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Abstract

In this deliverable, we study the current state of the Virtual Reality industry and analyse the potential evolution of the technology. We then explain why WORTECS objectives of high bandwidth and low latency wireless transmission are necessary and invaluable for developing the full potential of multiuser high quality Virtual Reality, eventually we provide evaluation of the impact of wireless XR solutions on the user experience..

Keyword list

Virtual Reality, Multiuser, High Quality / Low Latency, Wireless, High Bandwidth

Executive Summary

Virtual Reality devices and experiences can take many forms. The widespread availability of commercial Head Mounted Displays and the emergence of Location Based Entertainment venues herald a bright future for multiuser Virtual Reality. Industrial use for collaborative prototyping and proof of concept is also paramount. For multiuser experiences to allow total freedom for each user to walk around, the HMDs need to be free of any tethers connecting them to the computers running the simulation, either by wirelessly transmitting the video data or by integrating powerful GPUs within the HMDs themselves.

However current HMDs are quickly evolving towards higher and higher resolutions to try and match the extremely high requirements of perfect human visual acuity. By increasing resolutions, more computing power will be needed to simulate high quality Virtual Reality solutions. To that end, HMDs will need to rely on high end machines and will not be able to integrate GPUs powerful enough to compute the simulations on-board.

Additionally, the extremely low tolerance of human perception for latency between motion and vision implies that the transmission of images between the powerful computer and the HMD needs to have near zero latency which, in turn, implies low video compression

To evaluate the users' acceptance related to the latency induced by two components required in a wireless solutions (video converter and compression), a user's study has been conducted with 20 participants. The results of the evaluation show that the use of the two components developed as part of the project had no impact on the quality of experience perceived by users.

Finally, the VR market is in full expansion and it is predicted to be worth billions in the coming years so investing now in the future of VR makes complete sense.

The combination of extremely high resolution, low latency, and tetherless experiences implies low latency high bandwidth wireless communication. If multiuser applications are factored in, the need for Tbps communication becomes essential to provide the optimal Virtual Reality experience.

Impact on the other Work-packages

WP3 and WP4: in this deliverable Virtual Reality use case (WORTECS core use case)is described in much more details that what is done in D2.2 deliverable on use cases and requirements and will definitely be very helpful to drive theoretical studies (WP3) and implementation work (WP4) on Virtual Reality.

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List of Acronyms

Acronym	Meaning
AR	Augmented Reality
DoF	Degrees of Freedom
FOV	Field of view
HMD	Head Mounted Display
LBE	Location-based entertainment
LC	Light Communications
MR	Mixed Reality
VR	Virtual Reality
WORTECS	Wireless Optical/Radio TErabit CommunicationS

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1 A Brief History of Virtual Reality

1.1 What is Virtual Reality?

The origins of Virtual Reality (VR) can arguably be traced back all the way to 360 degree murals from the 19^{th} century [1]. But in the context of this project we will be focusing on the following definition of VR [2]:

> *Virtual Reality is a scientific and technical domain that uses computer science and behavioural interfaces to simulate in a virtual world the behaviour of 3D entities, which interact in real time with each other and with one or more users in pseudo-natural immersion via sensorimotor channels.*

According to that definition, there are two major categories of visually immersive VR equipment:

1. Room scale screens on which images are projected with the user fully immersed inside the virtual space wearing externally tracked 3D glasses and equipment. These environments are called CAVE or CAVE-like.
2. Head Mounted Displays (HMD) which are devices worn on the head of a user that have small optic displays in front of each eye.

Figure 1 - A CAVE-like environment (left) and an HMD (right).

Both approaches have their advantages and drawbacks, but their comparison is beyond the scope of this document. However, the main drawback of CAVE-like environments, in the context of WORTECS, is that they do not allow multiple users at the same time. Images displayed by the projectors are dedicated to one specific user's point of view and, even though solutions mixing active and passive stereo exist, they cannot address more than two or three users at the same time while conserving high image quality [3]. This is why we will only be focusing on HMDs.

Even within the HMD family, there are two main categories:

1. Tethered HMDs that have to be connected to a computer processing the VR simulation. Like the Oculus Rift or HTC Vive.
2. Integrated HMDs that do all the computations on the HMD itself. This family also includes slide-on HMDs which consist of a smartphone holder and lenses in which a smartphone is inserted to act as display and computation device, like the Samsung Gear VR or Google Daydream.

While integrated HMDs provide more freedom and mobility, tethered HMDs have access to more processing power and generally also provide positional tracking. Since tethered HMDs have access to powerful top of the line computers, they are able to provide more realistic and more complex processing hungry simulations required for high-level experiences or professional use cases.

1.2 The stakes of VR

The modern form of HMDs has been around since the early 1990s but the recent advances in portable technology and the launch of the Oculus Rift Kickstarter in 2013 pushed VR in the spotlight and made it affordable to the public. The commercial version of the Oculus Rift sold 243 000 units, the HTC Vive sold 420 000 units in 2016 and the Playstation VR sold 950 000 units in just 4 months after its release in November 2016 [4]. Ever since, other HMDs have emerged and VR has made its way into the mainstream.

With mass market adoption, VR is becoming a major player in location-based entertainment (LBE), also known as out-of-home VR or VR arcades (Figure 2). VR LBE has emerged as a key sector within the VR industry and fast-moving companies, such as The Void and Ctrl V, are quickly gaining momentum [5]. In order to accommodate multiple users, multiple stations, and provide enough room for the users to evolve freely in the VR environment, VR LBE needs large open spaces. More than 40% of LBEs have rooms of over 150 square meters, while 35% provide over 20 different gaming stations. And although some of the experiences offered provide specialized static simulators and equipment, over 83% of the players engage in multiuser experiences [6].

Besides VR LBE, there is also the professional use of VR in major companies that has been established for years [7]. Companies such as Ford, Audi and Airbus have been using VR for prototyping, decision making, design, training, maintenance, validation. The Marriott hotel chain has a temperature controlled VR booth that allows its clients to visit hotels in Hawaii or London. Retailers such as the North Face and The Line use VR for virtual shopping. Surgeons are trained through VR technology at UCLA. And there are a lot more seasoned or newcomers in business oriented VR. But most of these frameworks use CAVE-like environments and/or are unusable for collaborative work. Outside observers can watch a single user perform in the virtual environment but they cannot be immersed in the environment at the same time. With wireless HMDs, collaboration can be made possible. Engineers can work together on prototyping. Potential clients can walk around the virtual models while the company representative accompanies them. Trainee surgeons can be guided by their teachers inside the virtual world. There is a lot of potential for multiuser VR in all those fields.

