Final Implementation Plan

Cloud VR. Secure, Fast and Distributed Virtual Reality Solutions.

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May 2020

Contents

Acronyms

AES Advanced Encryption Standard. 10, 12, 13

FoV Field-of-View. 8

GPU Graphics Processing Unit. 4, 13

HMD Head Mounted Display. 7, 8, 9, 11, 12

IAM Identification and Access Management. 1, 10

IRH Industrial Reality Hub. 3, 17

ms Milliseconds. 7, 9

MTP Motion-to-Photon. 7, 9, 16, 17

QoE Quality of Experience. 9, 15, 16

TLS Transport Layer Security. 10, 13

VR Virtual Reality. 1, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14, 15, 16, 17

1 Introduction

Recent developments in the field of Virtual Reality (VR) offer all kinds of opportunities in the field of training and entertainment. For training purposes, the audiovisual entry into a virtual world is where the biggest value is. The capabilities of artificial environments allow users to manage scenarios and experiences that cannot be simulated in the real world. VR also allows users to access the virtual training at any time and less physical facilities are required for exercises. Examples VR experiences include training maintenance at high altitudes (such as windmills), working under heavy loads and weather conditions in construction (Strukton) or maintenance on naval ships (Thales). These companies (and more) form the Industrial Reality Hub (IRH), which is one of the stakeholders of this project.The IRH is an industry consortium of 17 partners in AR/VR - The European digital innovation hub for industrial applied Augmented and Virtual Reality, stimulating cooperation and innovation between companies, government and knowledge institutes, resulting in world class business, knowledge and facilities. The hub is the AR/VR Fieldlab in the Dutch Smart Industry program and is recognized by the European commission as Digital Innovation Hub for industrial AR/VR (IRH, n.d.).

2 Reason for Assignment

2.1 Graduation Assignment

The assignment for this graduation is to analyse the current state of cloud VR streaming. This includes existing commercial services, open source libraries/frameworks, relevant research papers and experimental technologies. The 4 research directions for this project are system architecture for a cloud VR system, Latency, Multi-User Experiences and GPU Scaling. This paper will focus on researching the system architecture and latency improvements. These findings will be presented in the form of a theoretical framework and a literature review.

Armed with the information from the initial part of the research, the student and the stakeholders will agree on a suitable research focus for the remainder of the project, including a proof of concept focused on reducing latency.

2.2 Client outline

The stakeholders in this project are the student (Leon Koster), Saxion's XR Lab (Matthijs van Veen) and the Industrial Reality Hub.

3 Problem Analysis

Together with the companies from the Industrial Reality Hub mentioned in the Client outline, Saxion wants to investigate how virtual reality can be rendered in the cloud in a safe and efficient manner. This involves looking at state-of-the art technology in the field of virtual reality, cloud computing, rendering and machine learning for one complete CloudVR pipeline.

In the bigger picture this project is a multi phase project, with this research being the initial phase. It aims to give an overview of the current situation regarding cloud VR streaming and focus on system architecture and latency optimization. These informations will subsequently be utilized in the later stages of the over arching research project.

4 Preliminary Problem Statement

One of the essentials for a good Virtual Reality (VR) experience is a powerful computer system to render semi-realistic worlds. However, there are two problems here. First, this type of system is not available in every location. Certainly if realistic images have to be rendered in the simulation, it requires specialized and expensive machines that are difficult to move.

The second problem is that for rendering the VR training scenario, all kinds of data about the scenarios need to be available on the system. This can pose a problem when it concerns sensitive information, for example about all kinds of information defence systems or business sensitive information.

The hypothesis is that both of these problems can be resolved by a cloud rendering solution. By separating the rendering and displaying locations, VR systems become much more versatile. For example with only a lightweight client necessary these experiences could be offered as a Pay-What-You-Use service, which would make them more accessible to a broader audience. Furthermore security would be improved since sensitive data never leaves the secure server location.

The aim of this report is to investigate the feasibility of a streaming based VR approach, with emphasis on Latency reduction and Security. Qualitative research methods will be used to gain in-depth insights about existing solutions and the current state of research into this topic. The data will be contextualized via a literature review of recent research papers and capabilities of existing solutions when applied to the research problem.

