with more planning to adopt in the near future.[22]

These examples represent types of innovation that have been widely deployed by ecosystem participants, allowing more efficient utilization of existing bandwidth, and providing households the ability to do more with the same internet connection. In Figure 6, we highlight four additional examples of how technology companies have found ways to deliver consumers better product experiences with less bandwidth.

FIGURE 6. CASE STUDIES ON BANDWIDTH UTILIZATION INNOVATION[23]

1 NETFLIX

Reduce bandwidth requirements for 4K streams while improving video quality

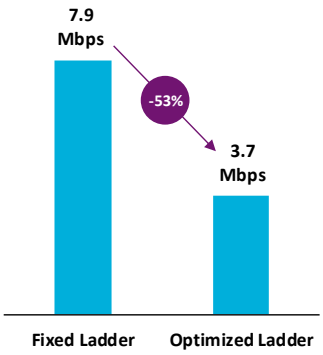
The Netflix engineering team improved the traditional 4K and 10-bit ladder by employing:

- Shot-based encoding
- Dynamic optimization
- Improved encoder settings

The "optimized ladder" results showed that for any given streaming resolution, Netflix could deliver a higher quality picture at a significantly lower bitrate.

Minimum Bitrate for a 4K Stream

Example based on a sitcom with some action



2 NVIDIA

Enable quality video conferencing on lower bandwidth using AI

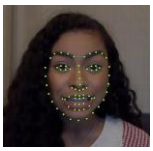
NVIDIA's Maxine uses AI to deliver high quality video conferencing by employing features like:

- Virtual backgrounds
- AI compression
- Face alignment
- Autoframing

Video conferencing services that use the Maxine platform can reduce video bandwidth usage down to 10% of H.264, the industry compression standard.

Bandwidth Reduction

Both use H.264 video compression standard



97.3 KB/frame
Transfers only key points over the Internet

0.17 KB/frame
Uses AI video compression

3 zoom

Deliver high video quality experience across all types of internet connection

Zoom's founder left Cisco Webex to build a new video conferencing product from scratch using:

- A cloud-native platform
- Multi-media routing and multi-bitrate encoding
- Quality-of-service application layer

Zoom surged in popularity during the COVID-19 pandemic due to its low bandwidth needs, high quality, and simple UX.

Packet Loss Quality Example

Picture quality comparison at 20% packet loss

Zoom

Webex

4 twitch

Improve the viewing experience of gaming livestreams with bitrate savings

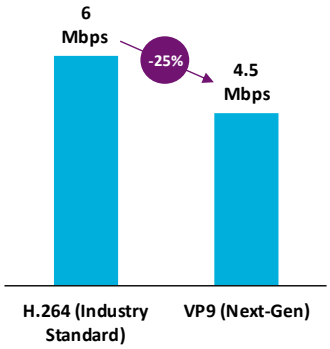
Twitch improved video quality, loading time, and buffering of gaming livestreams by:

- Moving from industry standard video compression (H.264) to next-gen compression
- Upgrading encoding hardware to enable compression improvements

The upgrades to compression efficiency delivered at least 25% in Bitrate savings, leading to high quality Twitch streams at a lower bitrate.

Bitrate Efficiency Gains

Next-gen encoding enables high quality streaming at lower bitrates



Sources: Company blogposts, News releases

There will be pressure on technology companies with applications and services that utilize broadband connections to continue to innovate, as the market will select winners and losers based on the quality of the services they deliver. Accordingly, companies have strong incentives to develop proprietary technologies that improve bandwidth efficiency to provide a competitive edge, with the hope of driving incremental market share and profitability.

For example, in the video conferencing ecosystem, the COVID-19 pandemic quickly put a spotlight on which services offer the most seamless user experiences. Newer players such as Zoom were able to successfully challenge market incumbents with a simple product that delighted customers and "just works", growing their user base from 10 million daily meeting participants in December 2019 to 300 million by April 2020, despite some initial security concerns.[24] In fact, Zoom achieved what many marketers consider to be the ultimate goal for viral awareness – the phrase "let's

Zoom" has now become synonymous with "let's video conference" in many households across the US. This was achieved, at least in part, by the company's bandwidth efficiency innovation that delivers consistent high-quality experiences.

Zoom, along with other video conferencing leaders such as Microsoft Teams, Cisco Webex, and Google Meet, are now aggressively adding new features that further improve user experiences, such as UI/UX improvements, higher participant counts, break out rooms, picture quality improvements, noise suppression, and AI powered background effects.[25]

Common Applications & Connectivity Requirements

Cartesian

BANDWIDTH NEEDS ARE DOMINATED BY VIDEO USE CASES

2.1 Application Bandwidth Testing Objective

We have established that US households are purchasing ever faster broadband speeds and are using these connections to conduct a range of bandwidth consuming activities, while technology companies are inventing new ways to utilize bandwidth more efficiently. In this section, we share the typical bandwidth recommendations that are published by developers of the most common household applications and compare these recommendations to the results of bandwidth tests we completed for each application. When included by the publishers, we note asymmetric downstream and upstream recommendations and evaluate against the typical usage ratio for the different application categories.

2.2 Applications & Associated Bandwidth Recommendations

We grouped the most common household applications into four categories based on their bandwidth consumption characteristics: (1) Real-Time, (2) Content Streaming, (3) File Transfers, and (4) Low Intensity (e.g., email, web browsing, non-video most smart devices). We divided the four application categories into 11 subcategories that capture the intended function of each application at a high level.

While most applications fit within a single category, some can span multiple if they perform multiple functions that consume differing amounts of bandwidth. For example, Instagram could be considered "Content Streaming" with similar associated bandwidth recommendations if used to watch previously published videos or scroll through photos. However, if used to broadcast or watch a live stream, the application is expected to have bandwidth needs that are more consistent with "Real-Time" applications.

FIGURE 7. APPLICATION CATEGORIES

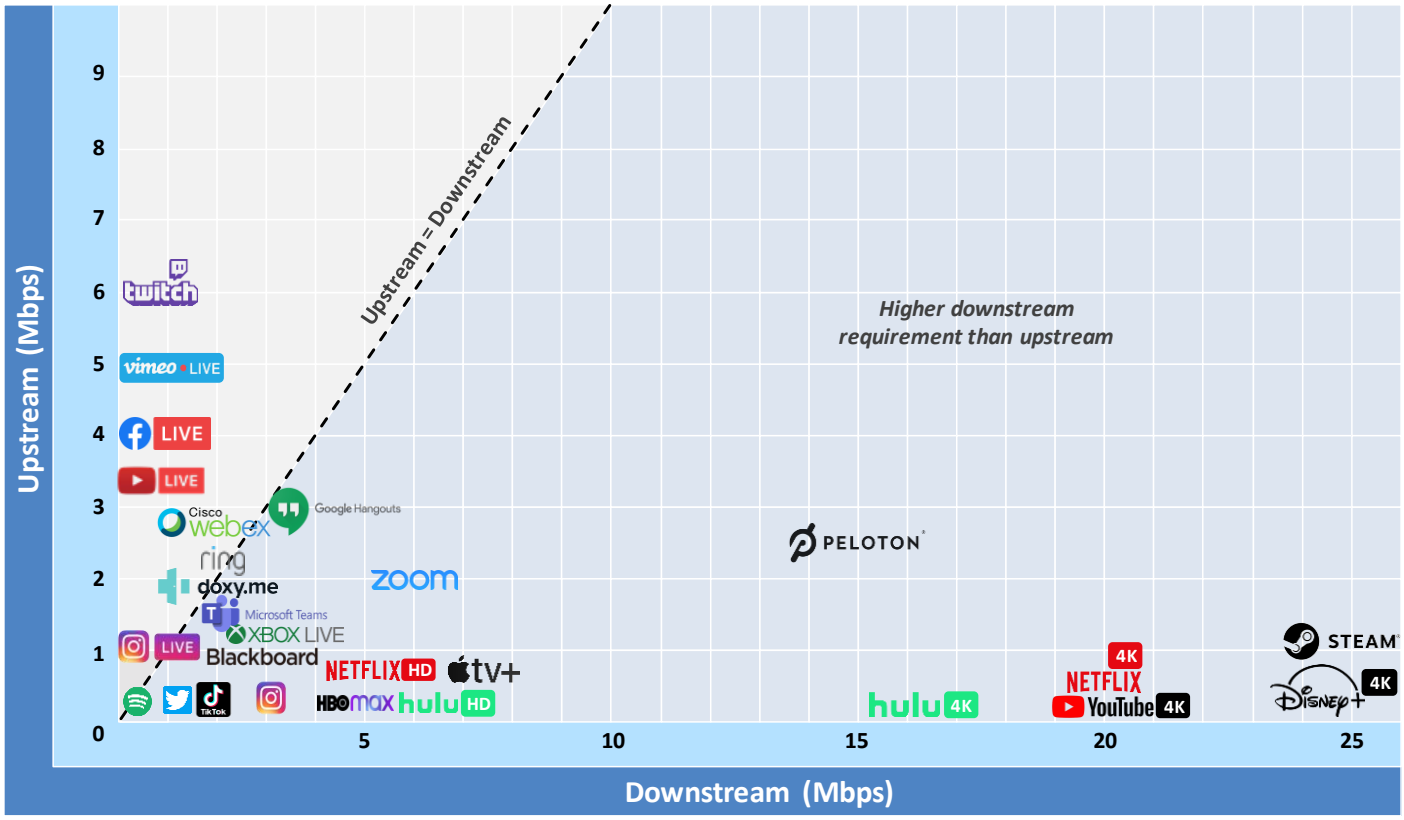
Application Type		Applications
1	**Real-Time** *Applications that require a constant stream of bandwidth for live content upload/download*	***Video Conferencing*** *(Including education, telemedicine, & fitness apps)*: zoom, Google Hangouts, Blackboard, FaceTime, Microsoft Teams, doxy.me, PELOTON ***Live Gaming***: STADIA, XBOX LIVE, STEAM, oculus, PlayStation Network ***Live Streaming***: LIVE, LIVE, vimeo LIVE, twitch, ring, LIVE
2	**Content Streaming** *Applications that can use algorithms such as adaptive bitrate streaming to optimize content delivery*	***Video Streaming***: Disney+, NETFLIX, peacock, HBOmax, hulu, YouTube, tv+, prime video ***Audio Streaming***: YouTube Music, MUSIC, pandora, Spotify ***Social Media***: TikTok
3	**File Transfers** *Asynchronous upload and download of data*	***Cloud Storage***: Google Drive, box, Dropbox, iCloud ***Other Uploads and Downloads***: *Game download*, *Mobile/PC update*, *Desktop app download*, *Mobile phone backup* ***VPNs***: ExpressVPN, Surfshark, NordVPN, IPVANISH
4	**Low Intensity** *Applications that consume a small amount of bandwidth intermittently*	***Web Browsing, Email, Shopping and SaaS***: amazon, PayPal, salesforce, Gmail, Google ***Non-Video Smart Home***: Google, LG, amazon alexa, PHILIPS

Source: Cartesian

For a representative sample of applications within each subcategory, we researched the bandwidth recommendations published by the application developers to identify the typical downstream and upstream needs per subcategory. We included multiple recommendations for the same application if the bandwidth recommendations are different for different functions (e.g., HD video streaming vs. 4K video streaming).

When individual application recommendations are compared, there are two notable patterns. First, most applications specify they need less than 8 Mbps downstream and 3 Mbps upstream. Second, applications that recommend more bandwidth than this can be downstream-intensive or upstream-intensive, but rarely both. The downstream-intensive applications are generally either 4K video streaming (e.g., Netflix 4K, Disney+ 4K) or live gaming / file transfers (e.g., Steam), while the upstream-intensive applications are nearly all live-streaming video (e.g., Twitch, Facebook Live).

