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A Survey of the Ability of the Linux Operating System to Support Online Game Execution

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ABSTRACT

Linux has suffered sluggish home user uptake due mainly to the dominance of rivals, and has seen numerous incarnations as a gaming platform fall flat. Gaming is a particularly sensitive application given its intensive bandwidth and system response requirements; these applications therefore place specific demands on the Operating System platform on which game play is supported. In this work, the ability of the Linux operating system to support execution of online games is explored through a survey of the state-of-the-art in this area. Given the recent increase in cloud-based online gaming, it can be concluded that the time is ripe for more widespread Linux uptake, especially in the gaming domain. This is particularly true today given the amount of exposure to Information Technology across society in general, and ongoing deployment of Internet of Things environments: Linux's open source, modular and freely customisable design may therefore not be as daunting as before, and the unique benefits of this platform may be exploited for the experiences it can bring to applications in general and, specific to the context of this work, players in their game play. This paper makes a unique contribution to the field: Although a number of articles are available within the general area of Linux and gameplay, a thorough survey on this issue has not been seen so far. This is therefore the gap to which this paper contributes.

TYPE OF PAPER AND KEYWORDS

Research Review: *cloud service streaming platform, Linux, operating systems (OS), online gaming, Quality of Service (QoS), Quality of Experience (QoE).*

1 LINUX: PRETENDER TO THE THRONE?

"You killed me!? How can you kill me when I've already killed you!?" You are not the most lethal killer in this particular game – latency is. Online gaming and the expected Quality of Experience (QoE) [29] has shone a light on a need for hardware and Operating Systems (OS) which facilitate a gaming experience that is slick and seamless. This is challenging however, due to the resource intensity of gaming applications and growth in the number of online players, together which place significant demand on the speed of network connections and performance optimisations of the OS. Particular OSs are used more widely than others and there is therefore an opportunity for growth in the use of the less frequently deployed systems to allow the unique benefits of other OSs to be explored.

Operating systems, in general, vary in their portability, cost and flexibility. Historically, portability and flexibility were not as important determiners in OS selection. In the early years of online gaming, there were two main competing OSs - Apple Macintosh and Microsoft Windows. Portability was, in the earlier days, of lower importance due to the more limited range of devices on which software could be supported in comparison to today. Furthermore, flexibility was also of lower importance because many users were without the level of knowledge that would lead them to need to customise their OS in response to any specific requirements or desire to optimise operation and performance of the system. The cost to license the more popular OSs was therefore accepted and any advantages associated with portability or flexibility, which could be achieved using other OSs, were ignored. By July 2018, Windows controlled 75.9% of the OS market globally and, since March 2003, Mac has increased its share from 1.8% to 9.5% [82]. Linux, however, in the same period has grown only from 2.2% to 6.2% [82]. This is in spite of its advantages in all areas of portability, cost and flexibility.

A decade ago, there was great hype surrounding the prospect of Linux as an OS capable of supporting online gaming: Loki, a Linux game publisher, for example, found its business in porting Windows-based games to Linux. Indeed, Linux historically has gaming at its roots - early prototypes of Unix were created when Ken Thompson, a computer scientist, became, "*interested in building a system for a game called 'Space Wars' which required a fairly fast response time*" [22]. Over ten years on, however, critics are noting that Linux has not fulfilled this prophecy, giving rise to the question of how suitable it is in supporting gaming applications: Within a few years of its operation (in 2013), Loki, as one example, had ceased trading [45].

The open source quality of Linux and minimal investment required in comparison to its main competition - Windows and Apple Mac - means that certain aspects of the system remain limited: Linux's graphical capabilities, for example, are lacking in sophistication. Nonetheless, Linux is supported by developers: In 2014, the Steam store, "*a digital game store for Windows, Mac and Linux platforms*" [69], hosted 2,759 compatible with the Mac OSX and 1,480 with Linux; in total, there were 9,093 games available [69]. By August 2018, games compatible with Linux had increased to 5,332, indicating that the platform is becoming a more equal contender with Windows, for which there were 5,330 games compatible, and Mac OSX with 4,753.