5 Theoretical Framework

In order to thoroughly understand the aim and subject of the report, it is important to explore different existing solutions and literature. Therefore, the subjects that will be discussed in the following theoretical framework are Cloud Streaming/Cloud Computing, Virtual Reality and Security in a streaming context. Within this theoretical framework definitions of the subjects will be given, as well as current insights into these subjects. The topics reflect knowledge needed to understand the problem space. Together all of the topics make up the 360 scan. Then this knowledge will be applied to the research problem by creating an overview of the individual parts of a cloud VR system and of the available components to create one. Lastly I will be proposing technology stacks, made up of said components, that can satisfy all necessary aspects of a cloud VR system as described in the overview.

5.1 Cloud Streaming/Cloud Computing

5.1.1 Definition

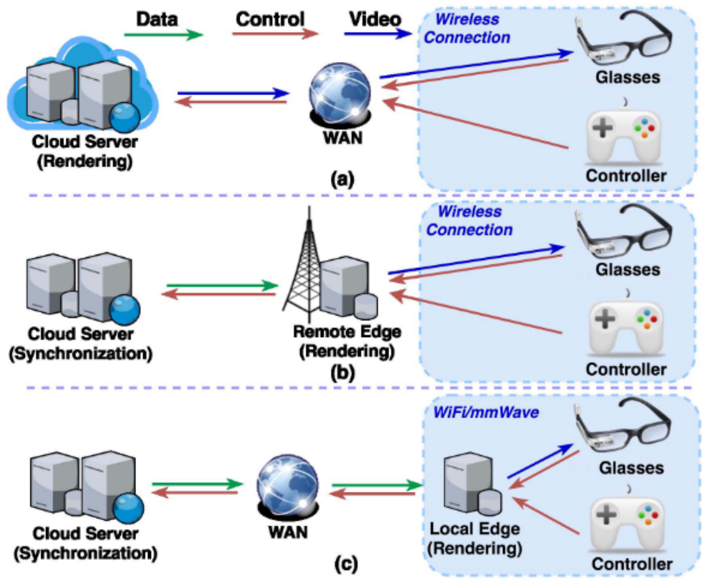
According to Armbrust et al. (2010) Cloud computing is defined as follows: "Cloud computing refers to both the applications delivered as services over the Internet and the hardware and systems software in the data centres that provide those services." (Armbrust et al., 2010) We can then further define Cloud streaming as the applications that are delivered over the internet as a service.

5.1.2 Existing Solutions and Technology

Several commercial gaming cloud streaming services already exist, such as Google Stadia (Google, 2019), XBox XCloud (XBox, 2019) and Nvidia GeForceNow (Nvidia, 2020b). These applications deliver conventional games from a powerful computer in a server to the client device at home. Despite initial setbacks, cloud streaming is now a mainstream technology. The start of 2020 also saw the first experimental cloud VR streaming development kits, such as Nvidia's CloudXR (Nvidia, 2020a), and closed beta's for commercial cloud VR streaming services (Shadow, 2020) (Available on Windows, macOS, Ubuntu, Android and iOS) . Additionally the first commercial retail product with cloud VR has been released (Zerolight, 2020), however it runs on custom made HMD's and not on consumer platforms . There is also a variety of Infrastructure-as-a-service (IaaS) platforms, such as Amazon's AWS (Amazon, n.d.), Microsoft's Azure (Microsoft, n.d.) and Google's Cloud Platform (Google, n.d.-a), that provide generic computing power and storage in a cloud computing/streaming context. These services generally cannot achieve the latency requirements of cloud VR streaming (Shi & Hsu, 2015) as it requires an extraordinarily low latency of $>$20ms from Motion-to-Photon (MTP), where most (game) streaming applications have a higher tolerance for latency. Some companies actively develop technology to minimize latency exactly for purposes like this (e.g. enabling compute power as physically close to the end user as possible (Amazon, 2020), but generally as time and technology progress the capabilities of cloud streaming services will grow alongside.