FIGURE 8. EXAMPLES OF APPLICATION-LEVEL BANDWIDTH RECOMMENDATIONS PUBLISHED BY DEVELOPERS[26]



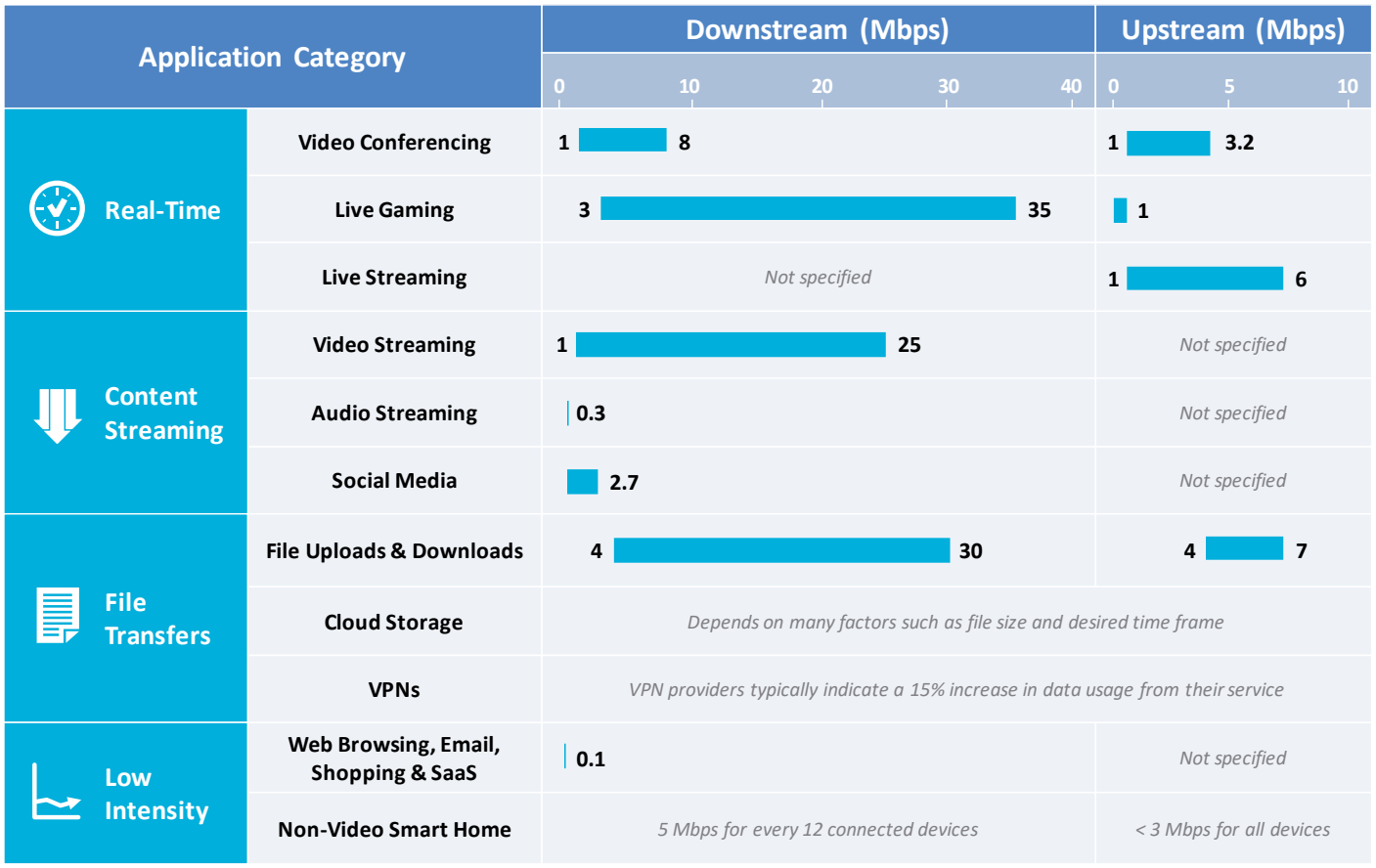
Sources: Application websites, Third party support pages

When these requirements are summarized, we find the most bandwidth-intensive application subcategories are:

- **Video Conferencing**: 1.2-8.0 Mbps downstream and 1.0-3.2 Mbps upstream
- **Live Gaming**: 3.0-35.0 Mbps downstream and 0.5-1.0 Mbps upstream
- **Live Streaming**: Unspecified downstream and 1.0-6.0 Mbps upstream
- **Video Streaming**: 1.0-25.0 Mbps downstream and unspecified upstream

Cloud storage and other file transfers (e.g., file downloads and file uploads) require special treatment. These use cases technically have very low minimum bandwidth needs, but the bandwidth levels to transfer large files within a timeframe that users would consider to be reasonable are much greater. We evaluate these needs in Section 2.3.

FIGURE 9. BANDWIDTH RECOMMENDATIONS PUBLISHED ON APPLICATION WEBSITES BY CATEGORY[27]



Source: Application websites

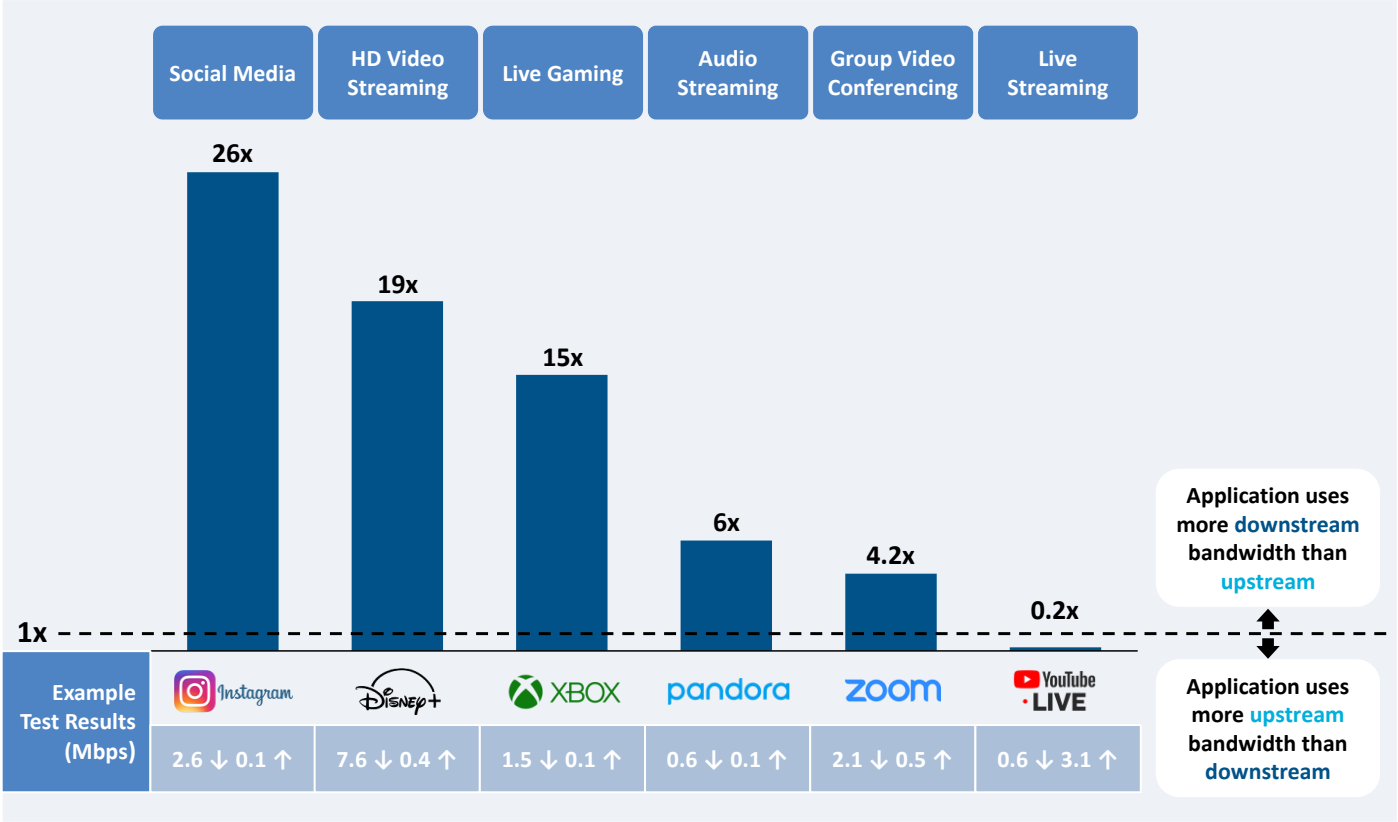
2.3 Application Bandwidth Testing Approach & Findings

We ran usage tests to measure the actual downstream and upstream bandwidth consumed by a sample of applications in each of the four categories outlined in Section 2.2. Each test was completed over 120-300 seconds, and during that period the application was used in a manner that is consistent with the intended use case being measured. In cases where differing usage patterns could reasonably be expected to influence bandwidth needs, we ran multiple tests (e.g., video conferencing with two individuals vs. video conferencing with nine individuals). Additionally, the tested application was the only active application running on the device. For each test, we captured packet-level data, measuring downstream and upstream bandwidth consumption at every second. Using this data, we analyzed downstream and upstream bandwidth usage patterns, including averages, frequency and shape of any downstream or upstream spikes and drops that occurred during the test.

The tests were all completed on broadband connections that far exceeded the recommended bandwidth levels for each application (see Appendix II). Accordingly, the results represent how these applications perform when there is excess bandwidth capacity and they can run unconstrained. Many of these applications can properly function at lower levels of bandwidth when there are constraints, sometimes with only minimal reductions in quality, as discussed in Section 1.3.

We found that the downstream and upstream bandwidth used by applications varied significantly by category, and the following are some representative application test results:

FIGURE 10. TESTED DOWNSTREAM TO UPSTREAM RATIO BY APPLICATION TYPE FOR EXAMPLE APPLICATIONS



Source: Cartesian

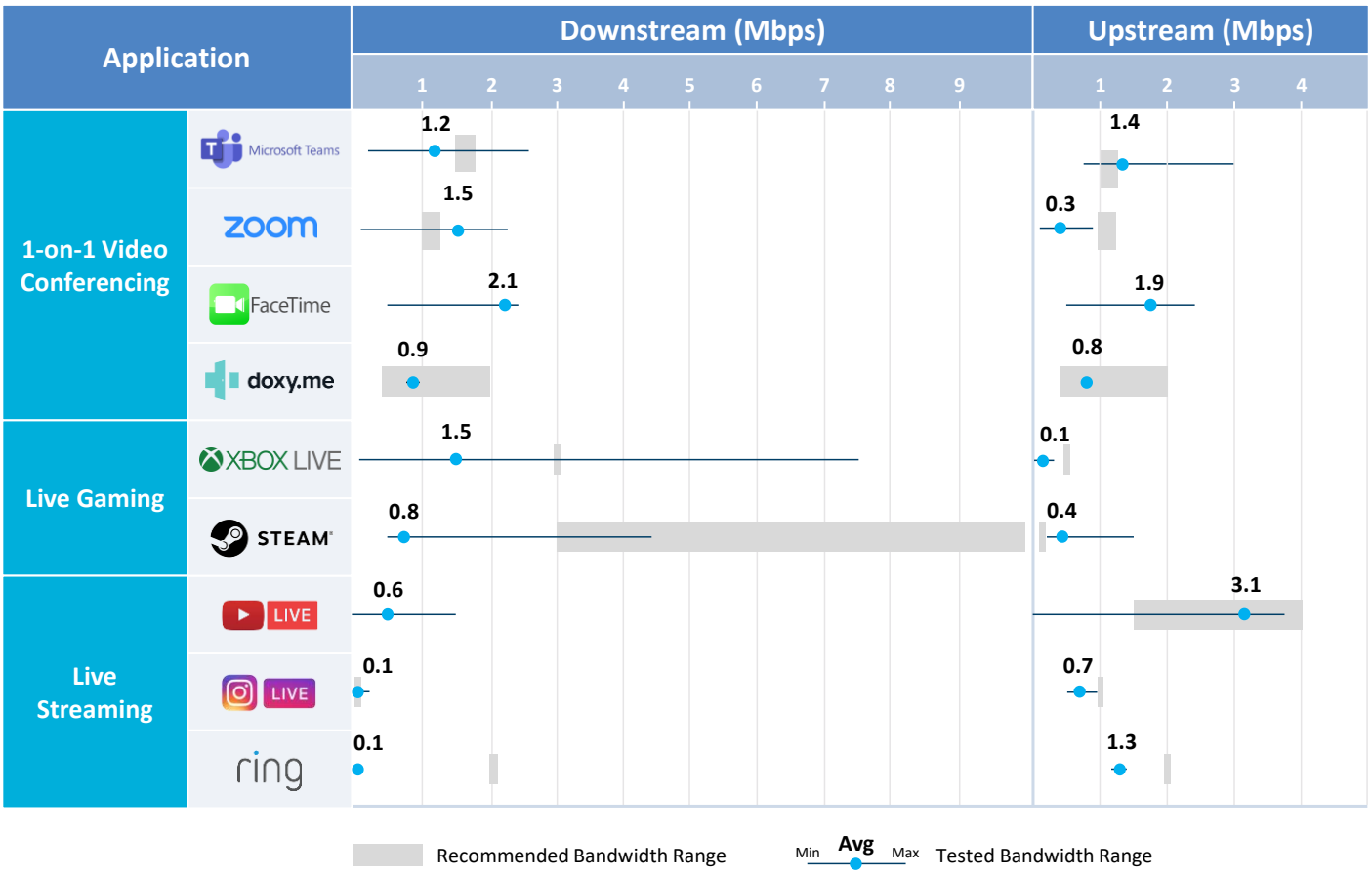
Below, we summarize our findings by application category:

1 Real-Time Applications

Real-time applications have unique bandwidth needs, as any disruption in minimum connectivity can cause the applications to degrade in delivery quality or fail. Additionally, two-way real time applications such as video conferencing and live gaming require a consistent level of necessary downstream and upstream capacity to function. For a sample of common applications across the three real-time subcategories, we compared the average, maximum, and minimum downstream and upstream bandwidth used in our testing to the recommended bandwidth ranges published by application developers.