Finally, the use of VR at home for entertainment purposes represents the mainstream that drives current VR development. Although VR at home faces many challenges such as available free space or equipment cost, the market seems very promising. However it is difficult to consider a VR experience involving multiple users collocated in a living room or a bedroom. Moreover, VR AAA games ("blockbuster"-like games) will require high quality content which implies high processing capabilities that could not be embedded in the HMD. In this case, considering untethered VR HMD is becoming a main challenge for most of VR hardware makers. Nevertheless, we will see later in this document that while single user VR experiences will not require Tbps wireless transmission, they will need wireless solutions with bandwidths close to 100Gbps.

2 State of the Art

2.1 Current VR technology

Currently, there are two major players in the VR HMD market (Oculus, HTC) and two new entrants (PiMax and Varjo). Oculus and HTC propose both tethered and untethered HMDs, untethered ones being able to embed computing (Oculus Go, Oculus Quest, HTC Vive Focus), or use a wireless communication between the graphic server and the headset (HTC Vive Cosmos with a Vive wireless adapter). We have seen in the last year the development of Inside-out tracking solutions which do no longer need external to track the headset and its controllers. This inside-out tracking solution can theoretically make them mobile in a boundless space but they are unfortunately still tethered and rely on a computer for processing power.

Name	Resolution per eye	Field of View	Refresh Rate	Release	Tethered	Inside-out Tracking	6DoF
Oculus Quest	1440x1600	100°	72Hz	2019	Both	Yes	Yes
Oculus Rift S	1280x1440	110°	90Hz	2019	Tethered	Yes	Yes
Oculus Go	1280x1440	100°	72Hz	2018	All-in-one	No tracking	3DoF
HTC Vive Cosmos	1440x1700	110°	90Hz	2016	Tethered	Yes	Yes
HTC Vive Focus	1440x1700	110°	75Hz	2018	Untethered	Yes	Yes
PiMax 8K	3840x2160 (panel) 2560x1440 (signal)	170°	80Hz	2019	Tethered	No	Yes
Varjo VR-2	1920x1080 (central) + 1440x1600 (periph.)	87°	60Hz (central) 90 (periph.)	2019	Tethered	No	Yes
Valve Index	1440x1600	130°	87Hz	2019	Tethered	No	Yes

Table 1 – Characteristics of some of the most popular HMDs

As we will detail in Section 3, the resolution per eye and the field of view are both critical components in fully immersive VR and current HMD technology is far behind what is needed for full VR presence.

Another problem posed by tethered HMDs is the actual tether. As we stated earlier tethered HMDs require to be plugged into a computer in order to work. To address this problem, some companies like MSI or HP build VR backpacks that allow the players to carry the computer on their backs while running through the simulation. Wireless VR is even more important for user comfort considering not only the weight of the backpacks, but also the freedom of movement required by the convoluted custom stages built by LBE VR companies to maximize user immersion.

Figure 2 - The Void multiuser experience with custom backpack and a custom built stage [8]

To address this problem, companies like TPCast provide external modules that can be plugged into the computer and the HMD to allow wireless video and audio transmission with extremely low latency [9]. The TPCast boasts latency under 2ms and uses a proprietary wireless protocol in the 60GHz band range for a data bandwidth of 7 Gbps. However, the problem with TPCast and other similar solutions is that they can only be used for one user at a time because it is impossible to get multiplex the signals on the 60GHz band.

2.2 Projected VR technology evolution

The current resolution of HMDs suffers from what is known as the screen door effect. The screen pixel density is low enough that, when viewed up close, the user can see the individual pixels and the black borders surrounding them as if they were looking at an image through a screen door.

Figure 3 - Example of screen door effect

To avoid this problem, the screens used by HMDs have been steadily increasing in resolution ever since the inception of the Oculus Rift DK1 which had a 640x800 pixel resolution per eye. There are currently three different classes of HMDs with varying screen resolutions: the *mass market* HMDs such as the Oculus Quest, the Oculus Rift S, the HTC Vive Cosmos, the HTC Vive Focus are currently at 1440x1600 (or 1440x1700) per eye; and *high-end mono panel* HMDs, such as the PiMax 8K with a resolution of 2560x1440 (with an upscaling on the screen with a perceived resolution of 3840x2160) pixels per eye; finally the *high-end multi-panels* HMDS such as the Varjo VR-2 where the perceived image is optically composed with two panels, one for the central field of view (1920x1080), and a second one for the peripheral field of view 1440x1600). HMD screen resolution is and will remain a major factor in the VR market competition and we believe the resolution will keep increasing with each generation until we reach the optimal resolution of 9000x7800 pixels per eye as detailed in Section 3.1, but multi-panels solutions could offer a sufficient perceived resolution without reaching this theoretical perfect resolution .