There are therefore signs that Linux uptake is evolving in gaming to match more closely the world of business and research: Most critical global business servers and mainframes run on UNIX variants [83]. Hollywood film-makers, for example, use Linux for reliability, performance, ease of setup, and cost purposes [46], and the films Titanic and Toy Story were produced using Linux machines. Even astronauts in the International Space Station (ISS) [40] and scientists at the European Organisation for Nuclear Research (CERN) [39] use Linux for its stability and cost benefits. There has been a significant push towards developing Linux as a technical and commercial gaming contender since July 2012 when SteamOS, an operating system specialized to gaming, declared their support for Linux as a gaming platform [69]. The online gaming industry has grown significantly in the last ten years due, in part, to the accessibility of online games [55]. By 2018, the estimated value of the gaming industry is $137.9 billion [66], with up to 661.6 million people expected to be playing games online by 2022 [68].

In this article, the suitability of Linux as a gaming platform is explored, taking into account the change in the nature of games being played, ability of the OS to support such game types, and evolution in the way in which gaming services are being demanded by the expanding and diverse market. Linux's compatibility with more state-of-the-art services in the form of cloud-streamed gameplay are additionally considered. This paper makes a unique contribution to the field: Although a number of articles are available within the general area of Linux and game play, a thorough survey on this issue has not been seen so far. This is therefore the gap to which this paper contributes.

The remainder of this paper continues as follows: In Section 2, the main characteristics of the Linux OS are reviewed in terms of its ability to support online games, and these are placed in context in relation to the other OSs available. These characteristics are also considered in relation to the QoS requirements of typical gaming applications, and the observed state-of-the-art in Linux game play is presented in Section 3. The impacts of cloud technology on game play in general, and the implication of this on use of the Linux platform is discussed in Section 4. This is followed in Section 5 with a discussion of the impact of a lack of marketing of the Linux platform in terms of the limiting effect which this might have had on its audience. Finally, the paper concludes in Section 6.

2 AN OS THAT FITS THE BILL

Linux is an open source OS which has been available since 1991 [41]. Compared to an OS like Windows for example, Linux is not a 'one-size-fits-all' system [11] and, by August 2018, was used on only 2.2% of desktops. Windows, on the other hand, runs on 88.31%

Table 1: Comparison of Linux and Windows OSs hardware requirements

OS	Processor	RAM	Hard Disk Space	Graphics Card
Linux Ubuntu [79]	2 GHz dual core	2 GB RAM	25 GB	VGA capable of 1024x768 screen resolutions
Windows 10 [85]	1 GHz	1 GB (32 bit) or 2 GB (64 bit)	16 GB (32-bit) or 20 GB (64-bit)	DirectX 9 or later with WDDM 1.0 driver

of desktops and Mac on 9.02% [47]. While popular due to the ease with which they are deployed, 'one-size-fits-all' OSs are inflexible in their customisation. By way of contrast, Linux is readily customisable, and is used on a range of devices, including servers, embedded systems and routers. However, despite several attempts to promote game-play on this platform, such as with the release of the Linux-based console Indrema, a video game console intended for independent game developers [4] and game terminals uWink [87], Linux has yet to gain a firm foothold in the gaming industry. Currently, gamers play on PCs, where Linux has a minor share [67], or on consoles which use their own OS.

The numerous distributions of Linux give users a choice and ability to tailor the OS for their specific needs. The Linux kernel is modular in its design, with options to add modules which are relevant and remove those which are not. Furthermore, there is variation in the gaming performance achievable across the OS platforms: Linux Ubuntu Desktop Edition, for example, requires 2 GiB RAM, while Microsoft Windows 10 requires 1 (32-bit) or 2 (64-bit) GB (1 Gibibyte equals 1.074e + 9 bytes and 1 Gigabyte equals 1e + 9 bytes). While also dependent on the hardware on which these systems are deployed, the default requirements of each OS has implications on the residual resources available and subsequently the responsiveness of each system, a fact which is particularly important when supporting game play. A wider range of differences between the Linux Ubuntu and Windows 10 OSs are presented in Table 1, and demonstrate the higher overheads of Linux in general. The fact that Linux has more intensive system requirements may also be responsible for making it a lower priority contender.

A key difference which influences the performance of Linux and Windows in terms of gaming ability is in the drivers used. The Windows Active X, and currently Direct X, series of drivers have been heavily invested in by Microsoft. By June 2018, "*Windows 10 is the new king by the numbers, but Windows 7 holds a steady second place nearly nine years later and remains the dominant OS for desktops in Asia and Africa*" [16]. Nonetheless, Windows 10 Direct X 12 is similarly successful as its Active X predecessor. Direct X is unfortunately, however, not supported in Linux.