All tested real-time applications were able to perform for the duration of each test using less than 8 Mbps downstream and 4 Mbps upstream. In most tests, the average upstream and downstream bandwidth fell within or below the recommended ranges, with the exceptions of Microsoft Teams slightly exceeding the high end of the recommended downstream range and Steam exceeding the upstream range. The peaks, or maximum bandwidth consumed during the test, sometimes exceeded the recommended ranges, but typically for only short periods of time.

FIGURE 11. REAL-TIME APPLICATION RECOMMENDED BANDWIDTH AND TEST RESULTS[28]



Note: Steam recommendations are for typical games and may exclude some outlier game titles with intensive bandwidth
Sources: Cartesian, Application websites

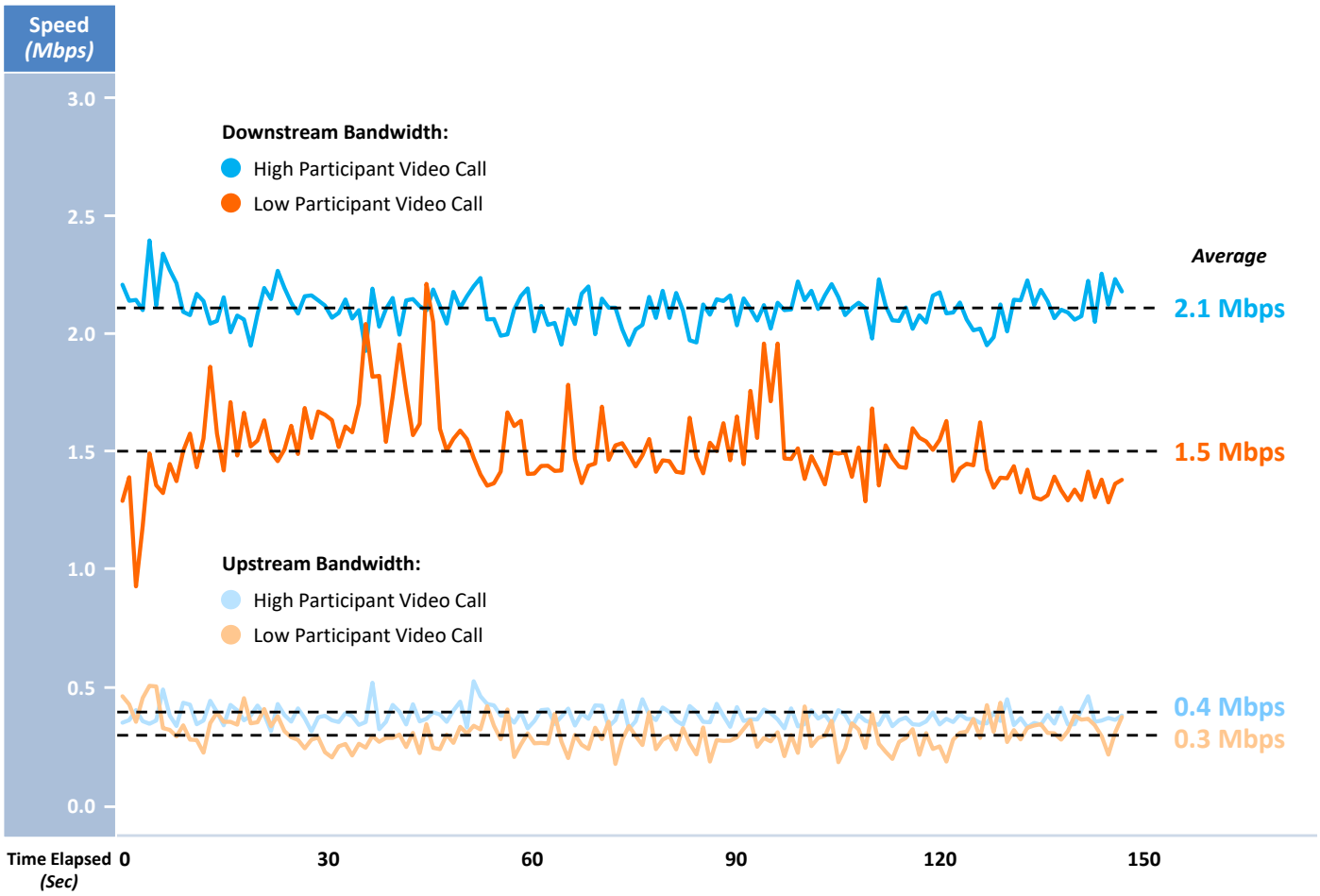
Video Conferencing

Video conferencing recommendations vary based on the number of people joining the call. For one-on-one calls, seven of the most popular video conferencing applications (e.g., Zoom, Microsoft Teams) recommend a downstream speed range of 1.2-2.6 Mbps and an upstream speed range of 1.0-3.2 Mbps.[29] Testing yielded results within these ranges, with the exception of Zoom utilizing an average of only 0.3 Mbps upstream with no significant peaks.

Typically, these applications define group calls as 3-10 people, and recommend a downstream speed of 2.0-8.0 Mbps and an upstream speed of 1.0-3.2 Mbps. Our testing of group video calls found that actual bandwidth consumption was in line with or below these recommendations. However, the number of participants is not the only influence on actual bandwidth usage; on-camera movement, screen-sharing, camera quality, desktop vs. mobile application, and other factors can affect both upstream and downstream requirements.

In line with the stated requirements, we found that bandwidth consumption does not scale linearly with number of participants. In Figure 12, we compare the downstream and upstream bandwidth consumption of two Zoom calls – one high participant call with nine people, and one low participant call with two people. When the number of participants, excluding the primary user, increased 8x from one to eight, the average downstream bandwidth needed to accommodate all of the additional video feeds increased 1.4x from 1.5 Mbps to 2.1 Mbps, while the upstream bandwidth increased 1.3x from 0.3 Mbps to 0.4 Mbps.

FIGURE 12. COMPARING VIDEO CONFERENCING BANDWIDTH USE FOR HIGH AND LOW PARTICIPANT CALLS



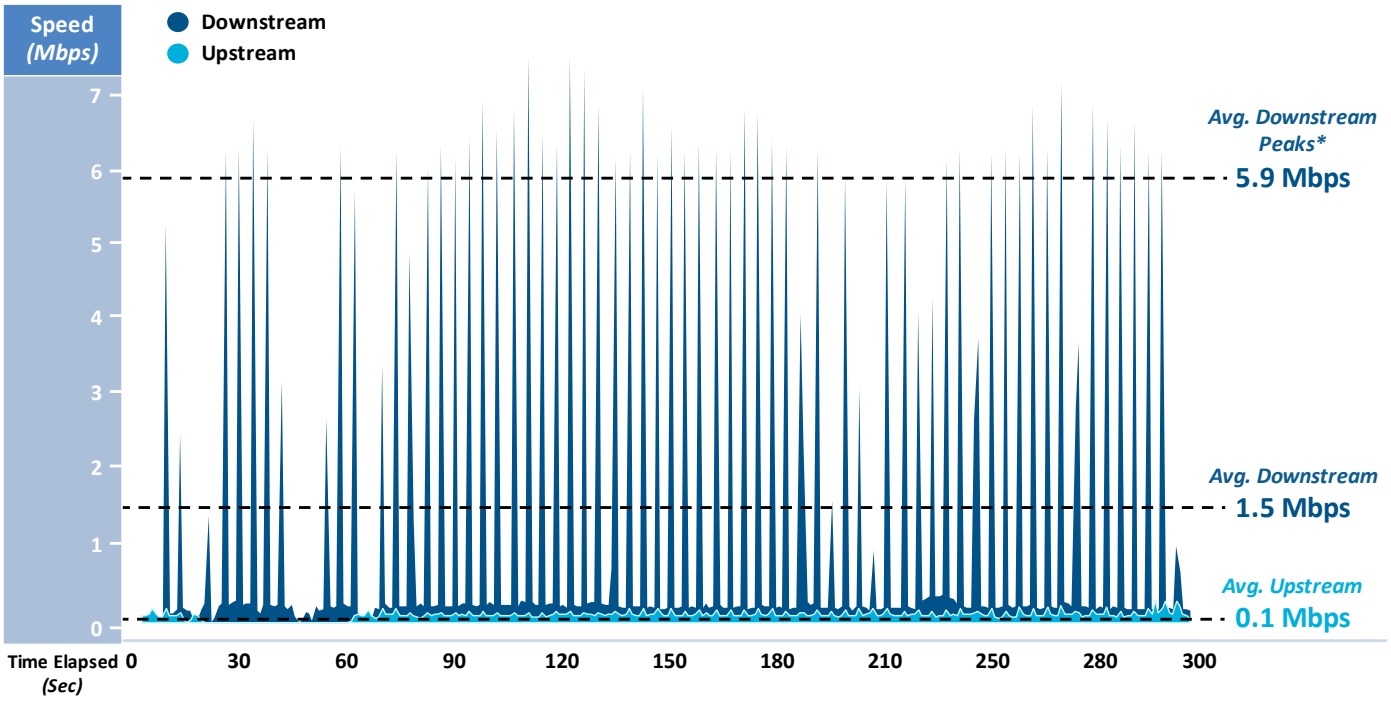
Source: Cartesian

Live Gaming

Live gaming bandwidth needs can vary significantly based on the application, the amount of game content that is stored locally vs. required to be downloaded during play, and the frequency and complexity of real-time interactivity with other users in the game.

Most online gaming platforms (e.g., Xbox, PlayStation) recommend 3.0-6.0 Mbps downstream and 0.5-1.0 Mbps upstream. In practice, we observed lower average bandwidth needs when testing on an Xbox One; however, we did observe frequent downstream peaks of 5-7 Mbps. These downstream peaks appeared in consistent intervals of approximately 2-4 seconds and were generally followed by subsequent drops to 0.1-0.2 Mbps in downstream bandwidth. This behavior indicates the game is downloading and caching content when excess bandwidth is available for an upcoming interval of gameplay, reducing the likelihood of game disruption if available bandwidth temporarily dropped below the average recommended bandwidth. The upstream needs were negligible, with no material peaks during gameplay.

FIGURE 13: LIVE GAMING APPLICATION BANDWIDTH USAGE OVER TIME



**Note: Test was conducted by playing Call of Duty: Black Ops Cold War on Xbox Live via the Xbox One*
Source: Cartesian

Additionally, we tested Fortnite, a bandwidth-intensive online multiplayer game. The results were similar to the Xbox results, with an average downstream speed of 0.8 Mbps, frequent peaks of 1.0-4.5 Mbps, and an average upstream bandwidth of 0.4 Mbps.

The live gaming ecosystem is complex with many different games and platforms on the market with unique behaviors and associated bandwidth needs. Our testing was limited to a small sample of commonly used platforms that we believe is representative of typical live gaming, although exceptions likely exist.