5.1.3 System Architecture types (for a cloud VR system)

Figure 1: Cloud Server, Remote Edge, Local Edge visualized (Hou, Lu, & Dey, 2017)

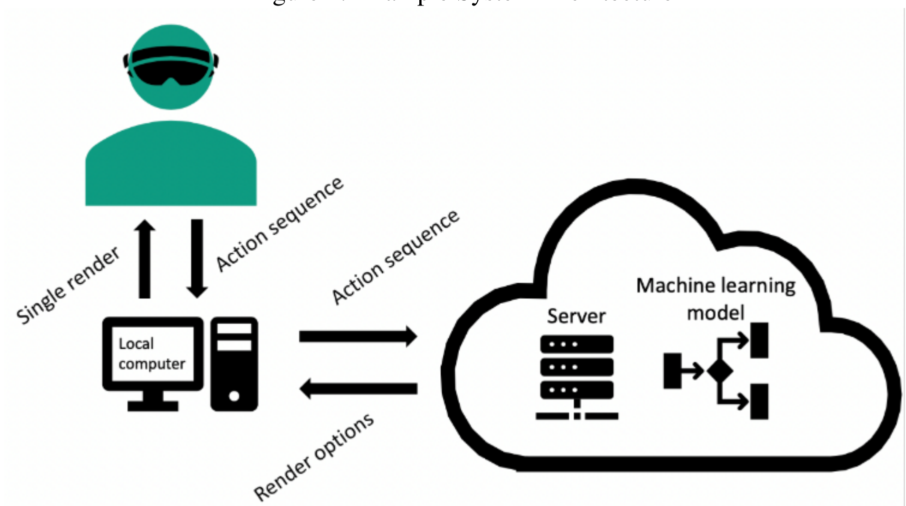


One of the main considerations when designing a cloud VR streaming application is the decision to either use a Cloud, Remote Edge or Local Edge computing device for the rendering of the frames (See Figure 1 and Hou, Lu, and Dey, 2017):

- A cloud server renders the Field-of-View (FoV) (current view) remotely and streams the corresponding video to the user's Head Mounted Display (HMD).
- A Remote Edge sever receives information about the context from a cloud server, renders the appropriate frame and streams the video to the user's HMD. The main advantage here is that edge servers are located closer to the end user (thus improving response time and saving bandwidth)
- A Local Edge server receives compressed models as well as textures, renders it locally and streams the video to the user's HMD.

For the purposes of this research I will ignore Local Edge system architectures. The reason is that one of the major motivations for this report was the desire to keep data as safe as possible, which in this case means keeping in the cloud. A Local Edge system, by design, requests and receives business data to render the frame for the user locally. For this reason a Local Edge approach would be the wrong direction to research in. An example architecture of a cloud VR solution that keeps the business data in the cloud can be seen in Figure 2.

Figure 2: Example System Architecture



Furthermore one also has to consider if the application will be hosted on a cloud service provider or on an in-house server. Both ways have advantages and disadvantages, which are elaborated upon in the Appendices, and the decision should be made based on the unique circumstances of each customer.

5.1.4 Latency

The most important metric for a system architecture is the latency between the user input, such as movement of the HMD, and the updated frame appearing on the users display. Recent measurements of cloud gaming services measure this latency at between 135 and 240ms (Chen, Chang, Tseng, Huang, & Lei, 2019). This is acceptable for most games, except maybe high intensity reaction games. VR unfortunately has severely stricter latency requirements, which are elaborated upon in Constraints of Virtual Reality

5.2 Constraints of Virtual Reality

As mentioned before, when developing a VR application, there are a few physical constraints that developers need to be aware of. The most important threshold to know is the 20ms MTP delay. Upon input from the HMD, the developer has to display a new rendered image within an average of 20ms to avoid motion sickness for users. The more this threshold can be undercut, the better the chances to have an acceptable gameplay experience without motion sickness. Interaction input, such as the input from the controllers, can safely be processed at delays of >100ms without any negative repercussions in terms of Quality of Experience (QoE).

5.3 Security (for streaming data)

From a technical standpoint there are 2 major categories of security implementations: Encryption and Access management. There are additional measures that companies can take such as having consistent security protocols and educating employees, but for this report the focus is on technical solutions:

5.3.1 Encryption

Encryption is the practice of scrambling data so that unauthorized users cannot use the data. Only an authorized party in possession of the decryption key can un-scramble the data and subsequently use it. One such encryption technologies is the Advanced Encryption Standard (AES), which comes with three different key sizes: 128, 192 and 256 bits. In 2016 it was estimated that it would take 500,000,000,000 years to decrypt just one AES-128 key. To encrypt the data in delivery, a technology such as the Transport Layer Security (TLS) can be used, which encrypts the data based on a shared secret that was negotiated at the start of the session, thus making the data only usable for the server and client who have the decryption key.