Linux's main advantage of being open source may in fact be hindering its evolution to become a platform suitable for online gaming, due to inadequate investment in improving the system. This is particularly important in the case of gaming applications, where the more sophisticated aspects of operation, such as the graphics and display, are important factors in promoting the system.

Gaming consoles dedicated to the task of running Linux have not yet proved to be successful. One example is the Ataribox from Atari, promised in 2018 but has so far failed to launch, and now the Atari VCS, scheduled for launch in July 2019. In March 2018, it was described that, "*The Ataribox lives, as a prototype, supposedly*" [48], and that, "… *many of its key pieces, like its AMD processor and customised Linux operating system, are still coming together*" [28]. Worringly, it has been identified that, "… *Atari says it doesn't yet know how well games like Borderlands 2 for Linux might run*" [28]. While the Atari VCS is still some way off launching, it was noted in April 2018 that, "… *the fact that so little is known about the console is worrying*" [24].

As an earlier example, the Ouya console is described as having an, "*aging Tegra 3 processor propping the whole device up*"; this is a characteristic which is considered to be responsible for the fact that, "*the Ouya stutters and lags on relatively simple games*" [13]. Devices, like Ouya do not have the capability to support online gaming in the way that a PC might, thereby attracting negative attention to the performance of Linux as a platform suitable for supporting game play.

In addition to its use on gaming consoles, Linux users can be supported using WINE (Wine Is Not an Emulator), which facilitates the execution of Windows applications on Linux systems [86]. The lead developer at WINE, Alexandre Julliard, when asked in 2001 about his personal view on the performance of WINE, said, "*so far, the effort has been spent entirely on ensuring compatibility. I'm confident that once we start seriously profiling and fixing performance hot spots, we'll get close enough to Windows speed for all practical purposes, and in many cases we have the potential to be noticeably faster than Windows*" [44].

Table 2: QoS requirements across applications [34]

Zero Loss Apps	Acceptable Delay	<5% Packet Loss Apps
Command/control e.g., interactive games	100 ms	Conversational voice and video
Transactions e.g., e-commerce, browsing, email	1 s	Voice/video messaging
Messaging downloads e.g., FTP	10 s	Streaming audio/video
Background	100 s	Fax

Table 3 Requirements for multiparty online game with voice communication [29]

Application Requirements
Browser takes advantage of available network capabilities to prioritise voice, video and data appropriately
Browser can transmit streams and data to several peers concurrently
Browser can receive streams and data from multiple peers concurrently
Browser can render several concurrent audio and video streams
Browser can mix several audio streams
Browser can apply spatialisation effects when playing audio streams
Browser can measure voice activity level in audio streams
Browser can change voice activity level in audio streams
Browser can process and mix sound objects with audio streams
Browser can send short latency unreliable datagram traffic to a peer browser

The issue with WINE, however, is that it has been more suited to, and therefore more used for, running applications such as Microsoft Word, rather than gaming. Its full potential in this role may therefore not be recognised; however, its utility, in general, is reputed to be somewhat average. Noted by Miller in 2017, "*it almost never works, but it often almost works*" [49]. He goes on to say that, instead of relying on WINE, "*I just have a Windows desktop for when the gaming itch hits me*" [49]. Some, therefore, do not consider it to be a reliable substitute to running Windows applications on a Windows platform.

PlayOnLinux [58], as another contender, can be used to, "*… [get] some software to run on Wine properly*" [42]. WINE is a software layer between the native operating system and the game. PlayOnLinux runs on top of WINE and accesses the necessary libraries to support Linux games on Windows. Reviews for PlayOnLinux, however, are generally similarly disappointing as for WINE: In October 2016, a platform tester summarised that, "*The results are far from perfect, and often you will encounter bugs, crashes, and weird, inconsistent behavior*" [12].

CrossOver is the paid for version of WINE, with a one-time fee and added features such as ability to support additional libraries, including DirectX [65]. This was an extension made available in 2015. It is more difficult to find negative perspectives on CrossOver, with one user reporting on an open forum: "*You have my word it works just great like in Windows*" [10].

Without the deployment of these additional software layers, Linux has long been considered to be a difficult OS to negotiate when gaming. Garnett (2013) jokingly advises, "*So, you want to play games on your Linux machine. Oh, boy, batten down the hatches*!" [21]. Zele (2013) also considers that Linux has been around for a considerable timeframe, but its, "*inherent complexity and limited support has always relegated its use to extreme enthusiasts and programmers*" [88]. More recently, a technically competent user reports in June 2018, "*Yes, Linux is a decent operating system for gaming …*", from the perspective of its customisation ability, security, and price [71]. Due to its weaknesses, which include software integration and number of games available for Linux, however, the author recommends that casual users opt for Windows instead of Linux, due to Windows' user-friendliness.