Live Streaming

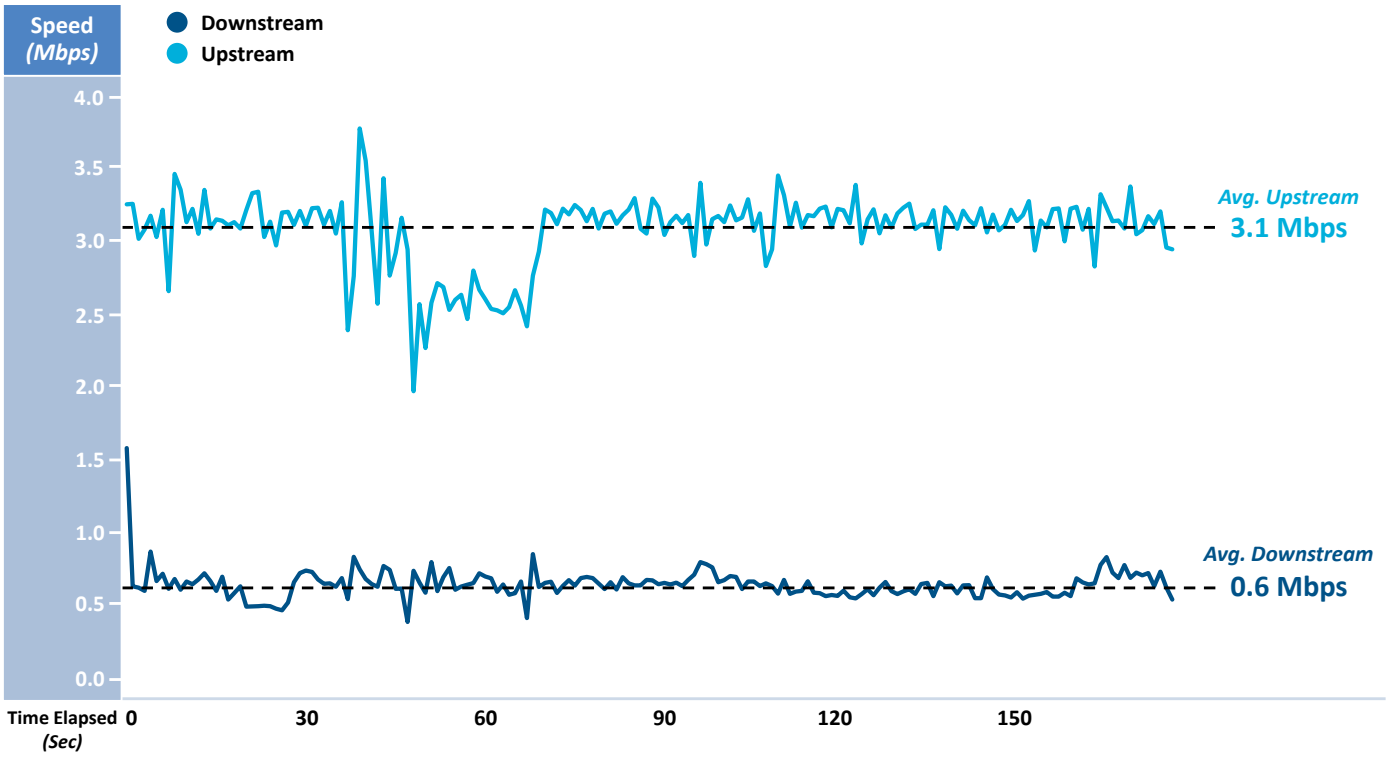
Live streaming is similar to video conferencing in that a consistent minimum level of connectivity is needed to support the real-time stream without interruption. However, there are two key differences.

First, the end user rarely consumes downstream content and transmits upstream content simultaneously. For example, when an Instagram user live streams a feed to their followers, the live streamer will primarily only need to transmit their content upstream, while each of the followers watching the live stream will only need to receive the content downstream.

Second, the quality standards and associated bandwidth recommendations are often greater than those of video conferencing. For example, the stream quality expectations and associated bandwidth recommendations for an end-user watching a live sports stream on large television are much greater than those of a typical video conference.

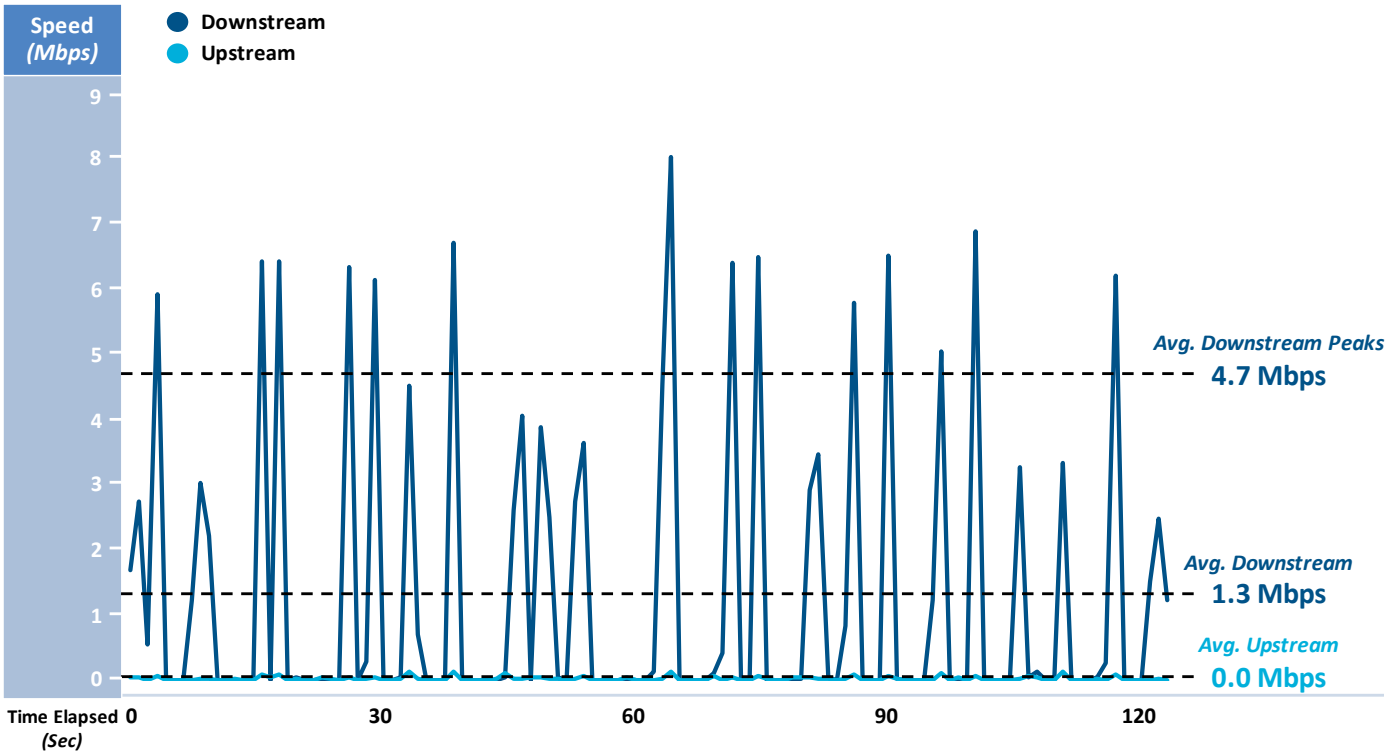
Our tests covered both unique use cases for live streaming. For livestream content broadcast which includes upload of live video content to the cloud, the results show fairly consistent upstream and downstream bandwidth demand, averaging 3.1 and 0.6 Mbps respectively. Watching content that is is streamed live was characterized by substantial peaks of downstream bandwidth consumption and negligible upstream usage.

FIGURE 14. BANDWIDTH USED DURING LIVESTREAM VIDEO BROADCAST



Source: Cartesian

FIGURE 15. BANDWIDTH USED DURING LIVESTREAM VIDEO VIEWING



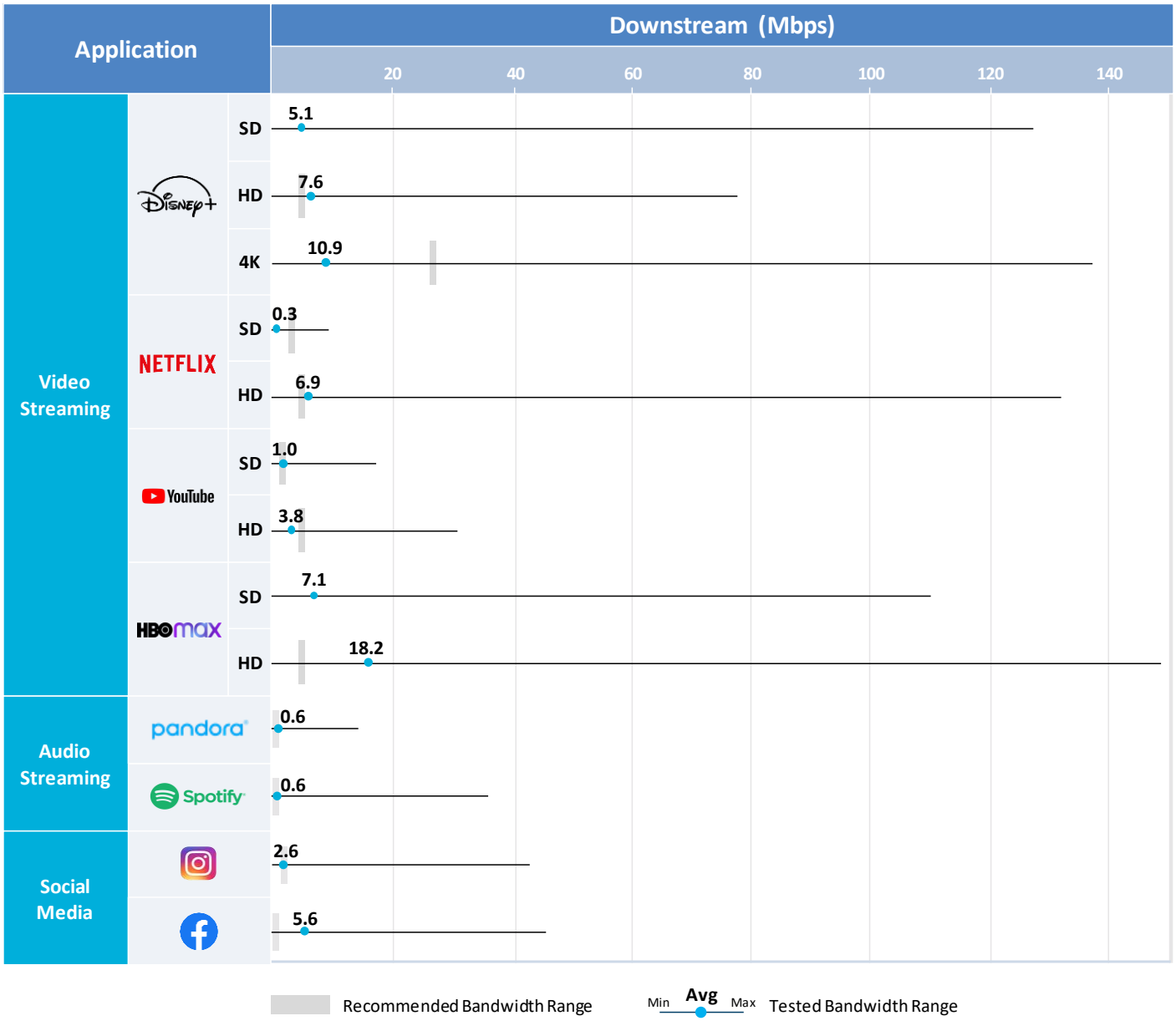
Source: Cartesian

2 Content Streaming

Content streaming recommendations vary by application and stream quality, with 4K video streaming suggesting substantially more downstream bandwidth than every other type of stream. Across all streaming applications tested, we found that it is common to have peaks of downstream bandwidth that are significantly higher than the averages. This behavior is consistent with the applications downloading and caching a large piece of the content well before it is required to be delivered to reduce the likelihood of buffering, which is not possible for live streams.

For a sample of common applications across the three content streaming subcategories, we compared the average, maximum, and minimum downstream and upstream bandwidth used to the recommended bandwidth ranges published by application developers.