5.3.2 Identification and Access Management (IAM)

An IAM solution tracks users and what they are allowed to do. There are multiple existing solutions for tracking the users privileges, but for this report only cloud based services are relevant since the premise of this research is the ability to have a cloud solution. All major cloud providers have IAM solutions in their ecosystem and in case of a in-house server a independent IAM service provider can satisfy that requirement.

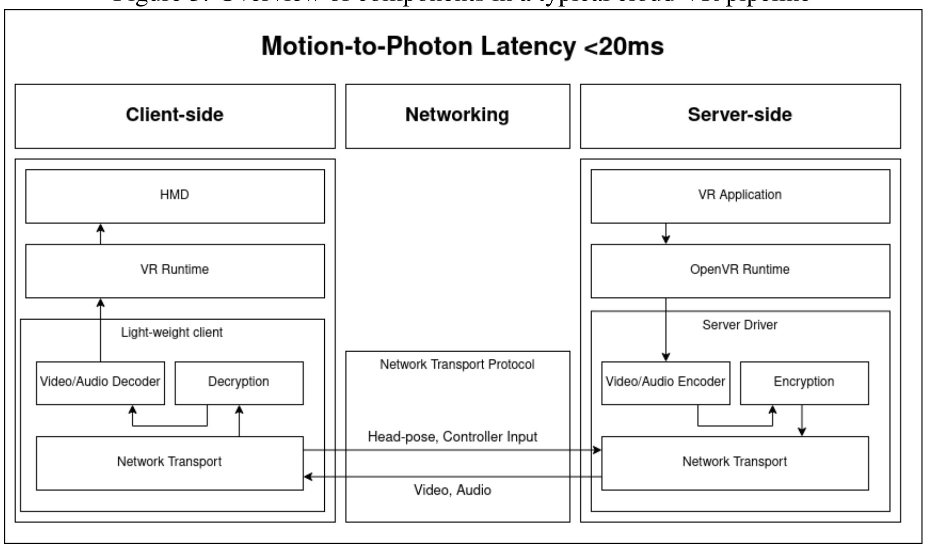
5.3.3 Latency Implications

As discovered by existing research, encryption does not greatly influence performance of the video stream in terms of latency (Kaknjo, Rao, Omerdic, Newe, & Toal, 2019).

5.4 Components of a cloud VR pipeline

In this section all the individual components of a cloud VR pipeline are being presented. Furthermore an overview of pre-made components will be presented and which part of the pipeline they address.

Figure 3: Overview of components in a typical cloud VR pipeline



Server-side rendering The actual VR application will be running on the cloud server and use the servers hardware to render the game. The application will be running on the OpenVR SDK, which allows access to VR hardware from multiple vendors without requiring that applications have specific knowledge of the hardware they are targeting (Valve, 2016).

Server-side encoding The rendered frames will be encoded with a video compression codec before they are sent to the networking layer.

Server-side encrypting Before transmitting the data (encoded frames) over the network it will be encrypted to maximise security.

Networking Through the network connection both the output (rendered, encoded and encrypted frames) and the input (HMD position and controller input) will be exchanged between the server and the client.

Client-side decrypting Once received from the networking layer, the frames are decrypted to prepare for decoding.

Client-side decoding Once decrypted to usable packages, the data will be decoded and then sent to the VR Runtime

Client-side rendering / displaying The decoded frames will be warped to fit the lenses of the HMD and then finally be displayed to the user.

5.4.1 Available components

Table 1: Available Components

Name	**Description**	**Solves**
NVIDIA CloudXR SDK	”NVIDIA CloudXR^{TM}, a groundbreaking technology built on NVIDIA RTX^{TM}, delivers VR and AR across 5G and Wi-Fi networks. With NVIDIA GPU virtualization software, CloudXR is fully scalable for data center and edge networks” (Nvidia, 2020a).	Server-side encoding, Server-side encrypting, Networking, Client-side decrypting, Client-side decoding, Client-side rendering / displaying
Seurat	Seurat is a system for image-based scene simplification for VR. It converts complex 3D scenes with millions of triangles, including complex lighting and shading effects, into just tens of thousands of triangles that can be rendered very efficiently on 6DOF devices with little loss in visual quality (Google, 2018).	Server-side rendering
H.264	H.264 is a video compression standard based on block-oriented, motion-compensated integer-DCT coding.[1] It is by far the most commonly used format for the recording, compression, and distribution of video content. It supports resolutions up to and including 8K UHD.	Server-side encoding, Client-side decoding
VP8	VP8 is an open and royalty free video compression format.	Server-side encoding, Client-side decoding
Advanced Encryption Standard (AES)	AES is a specification for the encryption of electronic data.	Server-side encrypting, Client-side decrypting