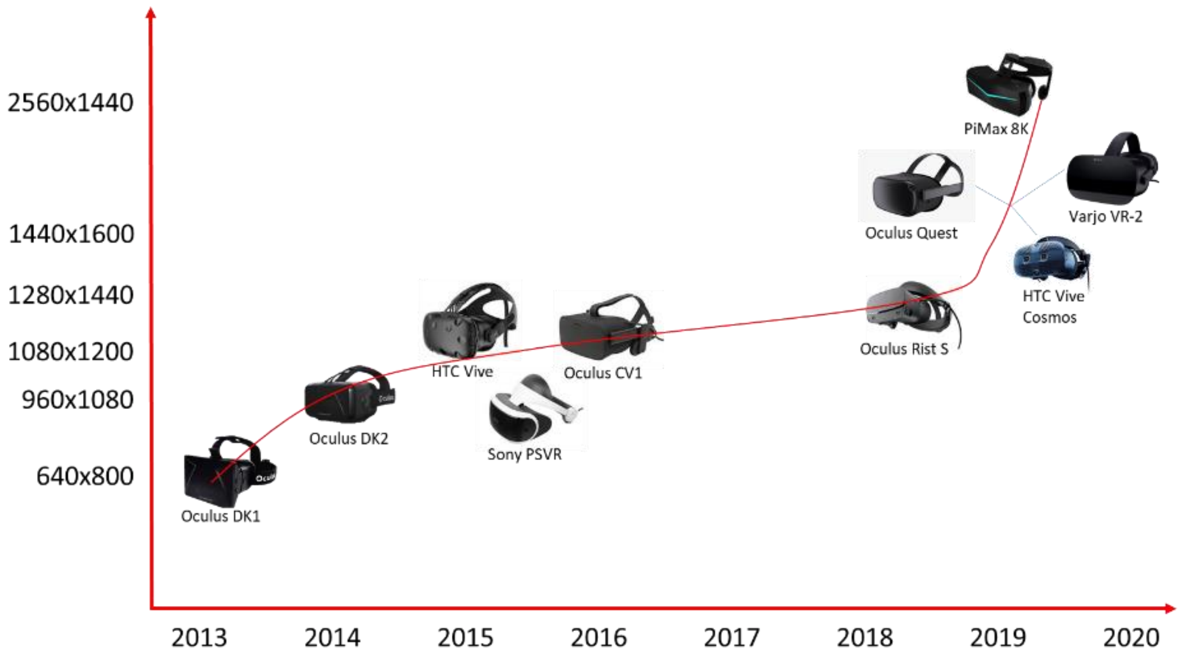

Figure 4 - Evolution of HMD resolution

Indeed, the growth of display resolutions raises the issue of real-time rendering, directly dependent on screen resolution: the higher the display resolution, the longer the rendering takes. To tackle this problem, foveated rendering has recently been proposed. The human retina only perceives extremely high levels of details around the centre of the field of vision. The further away from the retina, the lower the resolution we perceive [10]. By tracking the gaze of a user inside an HMD, it is possible to approximate this biological limitation by only rendering a section of the virtual image in high resolution and displaying lower resolutions on the portions of the screen where the user is not directly looking. However the speed of the human gaze is extremely fast (about 900°/s for saccades), so foveated rendering will have to be highly adaptive.

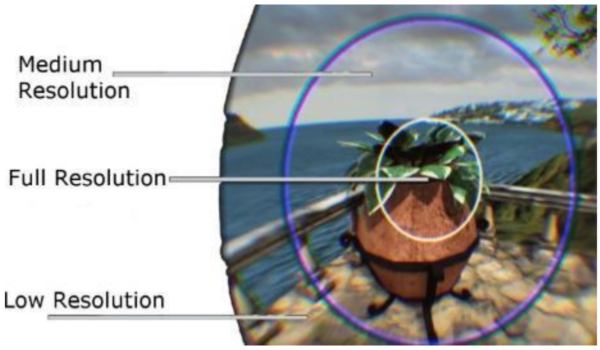

Figure 5 - Foveated rendering

Besides increasing resolution, another barrier for fully immersive free-roaming VR is the restrained area in which a user can move. In the context of tethered HMDs, the largest area in which a user can currently be tracked is 4x4 meters using the HTC Vive lighthouse tracking system. It is possible to build custom solutions using the independent tracking systems developed for CAVE-like systems (such as ART or OptiTrack) but they have to be custom built and custom software developed and externally integrated with existing systems.

The industry is currently working on a solution to this problem through two different approaches. Steam VR Tracking 2.0 will be released in 2018 and allow to use multiple external base stations to track areas up to 10x10 meters wide, and expect to extend this surface in the future [11]. Another method is to completely stop relying on external trackers and use cameras mounted on the HMDs themselves to identify the position and orientation of the HMD by analysing the images recorded by the cameras. Here, the system estimates the pose (position and orientation) of the device based on a well-known method called SLAM (Simultaneous Localization And Mapping) improved with inertial measurements fusion and leveraging stereoscopic cameras to get a better geometric knowledge and the scale of the surrounding environment as well as improving the pose estimation computation. This approach is used by the Hololens Augmented Reality HMD and is being made available for VR HMDs as well through the Microsoft Windows Mixed Reality label [12].

Both solutions do not, however, remove the need of a tether linking the HMD to a powerful computer. We will see in the next section that the amount of data to be transmitted at high resolution and low latency cannot be reliably transmitted with current wireless technologies.

The only obstacle currently standing between tethered VR and completely wireless VR with powerful computers is bandwidth.

3 Ideal VR and project requirements

This section will discuss all the important parameters to take into account while devising a wireless solution for VR.

3.1 Optimal VR resolution

The perception of detail of the human eye depends not only on the resolution and details of the image viewed but also on the distance at which that image is viewed. The farther an image is, the fewer details we are able to perceive [10]. Thus we prefer talking about angular resolution, namely the number of pixels for a specific view angle. The standard goal when testing for 20/20 eyesight is a resolution of one arc minute, this means that a person with good eyesight can distinguish details as small as one sixtieth of a degree. This is the current standard and many people can have superior visual acuity.

Furthermore, each eye has a field of view (FOV) of 150° with a 90° overlap in the middle, allowing human depth perception. The 60° to each side are used by peripheral vision and allow us to detect movement and warn us from danger. So in order to avoid the “diving mask” feeling when wearing an HMD and not feel that the field of view is confined, we need HMDs capable of the full 210° FOV.

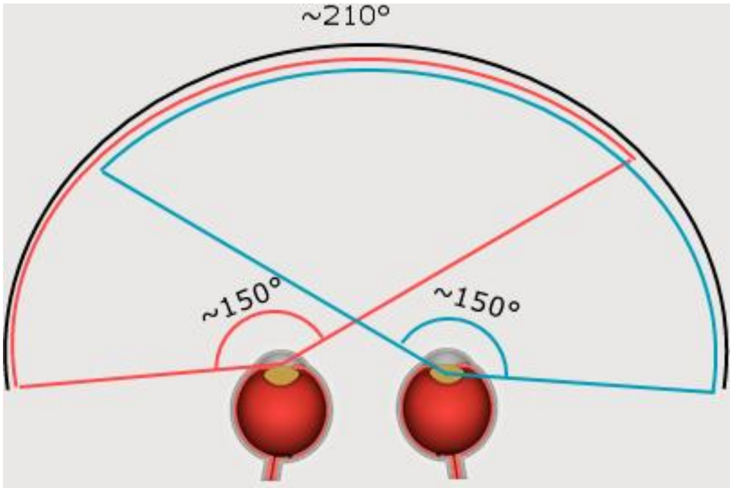

Figure 6 - Human Field of View

Considering the 20/20 eyesight standard resolution of one arc minute and the 150° horizontal FOV per eye, we would need a resolution of 9000x7800 pixels per eye in order to avoid the screen door effect. At this resolution, the human eye will be incapable of distinguishing the individual pixels and thus perceive a perfectly clean and clear image.

3.2 Optimal VR frequency

It is widespread knowledge that, in order to perceive perfectly fluid motions, a frequency of 24 images per second is sufficient. That might be the case for cinema and television, but it is definitely not enough for VR. When you look at a still image from a rapidly moving film, you do not see an image with crystal clear objects but all the fast moving objects will be blurry because they are in motion. This phenomenon of motion blur is inherent to the way video cameras record movement. This effect is interpreted by the human brain through what is called beta movement, and helps fill in the gaps between the images by providing motion information [13].

3D rendered images are, on the other hand, crystal clear and perfectly in focus. There is no motion blur to provide data to the brain in order to fill in the gaps. Some game engines do include motion blur effects to enhance the fluidity of perceived movement on lower frequencies but these effects can never predict the direction in which a user will change their point of view (and so cannot predict in which direction the motion blur has to be applied until the user has already moved his head).