Evidence in the literature emphasises Linux's inability to easily support a gameplay which fulfils QoS/QoE expectations. Quality of Service within the context of game playing refers to the delivery of voice, audio, video and data, measured in terms of latency and packet loss [34] (Table 2). Quality of Experience (QoE) in the context of online games considers the synchronised delivery of both data and audio, and the priorities applied with the delivery of different types of output [29] (Table 3). Normal modes of game operation require that state be updated quickly and voice audio delivered in line with game sound. Different types of data can also be delivered with variable levels of priority: when resource constraints exist, game state, for example, must have a higher priority than voice.

To understand Linux's ability to support online gaming with a satisfactory user QoE, it is necessary to establish the operational and functional requirements of online games; these include low latency links, moderate Internet bandwidth, and a reliable Internet connection. About Technology's wireless and networking expert Bradley Mitchell states that, "*PC and console games benefit from having a fast Internet connection when used online*" [50]. Plusnet, however, has found that online gaming, in comparison to streaming, only uses a small amount of bandwidth, stating that, "*You do not need a fast line for gaming as factors such as stable line, with less lag and latency are much more important*" [33]. It cannot therefore be taken for granted that all online games require a fast bandwidth connection to meet with QoS expectations.

Streaming online games in general, however, are traffic intensive; game performance in this context is therefore dependent on high speed network connections with a steady bit stream to secure a good level of QoS. Again, the intensity of this requirement is dependent on the specific gaming application: World of Warcraft, a massively multiplayer online role-playing game for example, requires approximately 55 Kbps per player, while League of Legends has a recommended internet speed of 6 Mbps to fulfil the real-time responsiveness required by the gamer's virtual world [74] [64] [9] [17].

It is also significant to consider the accumulated demands of games on the network: Battlefield 3, a first-person shooter video game (Figure 1) for example, can support up to 64 online players at one time. In this type of game, real-time reactions are crucial to support accurate states of game play. Low latency links and minimal packet loss are therefore vital QoE requirements during this specific type of play. In World of Warcraft (WoW) (Figure 2), the characters with text above them represent online players at one location at the same time. In this massively multiplayer online role-playing game (MMORPG), thousands of players interact simultaneously: There can be, on average in WoW, around 5,000 online players accessing a server simultaneously. Sufficient bandwidth to support the typical traffic intensity is therefore a vital QoE requirement to ensure reliably responsive game play.

These aspects are separate from the specific platform on which the game is being played. The time-sensitivity of games, on the other hand, is a factor which is influenced by the platform on which the game is played. The main sources of latency in the Linux OS are attributable to timer resolution (granularity of the clocking signal), scheduling jitter, and non-pre-emptible section latency (the unforeseen latency effects of interrupts). For the general purpose Linux kernel, a predicable schedule is needed to respect the application's temporal constraints. Kernel pre-emptability can improve the real-time performance of Linux, thus reducing OS latency. Fortunately, these can be largely alleviated by using a combination of improved timer resolution, priority adjustments, and a combination of low latency kernels with better interrupt processing using resource reservations.

3 LINUX AND ONLINE GAMING TODAY

As online gaming is on the rise, it might be a general expectation that games which are newly developed would be more flexible and subsequently readily available on every OS. Evidence in the past suggested that the development of games for Linux was a tedious process: "*I've sold about fifty copies on Linux, which is a drop in the bucket to what it cost me financially and emotionally to support that platform*," said Pittman in 2014, a blogger for GamaSutra [57]. Puppy Games also revealed in the same year that, "*To date, we've made just$12,000 from Linux games*," a figure which is just1% of Puppy Games' total profits [7]. Such examples may reveal Linux as a failed platform for gaming.

Bourbeau (2015), however, writes that, "*I just finished my last game … this game took me around 200 hours to complete … With the proper tools I found the development process quite straight-forward*" [6]. Also supporting this argument is Hayward (2014), stating that Linux is, *"a very stable and relatively up-to-date environment*" [25]. It may therefore be the case that some developers exploit the technologies available to support developments for this platform, while others do not.