FIGURE 16: CONTENT STREAMING APPLICATION RECOMMENDED BANDWIDTH AND TEST RESULTS[26]



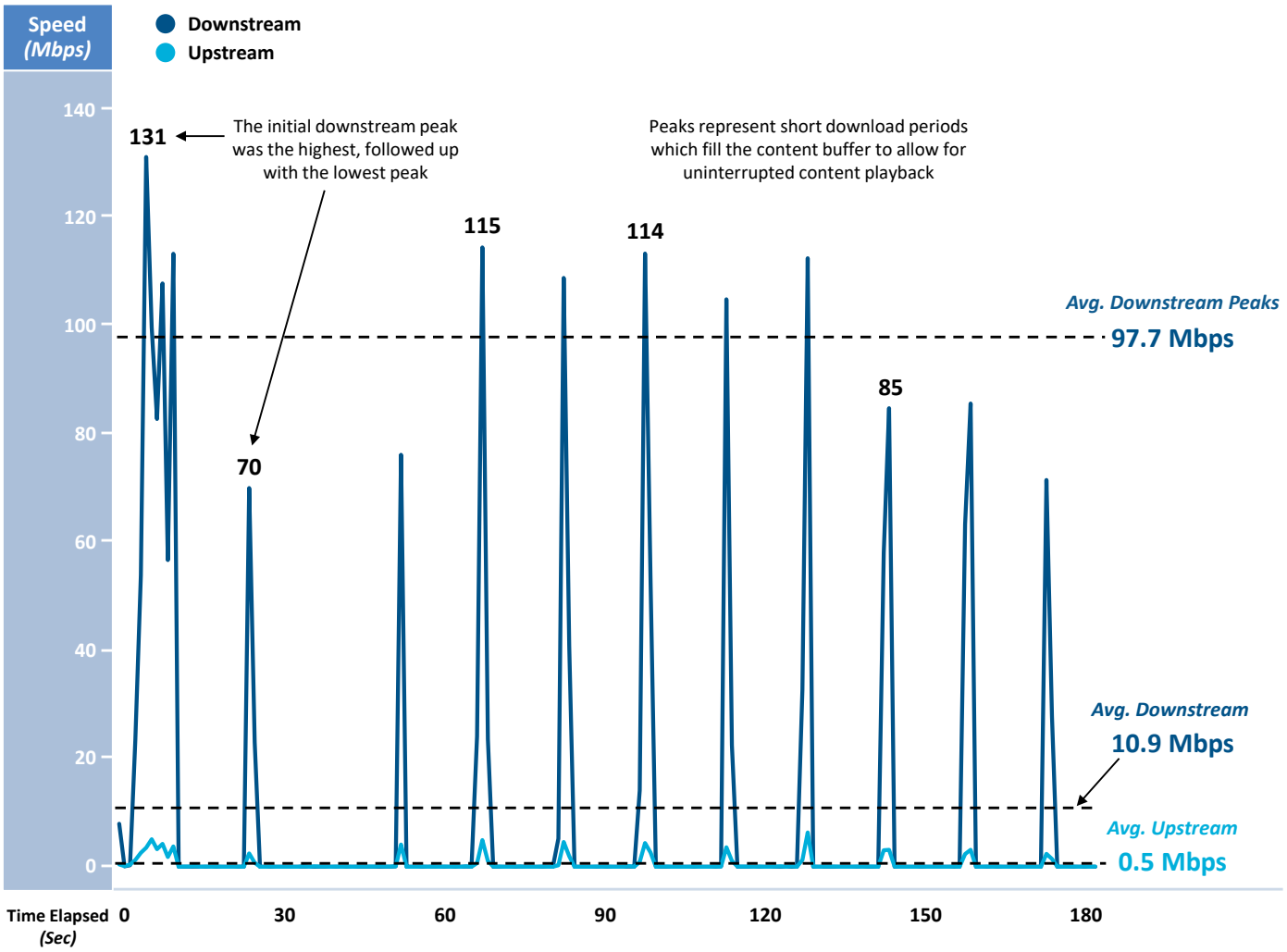
Sources: Cartesian, Application websites

Most content streaming applications in practice require an average of 10.9 Mbps downstream or less. HBO Max's HD stream was an exception, averaging 18.9 Mbps downstream. These applications often use bandwidth in "bursts" to load and cache content to fill the buffer, bandwidth permitting. On faster connections, these bursts were observed to be as high as 130 Mbps. However, the applications use little to no data in between bursts, resulting in a much lower overall average downstream bandwidth. The upstream usage was extremely low – each application only used an average of 0-0.5 Mbps across our tests.

4K streaming specifically also proved to be more efficient in practice than recommendations suggest. Disney+ recommends a downstream speed of 25.0 Mbps to watch 4K content, but our tests only used an average of 10.9 Mbps downstream with periodic bursts.

For example, during the Disney+ 4K stream shown in Figure 17, there was an initial burst of content downloaded early in the stream and continuing for approximately 10 seconds, peaking at 131 Mbps. After this initial large burst, subsequent bursts occurred approximately every 30 seconds, lasted 3-5 seconds, and averaged 97.7 Mbps. No downstream bandwidth was utilized between these bursts, leaving more bandwidth available for other applications on the network if needed. In Section 3, we show that 4K streams behave differently when there is no excess bandwidth available on the network.

FIGURE 17: BANDWIDTH USED WHILE WATCHING A 4K VIDEO STREAM



Source: Cartesian

3 File Transfers

The downstream and upstream bandwidth used for file transfers, including cloud storage, depends on the amount of available bandwidth. In our testing, we found that when downloading or uploading a large file, the activity would consume large proportions of any available downstream or upstream bandwidth on a network. For example, when downloading a 295 MB file, we found that Dropbox and Google Drive used 110-120 Mbps when bandwidth was available (i.e., 20-30 seconds to complete the download), and used 35-40 Mbps when less bandwidth was available(i.e., 90 seconds to complete the download).

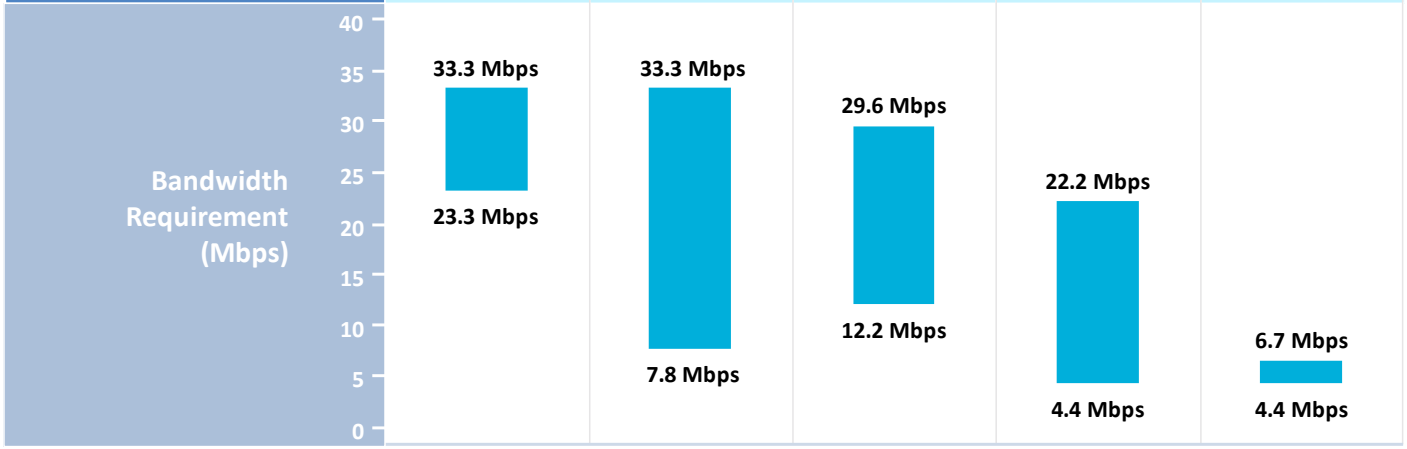
In some circumstances, applications will automatically limit bandwidth, or allow users to configure bandwidth limitations, to reduce the likelihood that large file transfers will cause a network disruption by preventing other applications from obtaining sufficient bandwidth. For example, Dropbox allows end users to set maximum downstream bandwidth rates, and by default applies dynamic upstream limitations that can be overridden with a user selection. Similarly, iDrive, a common cloud file backup application, defaults to throttling file transfers at 25% of the available bandwidth when the computer is in use but relaxes this constraint when the computer is not in use, allowing 100% bandwidth utilization.

Accordingly, we took an alternative approach compared to real-time and content streaming applications in order to determine the required bandwidth for the file transfer application category. We identified several benchmarks informed by consumer research that specify what a typical person would consider to be a reasonable amount of time to complete different types of file transfers (e.g., complete an iPhone update, download a large video game).[30] We then estimated, using a typical range of file sizes, the amount of downstream and upstream bandwidth required to complete the file transfers within the "reasonable time frame".

The results in Figure 18 show that the downstream and upstream bandwidth required to complete five typical scenarios during a "reasonable time frame" ranges from 4.4 to 33.3 Mbps depending on activity.

FIGURE 18. BANDWIDTH REQUIREMENTS FOR FILE TRANSFERS

Application/Activity	Google Drive, Dropbox		Game Download	iCloud Backup	iPhone Update
	Download	Upload			
Reasonable Time Frame[29]	2 – 10 min	2 – 30 min	45 min – 24 hours	30 min – 2 hours	30 min – 1 hour
Typical Size[29]	500 MB – 1.75 GB	500 MB – 1.75 GB	10 GB – 165 GB	5 – 20 GB	1.5 – 2 GB



Sources: Cartesian, Consumer Research

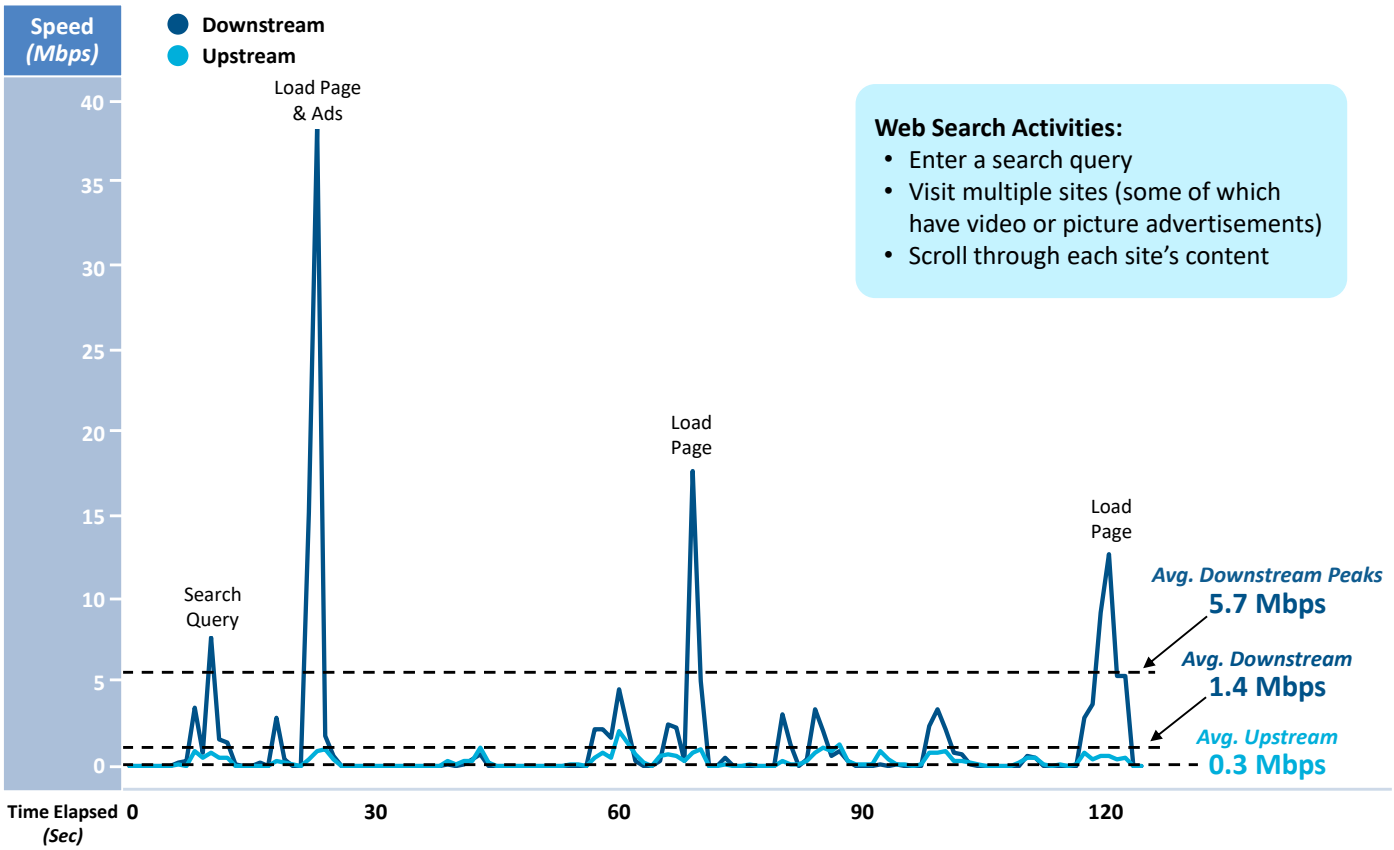
There are certainly exceptions that fall outside the scenarios outlined in Figure 18. For example, a popular game downloaded in 2020 was 'Call of Duty: Modern Warfare', which is approximately 250 GB in size, about 50% larger than the typical size game download in our research. Additionally, heavy users of cloud storage or VPNs for certain media use cases with large files sizes (e.g., video editing) may require more bandwidth to sync files quickly.

4 Low Intensity

The first three application categories cover all common bandwidth-intensive use cases. Applications that typically have lighter bandwidth needs include web browsing, non-video social media, email, web-based software as a service (SaaS) applications, and non-video smart home devices.

We found that a typical bandwidth range for web browsing is 0.1 Mbps to 5.0 Mbps, depending on the activity. Peaks generally occur when a new page is loaded, with the bandwidth utilization being a function of the amount of content that needs to be downloaded to render the page (e.g., images, videos, advertisements, JavaScript, CSS) and the amount of time the page takes to load. For example, one test on several news pages that contain many advertisements and videos near the top of the page found that an average downstream speed of 4.3 Mbps was used to load the pages quickly with no perceptible lag on a desktop computer, while 1.4 Mbps was used to load the mobile site versions. If less bandwidth was available, these pages and associated media would likely take longer to load. Similar trends were observed on non-video social media, email excluding file transfers, and web-based SaaS applications.