Another phenomenon related to the VR display frequency is judder smearing. Judder can be caused by different factors, but the most obvious and most related to VR can be caused by head movement. When you turn your head at normal speed, it’s about 120 degrees per second. To make things easier, let’s suppose we are using a 60 Hz display. This means that your head moves by two degrees each frame. As can be seen in Figure 7, even a two degree smear is extremely detrimental to visual quality [14].

Figure 7 - Illustration of a 2 degree judder smear

Because of the absence of motion blur, and judder smear, a frequency of at least 120Hz (some even argue 240Hz) is needed in order for the HMD user's brain to perceive fluid and continuous movement without smear or hiccups [14].

3.3 Latency and compression

When it comes to VR, low latency is fundamental for a comfortable experience and avoiding motion sickness. The time between when a user moves his head and when the corresponding image is displayed on the HMD screen is called photon to motion latency. Research indicates that 15ms might be the threshold for this latency, or it can even be as low as 7ms [15]. Knowing that the full motion to photon pipeline includes tracking, rendering, time warp and display, no more than 2 to 5ms can be allocated to the video encoding, streaming and decoding for wireless solutions (see Figure 9 below).

This means that, if we want to use wireless transmission to send the image from a computer to an HMD, we cannot rely on standard image encoding algorithms that can be way too slow. Few so called zero-latency algorithms based on intra coding are able today to handle 2x9000x7800 resolution at 120Hz with less than 2ms of delay by providing a compression ratio up to 4:1 (VC-2, TICO, etc.).

As can be seen in Table 2, a few solutions currently exist or are planned to address wireless transmission of VR video data. However they all use either the 5GHz or the 60GHz bandwidth which are insufficient for transmitting higher resolution video streams.

Name	Protocol	Bandwidth	Latency	Max Resolution
TPCast	Proprietary?	7 Gbps?@60 GHz	<2ms	2x1080x1200@90Hz
Kwik VR	802.11ac	1 Gbps@5 Ghz	<12ms	2x1080x1200@90Hz
DisplayLink wireless VR	802.11ac & 802.11ad	7 Gbps@60Ghz	3-5ms	4K panels (3840x2160)
Immersive VR	802.11ac & 802.11ad	7 Gbps@60 GHz	1ms	4K (lossy 20:1)
Immersive Robotics Mach-2K	802.11ac & 802.11ad	7 Gbps@60Ghz	2-3ms	4K panels@120Hz (10:1)
NGCodec	802.11ac	1 Gbps@5 Ghz	<12ms	2x1080x1200@90Hz (lossy 500:1)
Nitero	802.11ad	7 Gbps@60 GHz	1ms	2x1080x1200@90Hz

Table 2 - Wireless VR solutions

Most current wireless solutions struggle with the issue of balancing image quality (with lossless compression and very high resolution images), latency (with fast algorithms) and bandwidth (for transmitting large amounts of data). As illustrated in Figure 8, low latency and low compression mean high bandwidth, low latency and low bandwidth mean high compression, etc.

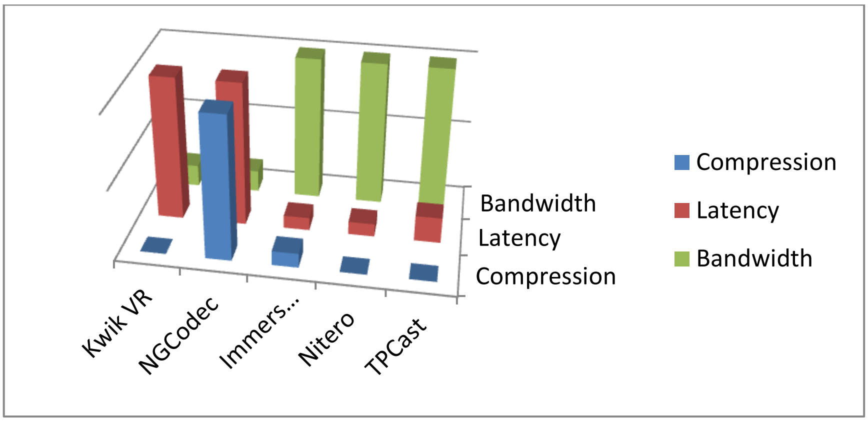

Figure 8 - Correlation between compression, latency and bandwidth in wireless solutions

3.4 Optimal Bandwidth

To recap the previous paragraphs of this section, we need an extremely high resolution image of 9000x7800 pixels per eye, computed at a frequency of 120Hz, and transmitted to the HMD wirelessly with extremely low latency as can be seen in Figure 9.

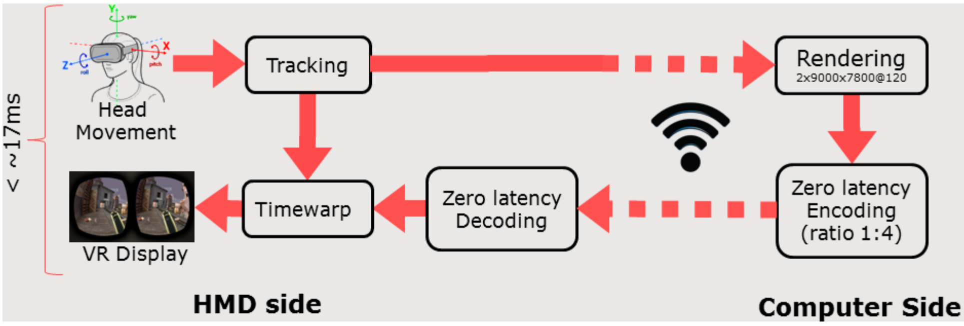

Figure 9 - Wireless HMD example

If we assume that a good low latency image compression algorithm can provide a ratio of 4 to 1, we can compute the required bandwidth per eye in the following table:

Resolution	Raw Bandwidth	Low-latency compression bandwidth(4:1)	Wireless technology
2x640x480 @60Hz	842 Mbps	210 Mbps	802.11ac
2x960x1080 @90Hz	4.16 Gbps	1004 Mbps	802.11ad
2x1080x1200 @90Hz	5.2 Gbps	1.27 Gbps	802.11ad
2x1440x1600 @90Hz	9.26 Gbps	2.23 Gbps	802.11ad
2x2560x1440 @90Hz	14.82 Gbps	3.7 Gbps	802.11ad?
2x3840x2160 @120Hz HDR	55.6 Gbps	13.9 Gbps	???
2x9000x7800 @120Hz HDR	470 Gbps	120 Gbps	???