One significant development in support of Linux-based games was Valve's Steam, a gaming software platform originally designed for Microsoft and which was introduced to Linux in February 2013: "*The Steam client is now available to download for free from the Ubuntu Software Centre … "The introduction of Steam*

Figure 1: Battlefield 3

Figure 2: World of Warcraft

to Ubuntu demonstrates growing demand for open systems from gamers and game developers"", said David Pitkin, Director of Consumer Applications at Canonical [80]. "*We expect a growing number of game developers to include Ubuntu among their target platforms. We're looking forward to seeing AAA games developed with Ubuntu in mind as part of a multi-platform day and date to release on Steam*" [80]. This indeed has been the case, as reported earlier in the paper, with 1,480 games developed for Linux by 2014, and 5,332 by 2018. Further to this, Hruska reports in August 2018 on the release of Steam Play by Valve [31]. One of its capabilities, similar to WINE, is its support of Windows games on Linux platforms, which again is expected to encourage the development of more games for Linux. This is particularly true given that Steam is offering gamers the opportunity to indicate which games they wish to be considered for Steam Play, using a system known as 'platform wishlisting'.

This anticipated trend is supported by a number in the field, which includes Byfield who suggested in 2014 that, "*The slow development of Linux gaming suggests that the development companies have failed to understand their market*" [7]. The author of [5] acknowledges that, even in 2018, "… *it's very rare to get a firm commitment from any developer or company regarding upcoming Linux support."* He also suggests that, "*... if you think that, as a Linux gamer, there is a game you want to see, please make your voice heard towards developers. Sometimes just asking for it is enough* …" [5]. This opinion also suggests that the games developers may not be fully aware of what their customers want, and it is for this reason that the Linux gap is not being filled.

This evidence therefore suggests that Linux is becoming more noticeable in gaming circles due to Valve's investment. Valve has seemingly turned to Linux during a time when Microsoft's recent Windows OSs have fallen short in providing users with a sound QoE. In 2013, Valve officially released Steam for Linux and in October 2014, the number of Linux-compatible games reached 700 [27]. This success has resulted in the development of Stream Machine gaming consoles, and the Linux-based OS called SteamOS [69]: "*Valve's cloud-based distribution of gaming content works around the traditional hurdles to gaming on Linux, providing open source the chance to play a big role in a niche where, traditionally, it has barely existed at all*" [78]. The Steam OS allows users to run their games through the Steam client within their Linux distribution.

Linux, without any supporting middleware, is recognised as having variable ability to support a range of online games. Table 4, for example, presents the recommended specification for DotA 2 [14], a multiplayer online battle game. Linux is presented as a platform which is suitable for meeting the minimum system requirements. World of Warcraft, shown in Table 5, on the other hand, is not recommended for running on Linux in either (minimum or recommended) case.

By way of contrast, the hardware requirements when CounterStrike is run on the Windows, Mac and Linux OSs are compared in Table 6, where each OS is shown to be equally able to support the game. CounterStrike, a first-person shooter video game, places similar demands on each of the three OSs. It is indicated that the game needs twice as much RAM when supported on Ubuntu as it does on Windows or Mac. One reason cited for this resource requirement is simply because developers do not test the game on all older machines, and release the game with a conservative hardware requirements which are known to work [59]. Other gamers describe that there are intensive RAM requirements, and are advised to change the configuration of the threading mode, to use a multi-threaded mode of operation to run the system more effectively [60]. The system requirements of more recently popular games are presented in Table 7, Table 8, and Table 9. It is interesting to note that, in each of these cases, Linux is not advised as a suitable platform for either the minimum or recommended cases.

Nonetheless, despite the fact that game specifications provide evidence that Linux is less popular as a gaming platform, Chapple reported in 2014 that, "*having previously taken a backseat to Windows, Mac and the console space, Linux has now been thrust into the limelight as more developers and platform holders take advantage of it*" [8]. Jim Zemlin of the Linux Foundation additionally suggested that, "*An open OS like Linux engenders widespread collaborative development and contributions, which will pave the way for gaming hits of the future*" [8]. By 2017, there is opinion that, "*It's truly a great time to be a Linux gamer, and the future looks brighter than ever*" [20]. Based on these perspectives, we might therefore expect to see gaming specifications such as those presented in Table 4, Table 5, and Table 6 to show increased leaning towards Linux as a suitable platform.