FIGURE 19. WEB SEARCHING AND BROWSING ON MOBILE PHONE TEST EXAMPLE



Source: Cartesian

Household Connectivity Bandwidth Scenarios

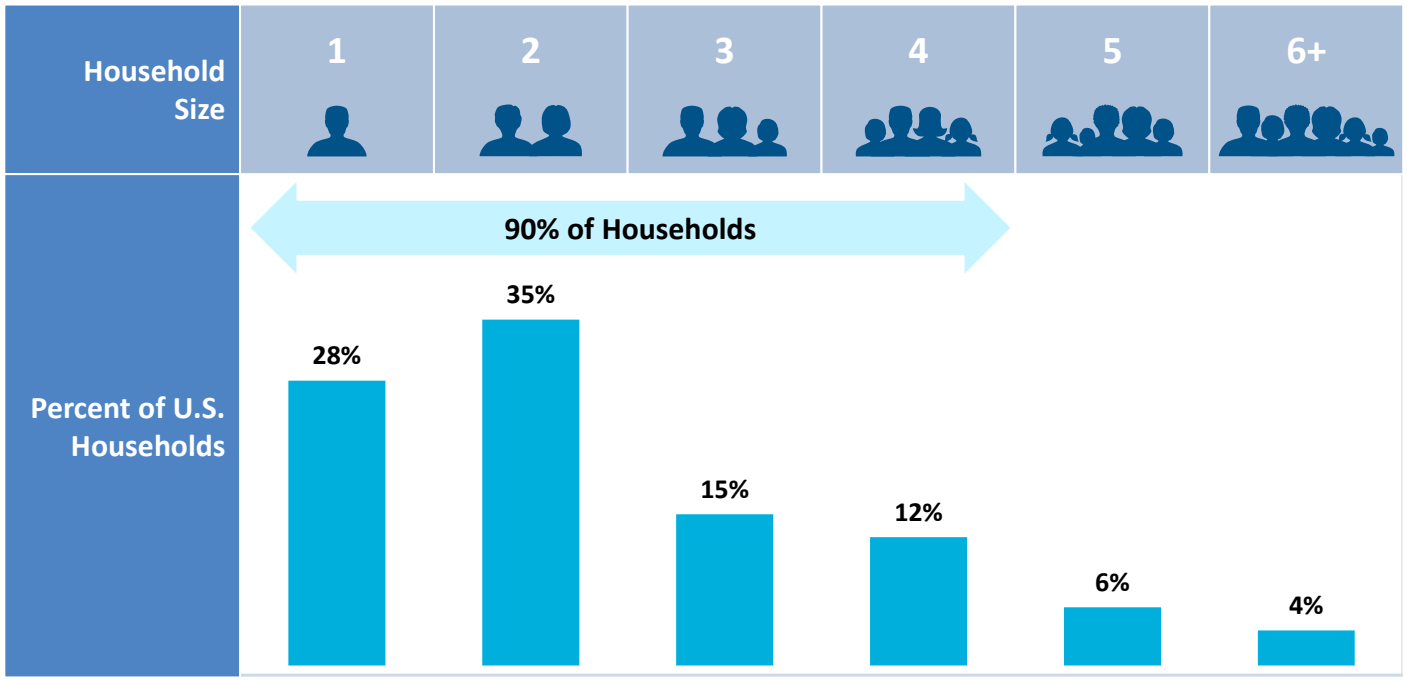
Cartesian®

MULTI-DEVICE CONNECTIVITY SCENARIOS REQUIRE MODERATE BANDWIDTH

3.1 Four-Member Household Multi-Device Scenarios

Many real-world scenarios for typical US households involve multiple users, devices and applications all competing for bandwidth at the same time. In this section, we summarize the test results for two multi-device usage scenarios that were focused on entertainment and video conferencing use cases. The scenarios were designed to represent demand for four-member households, as 90% of US households are comprised of 1-4 members.

FIGURE 20. DISTRIBUTION OF US HOUSEHOLDS BY SIZE



Source: US Census

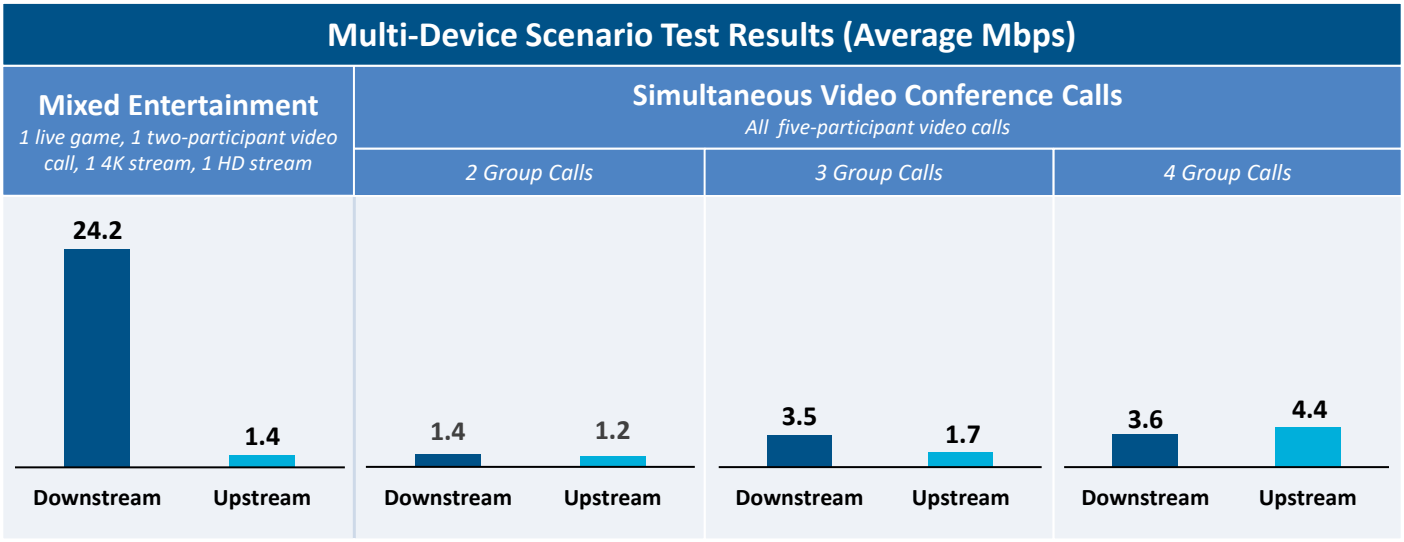
Our two scenarios were:

- **Mixed Entertainment**: Concurrent usage of 1 4k video stream, 1 HD video stream, 1 video conference call with two participants, 1 live online game
- **Simultaneous Video Conference Calls**: 2, 3, and 4 simultaneous video conference calls, each with five participants (three tests conducted in total)

We designed the scenarios to represent the bandwidth demand for typical US households during high usage situations (i.e., when all members are actively using the internet), though they are not intended to be exhaustive. File transfers were not considered due to their variability of bandwidth needs, as discussed in Section 2.3.

We conducted these tests using a router with connection speeds of approximately 200/20 Mbps, and for each test we captured the downstream and upstream bandwidth consumed by the router throughout the duration of the test (see Methodology in Appendix III). We selected the connection speed used to examine the level of bandwidth in different household scenarios without constraints, presenting a clear picture of bandwidth needed by different applications need to operate comfortably.

FIGURE 21. FOUR-MEMBER HOUSEHOLD SCENARIO RESULTS



Source: Cartesian

The mixed entertainment scenario was downstream intensive, in line with our expectations based on single-application test results. We observed an average of 24.2 Mbps in downstream bandwidth usage and 1.4 Mbps in upstream bandwidth usage, with a 17x downstream to upstream ratio. Downstream usage had intermittent peaks as high as 42.4 Mbps, while upstream usage remained relatively consistent and low throughout the test.

Testing two concurrent video calls with five participants on each call required average bandwidth of 1.4 Mbps downstream and 1.2 Mbps upstream. We noted that when additional concurrent group video calls were added on the same network, overall bandwidth consumption did not increase linearly. For example, when a third group video call was added, overall downstream bandwidth increased 150% to 3.5 Mbps and upstream bandwidth increased 42% to 1.7 Mbps. When a fourth group video call was added, overall downstream bandwidth increased only 3% to 3.6 Mbps, while upstream bandwidth increased 159% to 4.4 Mbps. These finding suggest that many factors beyond the number of applications running – such as hardware, operating systems, network conditions – can influence actual bandwidth requirements.

The average bandwidth consumed in both multi-device scenarios was lower than what would be expected based on collectively summing each application's standalone requirements. These results suggest that applications can behave differently when used simultaneously as compared to individually, and oftentimes only require moderate bandwidth speeds to carry out common household activities.

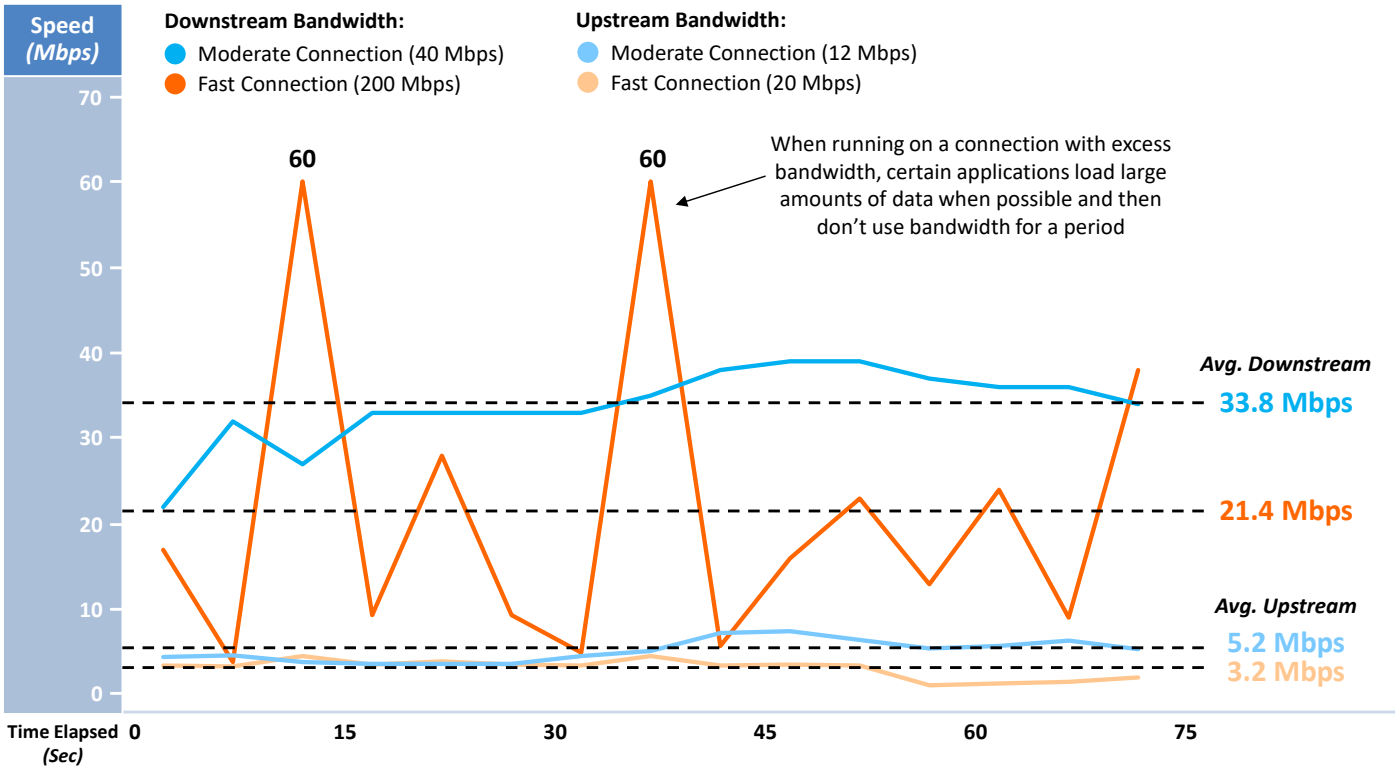
3.2 Comparing Multi-Device Scenario Performance on Different Connection Speeds

In a separate series of tests, we examined how a six-device entertainment scenario performed when run on two different internet connection speeds. Our objective was to compare how bandwidth on the network was utilized under different bandwidth availability constraints with even more competing traffic than was present in the four-member household tests.