Transport Layer Security (TLS)	TLS is a cryptographic protocol designed to provide communications security over a computer network by utilizing the AES technology.	Server-side encrypting, Client-side decrypting, Networking
WebRTC	With WebRTC, you can add real-time communication capabilities to your application that works on top of an open standard. It supports video, voice, and generic data to be sent between peers, allowing developers to build powerful voice- and video-communication solutions. The technology is available on all modern browsers as well as on native clients for all major platforms (Google, n.d.-b).	Networking
WebXR	The WebXR Device API provides the interfaces necessary to enable developers to build compelling, comfortable, and safe immersive applications on the web across a wide variety of hardware form factors.	Server-side rendering, Client-side rendering / displaying

5.5 Proposed Technology Stacks

Finally in this section different technology stacks will be presented, all of which meet the requirements as detailed in the previous section.

5.5.1 NVIDIA CloudXR (+ NVIDIA Quadro on Azure)

The CloudXR SDK from NVIDIA offers a complete solution package to stream VR/AR experiences from server to client. As the only complete package in this list it is a good starting point to create a cloud VR streaming prototype. Since Azure is the chosen cloud provider of Thales, one of the major stakeholders, the idea would be to deploy this tech stack there.

Pros:

+ Only complete solution
+ Increased prototyping speed
+ Custom made for streaming VR content
+ Works with cutting-edge GPU's

Cons:

- Forced to use NVIDIA products
- Not guaranteed to get access to solution (Have to apply to NVIDIA)
- Limited control about the solution
- Limited documentation about the solution, since it is brand new

5.5.2 WebRTC + WebXR + High Performance Video Codec

WebRTC is one of the premier web technologies to enable real time communications. Since it allows for streaming video and generic data it is a good candidate to create a cloud VR streaming prototype, because it can transfer both the video and input data. As it has a focus on real time communication it is optimized to reduce latency by default, however it is unclear if this is enough optimization by itself to support streaming VR content. To enable the application to run ”normally” WebXR will be used to provide an interface of the physical hardware on the removed remote server.

Pros:

+ Open source
+ Mature technology
+ Well documented and supported
+ Platform independent
+ WebRTC is developed by the same companies that offer cloud computing services (improved integration ?)

Cons:

- WebRTC is a generalized solution (it will take more work to optimize it for VR)
- Lower performance Web Technologies (but there are native clients for all major platforms available)
- Higher complexity (might run out of time while trying to create the prototype)

6 Final Problem Statement

As explored in the Theoretical Framework there are many existing products/technologies for all the individual parts of a cloud VR system. With this knowledge, the product will consist out of several pre-made components that are going to be combined to create a working prototype. Since there are already products on the market that prove the feasibility of creating a working solution by utilizing these technology components (Zerolight, 2020), there is no need to develop novel technology. Keeping this in mind, the problem statement of this report shifts towards finding the correct combination of available technology to satisfy the latency and security demands of the clients. The main problem is that the clients do not know which technology stacks work in practice. To identify if a tech stack satisfies the requirements, a prototype of the proposed stack will be created and subsequently compared to a ”traditional (local)” solution to measure the effectiveness of the prototype in terms of QoE and latency.

7 Research Questions

Main Question:

Which Technology stack(s) for building a cloud Virtual Reality (VR) streaming application satisfies the clients demands (low latency, security, QoE) best ?

Sub Question 1: Which technology stacks are available ?

Sub Question 2: What is the best way to measure MTP latency and how does it compare to a traditional VR setup?

Sub Question 3: How does security compare to a traditional VR setup?

8 Approach

To answer the research questions, I will create a prototype cloud VR system. I aim to include as many pre-existing solutions as possible in order to accelerate the prototyping speed. Initially I want to design and implement a Minimal Viable Product with components I understand. If time allows I plan to create more prototypes with different technologies, in order to be able to compare the effectiveness of different solutions when applied to the research problem.