Of course, this will be based on the ability to achieve, at least, a similar performance as running the games on the other popular OSs, such as Windows and Mac. Results in [2] demonstrate that improved performance is achievable when playing Team Fortress 2 on Linux Ubuntu as opposed to on Windows. Performance in this context is measured in the variability of average number of frames per second, with more frames being delivered to the Linux OS in the case of this game. When it is possible to achieve a similar level of QoS and QoE with fewer delivered frames, this is a positive result; fewer resources are required to support operation of the game,

Table 4: DotA 2 (released Jul. 2013) [14]

	Windows	Mac OS X	SteamOS + Linux
OS	Windows 7 or newer	OS X Mavericks 10.9 or newer	Ubuntu 12.04 or newer
Processor	Dual core from Intel or AMD at 2.8 GHz	Dual core from Intel	Dual core from Intel or AMD at 2.8 GHz
Memory	4 GB RAM	4 GB RAM	4 GB RAM
Graphics	nVidia GeForce 8600/9600GT, ATI/AMD Radeon HD2600/3600	nVidia 320M, or Radeon HD 2400, or Intel HD 3000	nVidia GeForce 8600/9600GT, AMD HD 2xxx-4xxx, AMD HD 5xxx+, Intel HD 3000
Hard Drive	15 GB available space	15 GB available space	15 GB available space
Sound Card	DirectX compatible	-	OpenAL Compatible Sound Card

Table 5: World of Warcraft (released Nov. 2004) [75]

	Minimum Requirements	Recommended Specifications
Operating System	Windows 7/Windows 8/Windows 10	Windows 7/Windows 8/Windows 10
Processor	Intel Core 2 Duo E8500 or AMD Phenom II X3 720	Intel Core i5-3330, AMD FX-6300 or better
Video	NVIDIA GeForce GT 440 or AMD Radeon HD 5670 or Intel HD Graphics 5000	NVIDIA GeForce GTX 750 Ti or AMD Radeon R7 260X or better
Memory	2 GB RAM	4 GB RAM
Storage	45 GB available hard drive space	
Internet	Broadband Internet connection	

Table 6: CounterStrike (released Nov. 2000) [70]

	Windows 7/Vista/XP	Mac OS X 10.7 or later	Ubuntu 12.04
Processor	Intel Core 2 Duo or AMD Phenom X3	Intel Core Duo Processor (2 GHz or better)	64-bit Dual core from Intel or AMD at 2.8 GHz
Memory	2 GB RAM	2 GB RAM	4 GB RAM
Graphics	Video card must be 256 MB or more; DirectX 9-compatible	ATI Radeon HD 2400 or better	nVidia GeForce 8600/9600GT
Hard Drive	15 GB available space	15 GB available space	15 GB available space

Table 7: Fortnite: Battle Royale (released Sep. 2017) [19]

	Minimum Requirements	Recommended Specifications
Operating System	Windows 7/Windows 8/ Windows 10 64 bit	Windows 10 64 bit
Processor	Intel Core i3 4xxx 2.4GHz	Intel Core i5-2.8GHz
Video	Intel HD 4000	NVIDIA GTX 660 Ti or AMD Radeon 7870 2GB
Memory	4GB RAM	8GB RAM
Storage	16GB	20GB

Table 8: PlayerUnknown's Battlegrounds (released Mar. 2017) [76]

	Minimum Requirements	Recommended Specifications
Operating System	64-bit Windows 7, Windows 8.1, Windows 10	64-bit Windows 7, Windows 8.1, Windows 10
Processor	Intel Core i5-4430 / AMD FX-6300	Intel Core i5-6600K / AMD Ryzen 5 1600
Video Card	nVidia GeForce GTX 960 2GB / AMD Radeon R7 370	nVidia GeForce GTX 1060 3GB / AMD Radeon RX 580 4GB
Memory	8 GB RAM	16 GB RAM
Pixel Shader	5:1	5:1
Vertex Shader	5:1	5:1
Available Disk Space	30 GB	30 GB
Dedicated Video RAM	2 GB	3 GB

Table 9: Overwatch (released May 2016) [56]

	Minimum Requirements	Recommended Specifications
Operating System	Windows Vista/7/ 8/10 64-bit (latest Service Pack)	Windows Vista/7/ 8/10 64-bit (latest Service Pack)
Processor	Intel Core i3 or AMD Phenom X3 865	Intel Core i5 or AMD Phenom II X3, 2.8 GHz
Video Card	Nvidia GeForce GTX 460, ATI Radeon HD 4850, or Intel HD Graphics 4400	Nvidia GeForce GTX 660 or ATI Radeon HD 7950
Memory	768 MB VRAM, 4 GB System RAM	2 GB VRAM, 6 GB System RAM
Storage	7200 RPM with 5 GB available HD space	7200 RPM with 5 GB available HD space

more resources are available to support other system and application processes, and the games can be supported on a greater range of devices with variable levels of expense.