Table 3 - Bandwidth requirements for wireless HMDs

So for an HMD running 9000x7800 image resolution per eye at 120Hz, we would need 120Gbps of bandwidth per user. It becomes clear that if the future of VR is simultaneous multiuser wireless applications, extremely high bandwidth wireless networks approaching Tbps are required.

3.5 Upload Bitrate

The data transmitted from the headset to the computer consists of sending the pose (which contains the position and orientation) of the headset and its two associated controllers. Generally, the position contains three values composing the translation and the orientation contains four values composing a quaternion.

No official data has been released concerning the current headsets, but some user studies show that for the HTC Vive, the 3 poses are sent at a frequency roughly equal to 225Hz [16]. This amounts to an upload data rate of about 277Kbps which is negligible considering the current context.

In one of our setups at b<>com, we use the Leap Motion sensor to track user hand gestures. The Leap Motion sends 8-bit depth images from two different IR cameras at 640x240 resolution at 115Hz. This allows us to estimate the data bandwidth of the Leap Motion at approximately 270Mbps. This bandwidth is relatively high and if such devices are needed in the future, they need to be taken into account.

Furthermore, it would be possible, outside the scope of the WORTECS project, to imagine audio communication between participants or even head mounted cameras that visualize the environment, extract other users and points of interest, and re-inject them in the virtual world. In such cases, the cameras would need to have the same quality and resolution as displayed by the HMD and would need as much upload bandwidth as the download bandwidth computed in Table 3.

3.6 Audio Bitrate

A fully immersive VR experience does not only rely on high resolution images, but also on high quality audio. The human ear has difficulty distinguishing sounds above 20 KHz, but the industry standard for high quality audio in video is 48 KHz (whereas audio CDs for example use 44.2 KHz). The dynamic range perceptible by the human ear is around 100dB which can almost be completely covered by 16 bit linear PCM audio [17].

So just for theory's sake, if we compute the bandwidth needed for 24 bit audio, sampled at 96KHz coming from 128 different objects at once we would need 281,25 Mbps of data bandwidth.

Even with this extreme audio scenario, the bandwidth needed is insignificant compared to the bandwidth needed to transmit video content.

4 Evaluation

4.1 Aim of the users' study

WORTECS project aims to deliver ultra-high wireless data rates combining high frequency (above 90GHz) radio communication with optical wireless communications using novel heterogeneous networking concepts.

In this chapter we present the evaluation, based on a virtual reality use case, of the users' acceptance of two technologies developed in the framework of WORTECS project. The two assessed technologies are 1) the video converter and 2) the compression algorithm.

The video converter adapts video signal from HDMI standard to IP one, while the compression algorithms adapts the video throughput to the wireless link capability. This components are the two core elements of the WORTECS wireless set-up and will be present in the system regardless to the wireless technology that will be used.

The integration of these two elements in a conventional virtual reality set-up will add processing steps (and increase the latency) to the normal video flow. Such extra processing will obviously imply an increase (even if minimal) of the video transmission time and potentially some modifications in the video signal delivered to the virtual reality headset.

The aim of our study is to assess if these modifications (in time and in the nature of the video signal) are significant enough to affect the user experience in the virtual environment. In particular we will focus our assessment of the users' experience on the following three aspects: 1) the safety of the system assessed via a virtual reality sickness questionnaire, 2) the global quality of the experience assessed via a presence questionnaire and 3) the visual quality of the experience assessed via a perceived quality questionnaire.

4.2 The evaluation of the users' experience

The aim of our evaluation is to assess the possible impact of the introduction of two technological components developed in the framework of WORTECS project (the video converter and the data compression algorithm) on the user experience during a virtual reality session.

For this reasons two separate experimental sessions were organized in two different days and with different participants.

The first session tested the impact of the video converter without any compression while the second session tested the impact of the video converter with a compression to simulate a maximal bandwidth of 860 Mbits. This bandwidth is equivalent to the one obtained during preliminary test using the Optical Wireless Connection (OWC) that is the weakest (in terms of bandwidth) of the three wireless technologies used in WORTECS.

The experiment took place at the b<>com headquarters in Rennes (France) the 22^{nd} and 23^{rd} of November 2019. A total of twenty attendees (ten each day) participate to the experience.

During each experimental session, two participants will experience the same virtual reality content (Virtual Arctic Expedition), one time using a conventional virtual reality set-up and the other time using the set up integrating the WORTECS technologies.

The evaluation of the user experience focused on the three following elements:

1. The safety of the system, assessed via a virtual reality sickness questionnaire.
2. The global quality of the experience, assessed via a presence questionnaire.
3. The visual quality assessed via a video quality and artefacts questionnaire.

1) The safety was assessed via a virtual reality sickness questionnaire. The virtual reality sickness (VR sickness) is the feeling of discomfort that a user can feel while experiencing virtual reality content. For our evaluation we adopted the French version of the SSQ translated and validated by the laboratory of cyber-psychology of the "Université du Québec en Outaouais" (UQO) [18].

2) The global quality of the experience was assessed via a presence questionnaire. Presence is the subjective feeling of the participant to be "really" inside the virtual environment and is often used as an indicator of the global quality of the user experience. The feeling of presence is multidimensional and could be negatively affected by the presence of visual artefacts or lack of reactivity in the system. For our evaluation we decided to adopt the The Igroup Presence Questionnaire (IPQ) [19].

3) The third and last aspects of the user experience that we decide to assess were the perceived video quality. At today there is no standardized questionnaire for the assessment of the perceived video quality. As a consequence we developed our questionnaire that is divided in 2 parts. The first part asks the participant to assess various aspects of the video quality (colour reproduction, contrast, outlines definition and fluidity). The second part of the questionnaire is constituted by 5 questions focusing on the presence (and degree of annoyance) of the following artefacts:
   - Flickering
   - Ghosting
   - Lack of reactivity
   - Compression macroblock (blobs of pixels)Freezing images or black screens

4.3 Results

In this section we will present for each of the assessed dimensions (virtual reality sickness, presence and perceived video quality) the results obtained introducing the video converter without compression in the first part, and with compression in the second part.

Considering the reduced number of participants (10 for each experimental condition), the nature of the questionnaires and the experimental design, the statistical test adopted for our analysis is the Wilcoxon signed-rank test for paired measures. The p-value (the probability of obtaining the observed results of a test, assuming that the null hypothesis is correct) was set to the usual level of 0.05.

4.3.1 Virtual Reality sickness

The analysis of the data, collected during the first day of study, shows that there is no statistical difference in the perceived virtual reality sickness between a conventional VR set-up and the VR set up integrating the video converter without compression. This results concerns both the global level (V=23 p=0.5261) and its two components that are Nausea (V=18.5 p=0.1058) and Ocular (V=6 p=0.7855).