The scenario included two live games, two group video conference calls, one 4K stream, and one HD stream occurring simultaneously, and this test was completed on connection speeds of 200/20 Mbps (i.e., "Fast Connection") and 40/12 Mbps (i.e., "Moderate Connection").

We found that the fast connection displayed volatile downstream bandwidth usage with intermittent peaks of up to 60 Mbps during the test, while the moderate connection had more consistent downstream bandwidth usage. The fast connection had lower bandwidth usage overall, with an average of 21.4 Mbps downstream and 3.2 Mbps upstream, while the moderate connection rarely deviated from the average of 33.8 Mbps downstream and 5.2 Mbps upstream. On both connections, the quality of user experience appeared similar.

FIGURE 22. SIX ENTERTAINMENT APPLICATIONS TEST ON TWO DIFFERENT CONNECTION SPEEDS



Source: Cartesian

The difference in bandwidth utilized throughout each test suggests that the applications were likely adapting to available bandwidth to deliver a consistent experience as described in Section 1.3.

Additionally, we saw more efficient bandwidth usage on the faster connection which had an average downstream speed of 21.4 Mbps compared to 33.8 Mbps on the moderate connection. This difference in efficiency can result from several variable factors, including the ability of applications to adapt to changing conditions particularly when multiple devices are competing for available bandwidth. On lower connection speeds and when less total bandwidth is available, some applications can operate in an unfettered "greedy" mode, resulting in higher total bandwidth consumed.

CONCLUSION

Amidst rapidly changing home internet habits due to the pandemic, we researched how demand for high-speed internet has evolved over time and conducted a series of tests to examine the typical bandwidth needs of US households today. In Section 1, we explored the drivers behind the continued growth in broadband demand and summarized the ways technological advancements are improving how applications utilize bandwidth efficiently. In Sections 2 and 3, we summarized the key insights from our testing of single and multi-device scenarios which demonstrated how the most common internet applications consume bandwidth, both in isolation and in simulated multi-user household environments.

We found that the most common applications typically needed more downstream bandwidth than upstream. For example, in one scenario reflective of concurrent household usage of entertainment applications, we observed an average downstream bandwidth of 24.2 Mbps and average upstream bandwidth of 1.4 Mbps, an overall ratio of approximately 17:1.

In line with recent technological innovations, we found that applications tended to adjust their bandwidth usage in response to changing network availability. Single-application tests also commonly resulted in lower bandwidth needs than recommended by the application publishers. These efficiencies were also observed in our multi-device scenarios, resulting in moderate bandwidth consumption overall, and all scenarios we tested required bandwidth levels that fall within the range of speeds commercially available to most US households.

It is important to note that connection speeds and bandwidth availability are not the only factors affecting home internet performance. Reliability is a critical factor to ensure bandwidth demands can be met without interruption. To serve household needs, connectivity services need to operate reliably throughout a user's home, in addition to delivering sufficient speeds for typical usage scenarios. Delivering consistent and uninterrupted connectivity to households should remain a focus for both ISPs and policymakers.

Appendix

APPENDIX I: PUBLISHED BANDWIDTH RECOMMENDATIONS BY APPLICATION

Category	Subcategory	Application	Downstream (Mbps)	Upstream (Mbps)	Latency	Source
Video Conferencing	1-on-1	Zoom	1.2	1.2	<50-150ms	*Zoom Support Pages*
		Microsoft Teams	1.5	1.0	<150ms	*Microsoft Teams Support Pages*
		Cisco Webex	1.0	1.5	--	*Webex Help Pages*
		Google Hangouts	2.6	3.2	<50ms	*Google Support Pages*
		Messenger Rooms	*Not available*		--	*bandwidthplace.com*
		Skype	1.5	1.5	<100ms	*Skype Support Pages*
		WhatsApp	1.2	1.2	--	*top10voiplist.com*
		Average	**1.5**	**1.6**	**<100ms**	
	Group	Zoom (single screen)	2.0	2.0	<50-150ms	*Zoom Support Pages*
		Zoom (dual screen)	4.0	2.0	<50-150ms	*Zoom Support Pages*
		Zoom (triple screen)	6.0	2.0	<50-150ms	*Zoom Support Pages*
		Microsoft Teams	2.0	1.5	<150ms	*Microsoft Teams Support Pages*
		Cisco Webex	2.5	3.0	--	*Webex Help Pages*
		Google Hangouts	4.0	3.2	<50ms	*Google Support Pages*
		Messenger Rooms	3.0	1.0	--	*bandwidthplace.com*
		Skype	8.0	1.5	<100ms	*Skype Support Pages*
		WhatsApp	4.0	1.2	--	*top10voiplist.com*
		Average	**4.2**	**1.9**	**<100ms**	
	Telemedicine	Doxy.me	0.4	*Not available*	--	*Doxy.me Help Pages*
		Vsee	0.6	0.7	--	*vsee.com/vidyo*
		AmWell	1.6	1.6	--	*vsee.com/vidyo*
		healow	2.0	2.0	--	*skinsolutionsderm.com*
		Average	**1.2**	**1.4**	**--**	
	Education	Blackboard	1.5	1.5	**--**	*ualr.edu*
	Fitness	Peloton	15.0	2.5	**--**	*Peloton Support Pages*
Live Gaming	Console Gaming	PlayStation	3.0	1.0	<150ms	*androidcentral.com*
		Xbox Live	3.0	0.5	<150ms	*highspeedinternet.com*
		Nintendo Switch	3.0	1.0	<150ms	*highspeedinternet.com*
	PC Gaming	Steam	25.0	0.04	--	*gameaccessory.com, Research Gate*
	Cloud Gaming	Google Stadia (720p)	10.0	*Not available*	--	*Stadia Help Pages*
		Google Stadia (4K)	35.0	*Not available*	--	*Stadia Help Pages*
	VR	Early Stage VR	25.0-50.0	*Not available*	<40ms	*venturebeat.com, Research Gate*
		Average	**18.4**	**0.6**	**<123ms**	
Live Streaming	Video Live Streaming	Instagram Live	--	1.0	--	*wearelive.nu*
		Facebook Live	--	4.0	--	*wearelive.nu*
		YouTube Live	--	7.4	--	*restream.io*
		Vimeo Live	--	5.0	--	*Vimeo Live FAQs*
	Gaming	Twitch Streaming	--	6.2	--	*restream.io*
	Smart Home	Ring	2.0	2.0	--	*getunwired.com*
		Average	**2.0**	**4.3**	**--**	
Video Streaming	SD 480p	YouTube	1.1	--	--	*Google Support Pages*
		Netflix	3.0	--	--	*Netflix Help Pages*
		Peacock	2.5	--	--	*Peacock TV Help Pages*
		Hulu	1.5	--	--	*Hulu Help Pages*
		Prime Video	1.0	--	--	*highspeedinternet.com*
		Average	**1.8**	**--**	**--**	
	HD 720p	YouTube	2.5	--	--	*Google Support Pages*
		Hulu	3.0	--	--	*Hulu Help Pages*
		Average	**2.8**	**--**	**--**	
	HD 1080p	YouTube	5.0	--	--	*Google Support Pages*
		Netflix	5.0	--	--	*Netflix Help Pages*
		Hulu	6.0	--	--	*Hulu Help Pages*
		HBO	5.0	--	--	*allconnect.com*
		Prime Video	5.0	--	--	*highspeedinternet.com*
		Disney+	5.0	--	--	*highspeedinternet.com*

		AppleTV+	8.0	--	--	*highspeedinternet.com*
		Twitch	4.0	--	--	*highspeedinternet.com*
		Average	**5.4**	**--**	**--**	
	4K	YouTube	20.0	--	--	*Google Support Pages*
		Netflix	25.0	--	--	*Netflix Help Pages*
		Hulu	16.0	--	--	*Hulu Help Pages*
		Disney+	25.0	--	--	*highspeedinternet.com*
		AppleTV+	25.0	--	--	*highspeedinternet.com*
		Average	**22.2**	**--**	**--**	
Social Media	**N/A**	Facebook	0.3	--	--	*wirefly.com*
		Instagram	2.7	--	--	*whistleout.com*
		TikTok	1.9	--	--	*whistleout.com*
		Twitter	0.8	--	--	*canstarblue.com*
		Average	**1.4**	**--**	**--**	
Audio Streaming	**Music Streaming**	Spotify	0.3	--	--	*highspeedinternet.com*
		Pandora	0.3	--	--	*highspeedinternet.com*
		Apple Music	0.3	--	--	*highspeedinternet.com*
		YouTube Music	0.3	--	--	*highspeedinternet.com*
		Average	**0.3**	**--**	**--**	
Low Intensity	**Web Browsing**	Web Browsing	1.0	--	--	*cbtnuggets.com*
	Non-Video Smart Home	Smart Home Per 12 Devices	5.0	--	--	*smartnutter.com*

Note: Facetime does not provide listed bandwidth requirements

APPENDIX II: SINGLE APPLICATION TESTS

Methodology

We tested the actual bandwidth usage for a sample of applications. Tests were conducted over Wi-Fi 5 on a Gigabit-speed connection according to the following methodology:

- The tests were run on a symmetrical gigabit connection, and a speed test was recorded prior to each test.
- A trial test was run to configure the application, ensure everything was running as expected, and check no other devices were consuming a significant amount of bandwidth on the connection.
- All applications on the test device were closed, with the exception of the application being tested.
- During the test, the tested application was used in a manner consistent with typical use cases.
- Packet activity from the application was tracked in 1 second intervals for 90 seconds using Wireshark.
- Activity data was analyzed to determine the following statistics: Average, minimum, and maximum upstream and downstream bandwidth consumption; the average for upstream and downstream "peaks".

Tests were conducted on the following device types: mobile phones, laptops, smart TVs, and gaming consoles.

Application Category	Application	Average		Other Summary Statistics					
		Downstream (Mbps)	Upstream (Mbps)	Downstream (Mbps)			Upstream (Mbps)		
				Min	*Peak Avg.*	*Max*	*Min*	*Peak Avg.*	*Max*
Two-participant Video Conferencing	**Zoom**	1.5	0.3	0.1	1.5	2.2	0.1	--	0.7
	Microsoft Teams	1.2	1.4	0.2	2.0	2.6	0.9	1.4	3.0
	Facetime	2.1	1.9	0.5	2.0	2.3	0.5	2.1	2.4
Group Video Conferencing	**Zoom**	2.1	0.5	1.4	2.1	2.4	0.3	1.2	1.3
	Microsoft Teams	3.7	1.7	2.4	3.7	6.7	1.2	1.7	2.4
	Facetime	1.1	0.9	0.5	1.3	1.4	0.6	1.0	1.1
Telemedicine	**Doxy.me**	0.9	0.8	0.7	--	1.1	0.6	--	1.0
Live Gaming	**Xbox Live**	1.5	0.1	0.0	5.9	7.6	0.0	--	0.3
	Steam Live	0.8	0.4	0.5	1.6	4.5	0.2	1.2	1.5
Live Streaming (Content creation)	**YouTube**	0.6	3.1	0.4	1.6	1.6	2.0	3.1	3.8
	Instagram	0.1	0.7	0.0	--	0.3	0.5	1.0	1.0
	Ring	0.1	1.3	0.1	--	0.1	1.1	1.3	1.4
SD Video Streaming	**YouTube**	1.0	0.0	0.0	3.4	17.7	0.0	--	0.6
	Netflix	0.3	0.0	0.0	9.7	11.3	0.0	1.2	1.2
	Disney+	5.1	0.1	0.0	54.6	129.1	0.0	1.4	1.6
	HBO	7.1	0.0	0.0	70.5	109.2	0.0	1.0	1.0
HD Video Streaming	**YouTube**	3.8	0.0	0.0	14.9	30.3	0.0	--	0.0
	YouTube (Live Sports)	1.3	0.0	0.0	4.7	8.0	0.0	--	0.1
	Netflix	6.9	0.1	0.0	39.7	126.6	0.0	1.2	1.4
	Disney+	7.6	0.4	0.0	22.2	74.4	0.0	1.7	3.2
	HBO	18.2	0.0	0.0	43.7	149.3	0.0	0.0	0.0
4K Video Streaming	**Disney+**	10.9	0.5	0.0	97.7	131.4	0.0	3.0	6.4
Social Media	**Facebook**	5.6	0.0	0.0	21.2	43.4	0.0	--	0.0
	Instagram	2.6	0.1	0.0	19.2	40.8	0.0	--	0.9
Music Streaming	**Spotify**	0.6	0.0	0.0	31.4	36.1	0.0	--	0.0
	Pandora	0.6	0.1	0.0	9.0	14.7	0.0	--	0.8
Web Browsing	**Google Search (Phone)**	1.4	0.3	0.0	13.0	38.4	0.0	1.4	2.1
	Google Search (Computer)	4.3	0.0	0.0	12.9	43.1	0.0	--	0.0

Notes: The group Zoom calls had nine participants, the group Teams call had 14 participants, and the group Facetime call had three participants; Peaks for video conferencing, live gaming, and live streaming were defined as >1 Mbps; Peaks for video streaming, social media, music streaming and web browsing were determined on a case by case basis; Applications with multiple use cases like Instagram and Facebook were used in a variety of ways over the course of the test (i.e., liking content, watching videos, and loading profiles)

APPENDIX III: MULTI-DEVICE TEST RESULTS

Methodology

We tested the actual bandwidth usage for a series of multi-device household scenarios. Tests were conducted over Wi-Fi 5 on a with the following methodology:

- A speed test was recorded prior to the test.
- A trial test was run to configure the applications and check no other devices were consuming a significant amount of bandwidth on the connection. In cases where the final test results were notably different from the trial run, the test was repeated to verify results.
- All applications on the test devices were closed, with the exception of the applications of interest.
- During the test, the tested applications were used in a manner consistent with typical use cases.
- Overall household downstream and upstream bandwidth was tracked in 5 second intervals from the Google Nest router for approximately 90 seconds using the Google WiFi App.
- Activity data was analyzed to determine the following statistics: Average, minimum, and maximum upstream and downstream bandwidth consumption.