Left 4 Dead [38] has also shown more successful performance on Linux Ubuntu in comparison to Windows: "*On a system running an Intel Core i7 3930k CPU, an Nvidia GeForce GTX 680 graphics card, and 32 GB of RAM – yes, that's GBs! – the company squeezed 270.6 fps (frames per second) from the Windows 7 Service Pack 1 65-bit and a whopping 315 fps on Ubuntu 12.04 32-bit. This translates into a 16.7% increase in performance, or a 14.3% decrease in the time taken to render frames*" [36]. A study in [1] also demonstrates an increased frame rate in Linux as being 'normal' performance, showing that Linux has a rendering time of 1.62 times faster than Windows, with the impact that it can render more than three frames when Windows can only render two within a given unit of time. The frame rate and speed are crucial to the QoE, and the results verify that Linux Ubuntu's rendering capabilities stand up to competitor Window's results.

4 CLOUD GAMING: CONDITIONS FOR A FAIRER FIGHT IN LINUX?

Stephane Kurower defines cloud gaming as, "*Incredible graphics on weak hardware – to put it bluntly, it's a new type of online gaming that allows you to stream high-end video games, on demand, straight to your computer without owning or buying any expensive hardware. A thin client, like a simple phone or a tablet is enough to play a game that would normally have to be installed on a very expensive PC*" [37]. Growth in this area could change online gaming as we know it, due to easier access to the volume of resources required. A key benefit of the Linux OS with regard to cloud gaming is its ability to be installed freely onto any device. Its open-source nature makes it so that it is not hardware dependent like Windows or the Mac OSX. With that said, Linux and cloud gaming could be considered to be a perfect match, as neither rely on a device's hardware – "*All the heavy lifting will be done 'in the cloud'*" [30].

In 2014, it was believed that, "*The cloud gaming industry is set for growth with industry analysts believing it could exceed $1 billion in 2019 from $281 million [in 2014]*" [73]. By 2018, the market is estimated to reach $4.284 billion by 2023 [63].

GamingAnywhere [18] and NVIDIA [52] [23] have made efforts to push the boundaries for cloud gaming. GamingAnywhere is a gaming platform which is supported on cloud, the first of its kind released in 2014 [61]. The latest GamingAnywhere version was released in 2015, although posts in the forum are as recent as May 2018, demonstrating its current applicability. The system developers have been active in investigating the performance of the platform, as captured in [32], measuring the QoS achieved in terms of responsiveness (processing delay, playout delay and network delay), network loads, and video quality (network delay, packet loss, and bandwidth). Their results demonstrate ability to meet stringent delay requirements, experiences lower traffic loads than gaming on StreamMyGame, and similarly, achieves higher video quality in 2014. There is limited evidence, however, that GamingAnywhere has ever been a popular platform: One blog post on reddit.com from 2015 seeks to find if anyone has used it with any success. Of the few respondents, there appears to be a general interest, but no one had in fact tried [61].

Nvidia has made a couple of attempts to break into the cloud gaming market, first with NvidiaGrid and more recently with GeoForce. The "*Latest Reviews of Nvidia Grid*", which captured positive experiences with the platform were published in 2013. GeoForce now offers a subscription-based cloud gaming platform, although the website currently instructs users to, "*Request access to the beta below, and we'll be in touch when there's availability*" [53].

In January 2018, techcrunch asked, "*Is the time finally right for platform-agnostic cloud gaming*?" [26]. They acknowledge that, "*It's a big ask, getting people back on board with a concept that's tried and failed to launch time and again, and one bad experience could be enough to sour users*." They draw attention to Parsec, "*Connect to a gaming PC from anywhere*" [54] and LiquidSky, "*Use out platform to host, compute and stream your AR, VR & other interactive applications with the lowest latency from our GPU cloud*" [43]. The success of each remains to be seen.