Similar results have been obtained when analysing the data of the second day of study. No statistically significant differences have been found in the perceived Virtual Reality Sickness of the participants as a consequence of the introduction of the video converter and the data compression at 860mbps. This is true for the global dimension of the VR sickness (V=11 p=1.0) as well as for each of its two individual components Nausea (V=4 p=0.4076) and Ocular (V=8 p=0.3613).

4.3.2 Feeling of presence

The assessment of the users' feeling of presence shows that the adoption of the video converter does not affect in a significant way the feeling of presence. The results presented in Table 4**Table 1** show that there isn't any statistically significant difference between the conventional set up and the set up including the video converter for any of the four dimensions (general presence, spatial presence, involvement and experienced realism) of the IPQ questionnaire.

IPQ Dimension	V	p-value	Significant at p=0.05
General presence	7	0.4840	Not Significant
Spatial presence	18	0.6356	Not Significant
Involvement	9.5	0.2567	Not Significant
Experienced realism	23.5	0.9526	Not Significant

Table 4: Wilcoxon signed rank test result for IPQ in the condition video converter without compression

Similar results have been obtained for the data collected in the second day of the study. The Wilcoxon signed rank test performed on the IPQ scores shows again a lack of statistical difference between the conventional VR set-up and the VR set-up integrating the video converter and the compression (860mbps) concerning the perceived feeling of presence. The results of this statistical analysis are detailed in Table 5.

IPQ Dimension	V	p-value	Significant at p=0.05
General presence	3	0.3458	Not Significant
Spatial presence	19	0.4428	Not Significant
Involvement	19	0.7197	Not Significant
Experienced realism	17.5	0.6049	Not Significant

Table 5: Wilcoxon signed rank test result for IPQ in the condition video converter with compression

4.3.3 Perceived video quality

The last aspect of the user experience we decided to assess was the perceived video quality. This assessment focused on two distinct aspects of the video experience: the first one concerns the general visual quality while the second one focuses on the presence of artefacts.

Concerning the data collected during the first day, the statistical analysis shows no difference between the answers of the participants using conventional set-up and the ones using the set-up integrating the video converter. This lack of statistical difference concerns both the assessment of the general video quality (Table 6) and the assessment concerning the artefacts (Table 7).

Video Quality	V	p-value	Significant at p=0.05
Colors	1.5	1.000	Not Significant
Contrast	0	1.000	Not Significant
Contours	9.5	0.4821	Not Significant
Fluidity	17	0.6698	Not Significant

Table 6: Wilcoxon signed rank test result for the perceived video quality in the condition video converter without compression

Artefacts	V	p-value	Significant at p=0.05
Flickering	10	0.1003	Not Significant
Ghosting	1	1.0000	Not Significant
Reactivity	5	1.0000	Not Significant
Macroblocks	4.5	0.5862	Not Significant
Freezing	3.5	0.7127	Not Significant

Table 7: Wilcoxon signed rank test result for the perceived artifacts in the condition video converter without compression

Similar results are found comparing the data of the classical VR set-up and the one integrating the video converter with the data compression. Like in the previous case, in fact there is a general lack of statistical differences between the 2 VR set-ups for both the general video quality (Table 8) and the artefacts (Table 9).

Video Quality	V	p-value	Significant at p=0.05
Colors	7.5	0.4237	Not Significant
Contrast	24	0.0726	Not Significant
Contours	22	0.6082	Not Significant
Fluidity	15	0.3741	Not Significant

Table 8: Wilcoxon signed rank test result for the perceived video quality in the condition video converter with compression

Artefacts	V	p-value	Significant at p=0.05
Flickering	3.5	0.3430	Not Significant
Ghosting	5	0.4227	Not Significant
Reactivity	3	0.3711	Not Significant
Macroblocks	5	0.4227	Not Significant
Freezing	4	0.7893	Not Significant

Table 9: Wilcoxon signed rank test result for the perceived artifacts in the condition video converter with compression

4.3.4 Conclusions

In this study we assessed the impact of two of the WORTECS technologies (the video converter module and the data compression algorithm) on three aspects of the users' experience during a virtual reality session. The three chosen aspects were the virtual reality sickness, the feeling of presence and the perceived visual quality.

The study takes place in two independent experimental sessions, one to assess the impact of the video converter without compression, and the other to assess the impact of the video converter and the data compression.

Within the limit of the reduced number of participants (ten for each independent session) the results of this study support the hypothesis that the tested technologies (with or without compression) do not impact in a statistically significant way any of the investigated aspects.

5 Economic environment

5.1 Current context

VR has broken into the mass market and has become more commonplace. As can be seen in the 2017 Gartner Hype Cycle [18] in Figure 10, VR is set to reach the Plateau of Productivity in the next 2 to 5 years. It should be noted that in 2018 Gartner Hype Cycle, VR technology has disappeared, showing that it has become mature enough. Furthermore, the need for wireless untethered VR is also currently being addressed as we saw earlier in Table 2.

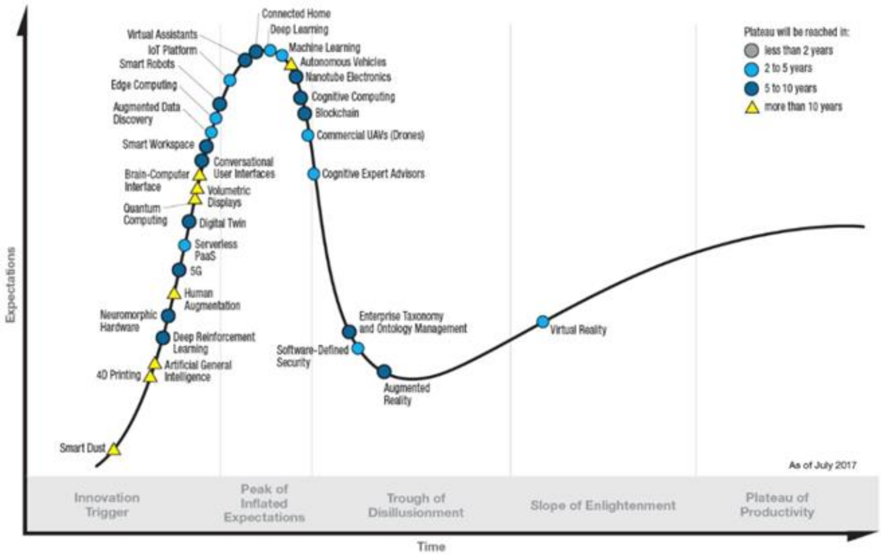

Figure 10 - Gartner Hype Cycle for Emerging Technologies as of July 2017

As can also be seen in the Gartner graphic above, Augmented Reality (AR) is also set to move on to the Plateau of Productivity in the next 5 to 10 years. Both technologies work hand in hand to bring new experiences to users and massive investments are being made in both emerging fields [19, 20].