We conducted tests on the following device types: mobile phones, laptops, tablets, smart TVs, and gaming consoles.

Applications Tested	Scenario Type	Devices in Test	Connection Speed	Traffic	Test Minimum (Mbps)	Test Average (Mbps)	Test Maximum (Mbps)
2 Group Video Calls	Video Conferencing	2	Fast	Down	0.7	1.4	2.1
				Up	0.8	1.2	2.6
3 Group Video Calls	Video Conferencing	3	Fast	Down	1.8	3.5	4.8
				Up	0.8	1.7	2.6
4 Group Video Calls	Video Conferencing	4	Fast	Down	3.0	3.6	4.7
				Up	3.8	4.4	5.5
1 4k Video Stream, 1 Live Game, 1 HD Video Stream, 1 Video Call	Mixed Entertainment	4	Fast	Down	8.6	24.2	42.4
				Up	1.2	1.4	1.7
1 4K Video Stream, 1 Live Game	Mixed Entertainment	2	Moderate	Down	3.2	19.5	37.0
				Up	0.6	1.6	3.5
1 Video Call, 2 HD Video Streams	Mixed Entertainment	3	Moderate	Down	3.9	23.9	34.0
				Up	2.5	3.0	4.1
1 4K Video Stream, 2 Video Calls, 1 Live Game	Mixed Entertainment	4	Moderate	Down	3.1	19.1	38.0
				Up	4.5	5.8	9.3
1 4K & 1 HD Video Stream, 2 Video Calls, 2 Live Games	Mixed Entertainment	6	Fast	Down	3.9	21.4	60.0
				Up	1.2	3.2	4.6
1 4K & 1 HD Video Stream, 2 Video Calls, 2 Live Games	Mixed Entertainment	6	Moderate	Down	22.0	33.8	39.0
				Up	3.6	5.2	7.5
1 4K & 1 HD Video Stream, 4 Video Calls	Mixed Entertainment	6	Fast	Down	6.8	31.1	66.0
				Up	5.3	8.2	10.0
2 HD Video Streams	Video Streaming	2	Moderate	Down	1.5	19.2	33.0
				Up	0.1	0.5	1.3
6 HD Video Streams	Video Streaming	6	Moderate	Down	31.0	37.6	39.0
				Up	2.0	2.9	3.8

References

[1] CommScope. “Managing the Coronavirus Bandwidth Surge: How to Cope with the Spikes and Long-term Growth (2020)”. https://www.nctatechnicalpapers.com/Paper/2020/2020-managing-the-coronavirus-bandwidth-surge

[2] Reardon, Marguerite. “Coronavirus Has Made Peak Internet Usage into the New Normal.” CNET. CNET, March 23, 2020. https://www.cnet.com/news/coronavirus-has-made-peak-internet-usage-into-the-new-normal/.

[3] Speedtest.net. “Monthly Comparisons of Internet Speeds from around the World.” Speedtest Global Index. Ookla. Accessed December 8, 2020. https://www.speedtest.net/global-index.; “Akamai Announces First Quarter 2010 State Of The Internet Report.” Akamai, July 27, 2010. https://www.akamai.com/us/en/about/news/press/2010-press/akamai-announces-first-quarter-2010-state-of-the-internet-report.jsp.

[4] CommScope. “Managing the Coronavirus Bandwidth Surge: How to Cope with the Spikes and Long-term Growth (2020)”. https://www.nctatechnicalpapers.com/Paper/2020/2020-managing-the-coronavirus-bandwidth-surge

[5] "Broadband 2021: Where Are All the Subs Coming From?". Moffett Nathanson, December 16, 2020.

[6] Saperstein, Mike, “Broadband Investment Remains High in 2019,” USTelecom, December 23, 2020, https://www.ustelecom.org/research/broadband-investment-remains-high-in-2019/; Rep. 2020 Broadband Deployment Report. Federal Communications Commission, April 24, 2020. https://docs.fcc.gov/public/attachments/FCC-20-50A1.pdf.

[7] “Successful Rural Digital Opportunity Fund Auction To Expand Broadband To Over 10 Million Rural Americans.” FCC Auction to Bring Broadband to Over 10 Million Rural Americans. Federal Communications Commission, December 7, 2020. Federal Communications Commission. https://docs.fcc.gov/public/attachments/DOC-368588A1.pdf.

[8] Deloitte Survey: Connectivity Cravings Drive Consumer Appetite for 5G, Home Automation, and More Control of Personal Data. Deloitte, December 4, 2019. https://www2.deloitte.com/us/en/pages/about-deloitte/articles/press-releases/deloitte-launches-connectivity-mobile-trends-survey.html#:~:text=US%20households%20have%20an%20average,smart%20screens%20to%20view%20content.'.

[9] Rep. The Global Internet Phenomena Report COVID-19 Spotlight. Sandvine, May 2020. https://www.sandvine.com/hubfs/Sandvine_Redesign_2019/Downloads/2020/Phenomena/COVID%20Internet%20Phenomena%20Report%2020200507.pdf.

[10] Stanford Research Provides a Snapshot of a New Working-from-Home Economy. Stanford University, June 29, 2020. https://news.stanford.edu/2020/06/29/snapshot-new-working-home-economy/.

[11] Landi, Heather. “Half of Physicians Now Using Telehealth as COVID-19 Changes Practice Operations.” FierceHealthcare, April 23, 2020. https://www.fiercehealthcare.com/practices/half-physicians-now-using-telehealth-as-covid-changes-practice-operations.

[12] Back to school statistics. National Center for Education Statistics (NCES). Accessed December 15, 2020. https://nces.ed.gov/fastfacts/display.asp?id=372.

[13] 78% Of US Households Have an SVOD Service. Leichtman Research Group, August 28, 2020. https://www.leichtmanresearch.com/78-of-u-s-households-have-an-svod-service/.

[14] Freeletics Surveys Americans to Uncover What is in Store for the Fitness Industry Post-COVID-19. Freeletics, July 15, 2020. https://www.freeletics.com/en/press/news/freeletics-surveys-americans-to-understand-what-is-in-store-for-the-fitness-industry-post-covid-19/.

[15] Rachel, King. Most Americans Plan to Continue at-Home Workouts Even Once Gyms Fully Reopen. Fortune, August 17, 2020. https://fortune.com/2020/08/17/covid-workouts-at-home-gyms-reopening-coronavirus-fitness/.; SWNS. Most Americans Believe Gyms Will Become Thing of the Past after Coronavirus. July 16, 2020. https://nypost.com/2020/07/16/survey-says-the-at-home-workout-is-here-to-stay-even-if-covid-19-disappears/.

[16] Martin, Chuck. Smart Home Technology Hits 69% Penetration in US. MediaPost, September 19, 2019. https://www.mediapost.com/publications/article/341320/smart-home-technology-hits-69-penetration-in-us.html#:~:text=The%20majority%20(69%25)%20of,Consumer%20Technology%20Association%20(CTA).

[17] "How QoS Improves Performance." NETGEAR Support. NETGEAR, November 28, 2016. https://kb.netgear.com/972/How-QoS-improves-performance.

[16] "ISO/IEC 23009-1:2012." ISO, May 12, 2014. https://www.iso.org/standard/57623.html.; "HTTP Live Streaming." IETF Tools, August 2017. https://tools.ietf.org/html/rfc8216.

[18] Rep. Bitmovin Video Developer Report 2019. Bitmovin, 2019. https://cdn2.hubspot.net/hubfs/3411032/Bitmovin%20Magazine/Video%20Developer%20Report%202019/bitmovin-video-developer-report-2019.pdf.; Joint Video Team. ITU. Accessed December 16, 2020. https://www.itu.int/en/ITU-T/studygroups/com16/video/Pages/jvt.aspx.

[19] Jones, Welton. "H.264 Video Compression." Haivision. Accessed December 16, 2020. https://www.haivision.com/resources/streaming-video-definitions/h-264/.

[20] Rep. H.264/MPEG-4 AVC Video Compression Tutorial. LSI Logic Corporation, January 2003. http://web.cs.ucla.edu/classes/fall03/cs218/paper/H.264_MPEG4_Tutorial.pdf.

[21] Ohm, Jens-Rainer, and Gary Sullivan. "High Efficiency Video Coding." MPEG High Efficiency Video Coding (HEVC). MPEG, January 2011. https://mpeg.chiariglione.org/standards/mpeg-h/high-efficiency-video-coding.

[22] Rep. Bitmovin Video Developer Report 2019. Bitmovin, 2019. https://cdn2.hubspot.net/hubfs/3411032/Bitmovin%20Magazine/Video%20Developer%20Report%202019/bitmovin-video-developer-report-2019.pdf.

[23] Mavlankar, Aditya, Liwei Guo, Anush Moorthy, and Anne Aaron. "Optimized Shot-Based Encodes for 4K: Now Streaming!" Medium. Netflix Technology Blog, August 28, 2020. https://netflixtechblog.com/optimized-shot-based-encodes-for-4k-now-streaming-47b516b10bbb.; "How Zoom Provides Industry-Leading Video Capacity." Zoom Blog, June 25, 2020. https://blog.zoom.us/zoom-can-provide-increase-industry-leading-video-capacity/.; "NVIDIA Maxine Video Conferencing Platform." NVIDIA Developer, October 16, 2020. https://developer.nvidia.com/maxine.; Shen, Yueshi. "How VP9 Delivers Value for Twitch's Esports Live Streaming." Twitch Blog, December 19, 2018. https://blog.twitch.tv/en/2018/12/19/how-v-p9-delivers-value-for-twitch-s-esports-live-streaming-35db26f6322f/.

[24] Iqbal, Mansoor. Zoom Revenue and Usage Statistics (2020). Business of Apps, October 30, 2020. https://www.businessofapps.com/data/zoom-statistics/.

[25] Warren, Tom. "Google and Microsoft Chase after Zoom with New Features and Free Services." The Verge. The Verge, April 29, 2020. https://www.theverge.com/2020/4/29/21240942/google-meet-free-zoom-response-microsoft-teams-features.

[26] Refer to Appendix I

[27] Refer to Appendix I

[28] Refer to Appendix I and II

[29] Includes Zoom, Cisco, Microsoft Teams, Google Hangouts, Messenger Rooms, Skype, and Whatsapp requirements.

[30] Orland, Kyle. "Despite 100GB Video Games, Average Download Times Are Decreasing." Ars Technica, June 9, 2020. https://arstechnica.com/gaming/2020/06/ars-analysis-were-spending-less-time-downloading-games-on-average/.; "Video Game Download Times around the World Revealed." uSwitch, December 4, 2020. https://www.uswitch.com/broadband/guides/video-game-download-times-around-world/.; Taylor, Joy. How Long Does It Take to Backup an iPhone to iCloud. iMobie, November 10, 2020. https://www.imobie.com/support/how-long-does-icloud-backup-take.htm.; Taylor, Joy. How Long Does the iOS 14 Update Take? iMobie, September 29, 2020. https://www.imobie.com/iphone-tips/how-long-does-the-ios-update-take.htm.; Kotlyarenko, Alice. "All Your Questions about the New IOS 12, Answered." MacPaw, December 17, 2018. https://macpaw.com/how-to/apple-ios-12-update.; Rep. Lower Bandwidth Consumption and Less Waiting with Dropbox Business. Principled Technologies, October 2016. https://www.principledtechnologies.com/clients/reports/Dropbox/Dropbox_large_file_performance_1016.pdf.