Sony took a step into the world of cloud gaming with their acquisition of Gaikai in 2012. In relation to the work involved in delivering this service, Sony states that, "*It's worth it. Because, when you find yourself playing a PlayStation game within seconds of pressing a button, without downloading or installing anything, on a device that was never designed to do that, it's nothing short of magical*" [72]. Sony also purchased OnLive in 2015, which was one of the first contenders in the cloud gaming market but unfortunately was operational for only five years. From OnLive, Sony created PlayStation 4 and PlayStation Vita for remote playing. Steam is also participating in this area, and allocates 1 GB of cloud space per user account, where users can have game settings and saved game play stored.

Cloud gaming, however, changes the QoS requirements of applications: "*While cloud gaming reduces client hardware requirements and provides other benefits, most such games are traffic-intensive and may significantly increase the network requirements necessary to secure a good level of QoE*" [74]. In

support of this statement, one study concludes that the cloud will cause latency issues in gaming, which will affect fulfilment of real-time responses [74]. This could be particularly problematic in multi-user situations, affecting the QoE due to an inability to capture accurate state of play.

5 A GAP IN MARKETING FOR LINUX?

It was noted in May 2011 that, "*What Linux needs is Some Good Marketing*" [51]. The author notes that Linux's success has been achieved largely without any significant marketing investment, thereby proving the quality of the product. However, some may question the fact that, with Linux being an open source product, and therefore free, why should marketing be important? By December 2017, the need to market Linux continues to be questioned: "*I don't have to try to sell anything, so why would I need marketing*?" [3]. While buying into Linux is not a financial transaction, the author of [3] identifies that the exchange is between ideas and people's time and attention.

Without this being positioned to the consumer, they are unlikely to transact, particularly in a competitive marketplace, whether the product is free or not. In February 2018, it is discussed that, "*To capture more of the desktop market, Linux needs to target the average user*" [84]. In this report, the limited uptake of Linux is attributed to the fact that, when it is being discussed, the language used may be off-putting to general users, with terms such as 'command line', 'terminal window', and 'open source' being used. In this article, it is recommended instead that the attractive desktop is shown, together with its ability to run popular applications. It may therefore not be the fact that Linux cannot support online games, but rather that general users would not consider Linux as the optimum platform.

6 CONCLUSIONS

Some developers continue to doubt Linux's ability to be a serious competitor in the online gaming arena, with opinions that, "*commercial gaming is a bubble consisting more of speculation than realised potential*" at the moment [7]. In 2013, Edge Online stated that, "*Linux has never been considered a player in gaming, but it's never had a supporter like Valve before*" [15]. As a gaming platform, Linux has slowly gained ground; the future for Linux games looks promising due, in part, to the flexibility and adaptive characteristics of the operating system. This is highlighted by Valve co-founder Gabe Newell, stating that Linux is the future of gaming [77]. Valve, the video game development and online distribution company prefers Linux to Windows, stating that, "*Our mission is to strengthen the gaming scene on Linux*". This bodes well for the future of Linux, with the Steam game console and the ever-increasing library of native Linux games. The world's fastest computer, Summit, runs Linux due to its ability to integrate all of the necessary platform resources with one another [35].

By 2017, one avid fan of Linux reported in a blog that, "*In 2018 Linux will become a serious gaming OS …*" [62]. The general consensus of respondents to this posting, however, was a belief that the Linux market share will continue to experience slow growth. This growth rate is for reasons which include gaps in the operating system's capabilities, and the fact that the majority of gamers are unlikely to uninstall an operating which works well on their hardware for one which they are less certain of.

Evidence in 2018, however, reveals that this fan's opinion may indeed be accurate and that the ground is being set for Linux to grow: "*Valve is taking another crack at bringing a wide assortment of Steam games to Linux*" [81]. This involves integrating the WINE platform and using it to install Windows on top of Linux, as opposed to converting the games to run in Linux natively.

On paper, Linux is perfectly capable of supporting online games, and that the obstacle to its success in breaking into this market is more to do with poor marketing and investment compared to the competition rather than limitations with the OS itself. It is robust in supporting applications, has lower latency than OSs due to organisation of the kernel and its subsequent ability to schedule tasks, and frees up as much RAM as possible for gaming due to its minimal overheads.

The decision however, ironically, to provide Linux without cost may have doomed it as a competitor to Windows. As a result of this decision, control of the Linux gene pool was lost. Unity has become impossible because Linux has mutated into many specialised variants, each with its own passionate army of supporters. Without a centralised vision and sustained financial backing, Linux may continue to be the wily outsider of the OS market for some time yet.

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