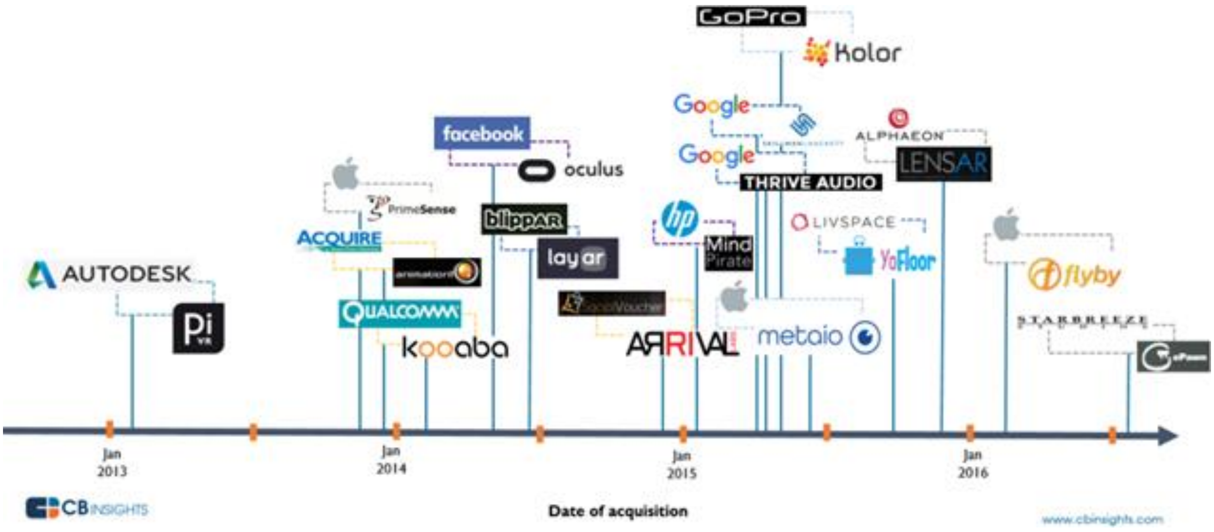

Figure 11- VR/AR's Major Acquisitions as of 2017

5.2 Market analysis and key trends

The market for VR is set to be huge. Although projections vary, they agree on two things: the market will be worth billions, and it will generate exponentially more revenue [21, 22, 23].

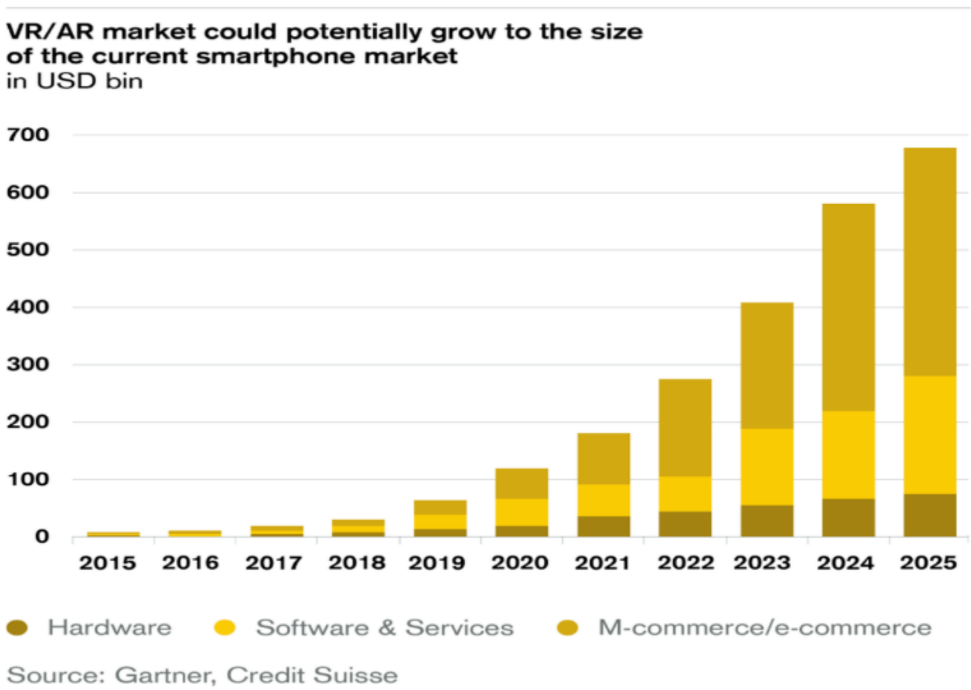

Figure 12 - VR Market projections

VR revenues are currently mostly generated by hardware sales, and the trend will remain in the near future [23] as illustrated in Figure 13.