As I outlined earlier, the main focus for this report is on latency reduction and security. To compare solutions and understand their effectiveness I will measure Motion-to-Photon (MTP) latency as the primary benchmark. It is harder to measure security, but by understanding what the state-of-the-art security practices are and implementing them to the best of my ability, I aim to create a solution that keeps the clients data safe.

To obtain the needed knowledge to execute upon the presented approach, I plan to refer to Research Papers and Experts. There is a multitude of research papers for individual parts of the prototype (Networking, Latency Reduction, Encryption, Encoding, etc.) that contain concentrated knowledge. To assert which information are useful when applied to the research problem and to discover potential pitfalls, I plan on talking to experts that have real world expertise in developing similar products. I want to source experts from inside the Industrial Reality Hub (IRH) and outside of it in order to maximise my chances of picking the right information/technology.

9 Scope

In this project/report I will outline the available technology that is useful for a cloud VR system. I will furthermore work to create a Prototype solution that demonstrates the viability of cloud VR, with a focus on latency reduction and security.

I will not create a production ready product and I will not be responsible for setting up a networking system.

10 Graduation Schedule

I was asked to give an overview of the time line for this project. These times are from the graduation manual, translated to the time frame of my graduation project.

Start of Project The project started on the 4th May 2020.

Preliminary Implementation Plan To be handed in at the end of week 2: 17th May 2020 23:59

Final Implementation Plan To be handed in at the end of week 5: 7th June 2020 23:59

Graduation Report Draft To be handed in at the end of week 10: October 2020 23:59

Final Graduation Report To be handed in at the end of week 16: November 2020 23:59

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11 Appendices

11.1 Cloud Computing SWOT Analysis

11.1.1 Cloud service provider

Table 2: SWOT Cloud Service Providers

Strengths	Weaknesses
Scalability: Using a cloud service enables effortless scaling	*Service Outages*: They do not happen often, but when they happen they are out of the customers control
Lower Costs: Paying only for what the customer uses and not having to worry about maintenance drives down costs	*Longer Upload/Download times*: Compared to an in-house server it will take longer to move large files, as the internet speed is the limiting factor
Lower Capital Expense: Since the customer is not the one buying the hardware	
Global Connectivity: Cloud service providers have a global network of servers and thus the customer can offer his clients a fast connection to a local server	
Security: Cloud service providers have invested heavily into security, since their reputation would be at stake if a breach happened. The customer will always have cutting edge security from a technical standpoint.	
Integration: Since the service is offered as a platform, the customer has access to other services within the providers ecosystem. Big providers like AWS or Microsoft Azure offer an ever expanding selection of services apart from pure server hosting	
Opportunities	**Threats**
Technological Advancements: A cloud service provider will always seek to have the best technology to offset themselves from competition, which benefits the customer	*Termination of Service*: It seems very unlikely, but in theory the service provider could go out of business/terminate the service and thus disrupt the business

11.1.2 In-House Server

In-House servers for rendering purposes can be acquired from graphic card manufacturers such as NVIDIA: https://www.nvidia.com/en-us/design-visualization/quadro-servers/rtx/

Table 3: SWOT In-House Server

Strengths	**Weaknesses**
Total Control: If the customer owns and operates the server, they have complete control over it. They can adjust the server to specifically fit their requirements and thus optimizing performance	*Increased complexity/costs*: Operating a server infrastructure requires experts to administrate and maintain
Faster development/response time: An in-house server is local by nature and thus modifying/fixing things on the server is faster compared to external servers	*Higher Capital Expense*: Since the customer has to buy all the necessary hardware for an in-house server, the upfront investment is higher
Well understood It is easier for developers to become familiar with and develop in-depth knowledge in a server infrastructure they can easily interact with	*Physical Requirements*: Building an in-house server infrastructure requires not only sufficient physical space, but also auxiliary systems such as cooling, (emergency-) electricity and cabling
Opportunities	**Threats**
TBD:	*Obsolescence*: As the owner, the customer would be responsible to upgrade the system if they want/need new features. This of course comes with more costs

11.2 Cloud service providers

The cloud service providers are ranked based on annual revenue from 2018 in Millions of US Dollars (Costello & Goasduff, 2019).

Table 4: Cloud Service Providers by Revenue

Rank	**Company**	**Product**	**Revenue 2018**
1	Amazon	AWS	15,495
2	Microsoft	Azure	5,038
3	Alibaba	Alibaba Cloud	2,499

4	Google	Google Cloud Platform	1,314