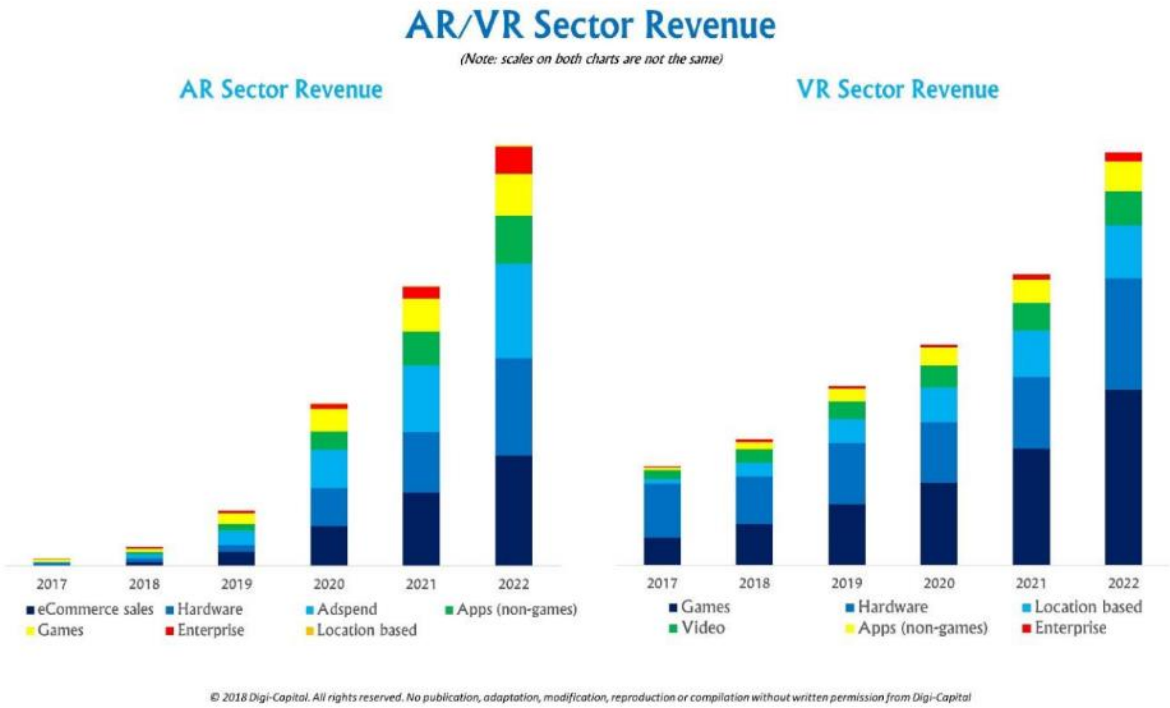

Figure 13 - Total revenues by category for AR and VR sectors from 2017 to 2022

This means that companies, consumers and businesses do and will need to equip themselves with cutting edge hardware to access the latest VR technologies. And looking at the emerging market for wireless accessories presented in Table 2, there is and will still be a need for cutting edge wireless untethered VR. As can be seen in Figure 13, VR has been adopted societally in various markets such as LBEs, enterprises and companies, advertisers, services and other consumer markets.

5.3 Competition and ecosystem analysis

Major historical technology players such as Google, Facebook and Apple are heavily investing in the VR/AR industry and acquiring small promising tech companies to stay ahead of the competition [19, 20].

Pushing the boundaries of the current VR paradigm by providing an extremely high performance wireless VR solution could provide an edge in the current market competition.

One might argue that another solution for untethered VR would be to integrate the entire computing power into the headset itself, and thus get rid of the need for a powerful high end computer with wireless transmission. Although this solution is viable for the current state of VR, the computing power and energy consumption of current and future embedded graphics processors will not be able to cope with the extremely high resolutions needed for realistic VR [24], as is projected in Figure 14.

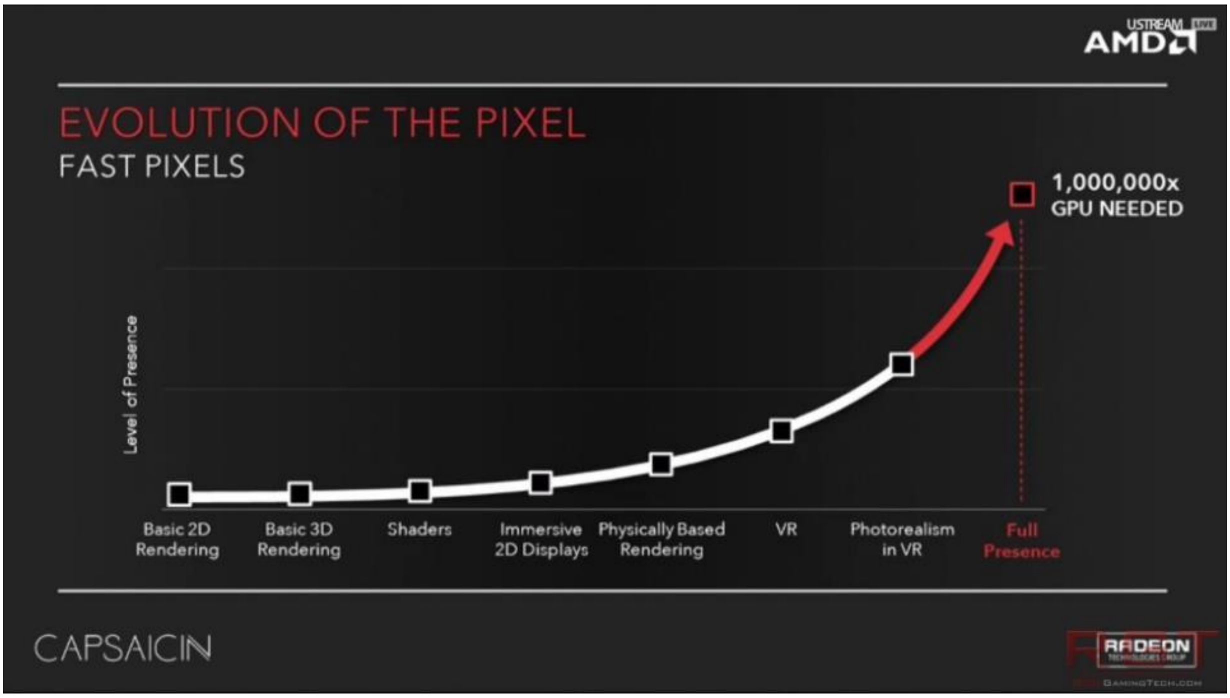

Figure 14 - Evolution of the GPU computing power for full VR presence

6 Conclusion

Virtual Reality is quickly becoming a fast growing market and the technology is fast evolving. In order to accommodate the growing market of multiuser VR, untethered VR is mandatory. But growing resolutions and graphics performance to enhance immersion of the end user means that more and more computer power will be needed to simulate realistic VR worlds in ultra-high resolutions of 9000x7800 pixels per eye in HDR. Furthermore, the low photon to motion latency required to avoid motion sickness implies that zero latency compression is needed to transmit the video data, resulting in the need for extremely high bandwidth needs.

At its most ideal resolution a bandwidth of 470 Gbps is needed per user in the case of uncompressed video, while zero latency encoding can bring it down to around 120Gbps par user. The key performance indicators (KPI) table below recaps the different bandwidth requirements for optimal wireless multiuser VR.

Name	Requirement		
	Mass Market VR	**High End VR**	**Prototype VR**
Potential HMD	HTC Vive Cosmos / Oculus Quest	Pimax 8K	N/A
Resolution	2 x 1440 x 1700	2x3840x2160 (2x4K)	2x7280x4320 (2x8K)
Bits per pixel	24	30 (HDR)	30 (HDR)
Frequency	90Hz	120Hz	120Hz
Connection density	10 users / 100m²		
DL Data Rate per user	9.8Gbps	55.62Gbps	210.88Gbps
DL Traffic Density	98.5Gbps / 100m²	556.2Gbps / 100m²	2.06Tbps / 100m²
Low latency video compression bandwidth for 10 users (4:1)	24Gbps	139Gbps	527.2Gbps
Video Stream Latency	<2ms	<2ms	<2ms

Table 10 - KPI and estimated requirements for wireless multiuser VR in 2020

This clearly shows the need for Tbps connections and beyond in order to allow the spread and growth of multiuser VR applications.

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