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## WORTECS

### Networking research beyond 5G

## Deliverable D2.3a

Focus on Virtual Reality

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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.*



**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.*

*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 19th 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 three major players in the tethered HMD market: the Oculus (Rift CV1), The HTC (Vive) and the Sony (Playstation VR). All three HMDs are wired and also rely on some external devices to track the headset and its controllers. This last point is addressed by some of the next generation HMDs like the Samsung Odyssey or any other headset relying on Windows Mixed Reality technology: these headsets, based on inside-out tracking technology, can estimate their position and orientation without relying on external devices. This theoretically can 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 | External Tracking | 6DoF |
|---|---|---|---|---|---|---|---|
| Oculus Rift CV1 | 1080x1200 | 110° | 90Hz | 2016 | Yes | Yes | Yes |
| HTC Vive | 1080x1200 | 110° | 90Hz | 2016 | Yes | Yes | Yes |
| Playstation VR | 960x1080 | 110° | 120Hz | 2016 | Yes | Yes | Yes |
| Oculus Go | 2560x1440 | 110° | 90Hz | 2018 | No | No | 3DoF |
| Samsung Odyssey | 1440x1600 | 110° | 90Hz | 2018 | Yes | Yes | Yes |
| Windows Mixed Reality | 1440x1440 | 105° | 90Hz | 2017 | Yes | Yes | 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 Rift or the HTC Vive are currently at 1080x1200 pixels per eye; *high-end* HMDs, such as the StarVR promise resolutions of 2560x1440 pixels per eye; finally *prototype* HMDS such as the soon to be released Pimax 8K VR claims a 3840x2160 pixel resolution per eye. 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.

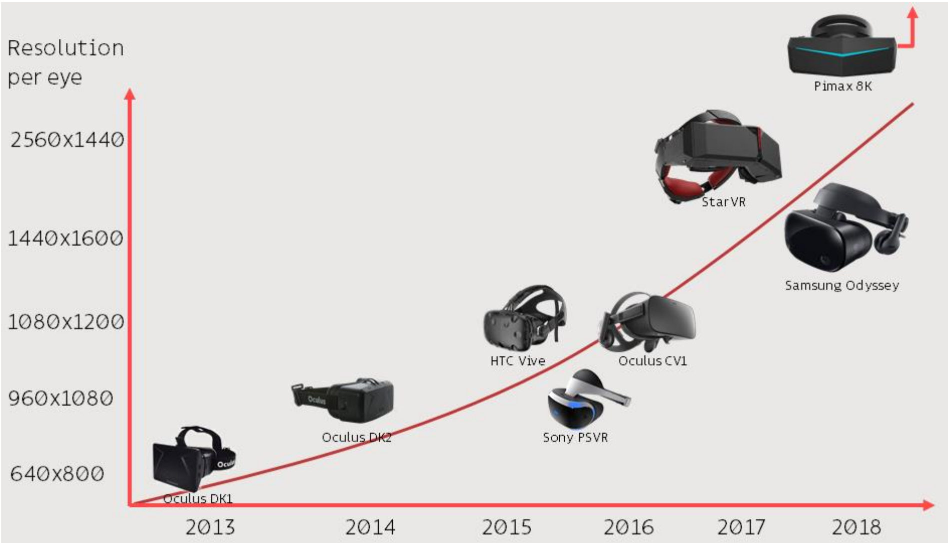


**Figure 4 - Evolution of HMD resolution**

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.

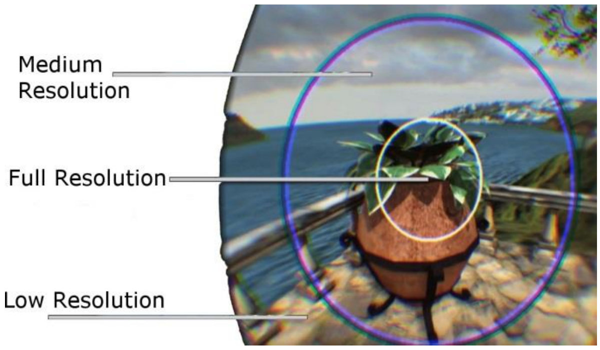


**Figure 5 - Foveated rendering**

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.

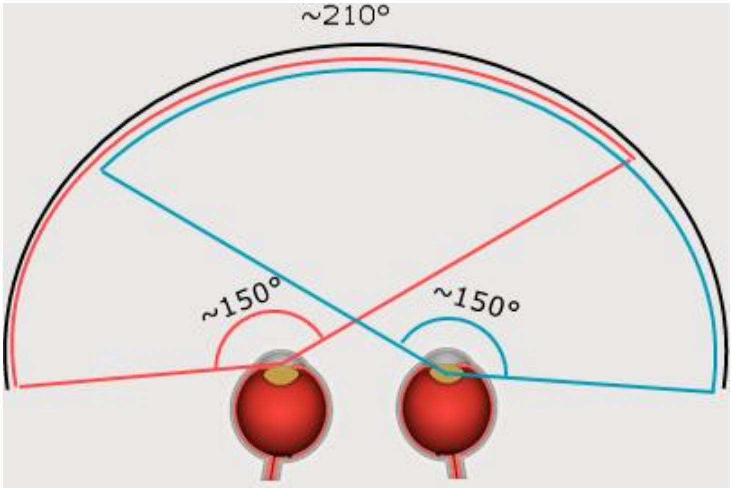


**Figure 6 - Human Field of View**

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 |
| Immersive VR | 802.11ac & 802.11ad | 7 Gbps@60 GHz | 1ms | 4K (lossy 20:1) |
| 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.

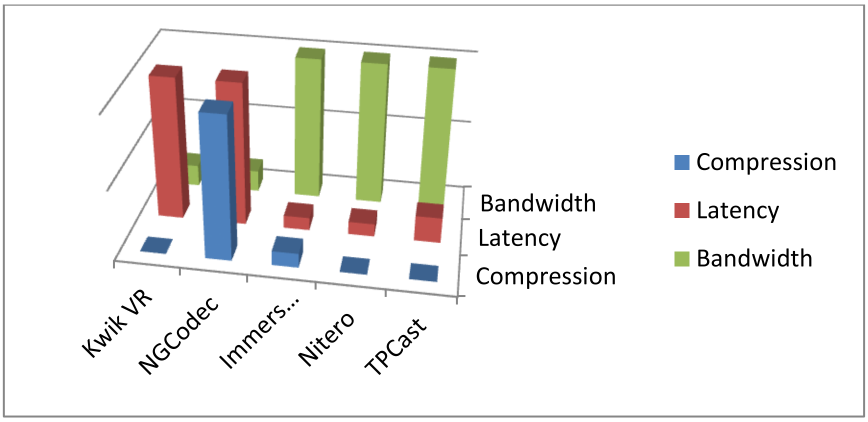


**Figure 8 - Correlation between compression, latency and bandwidth in wireless solutions**

## 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.

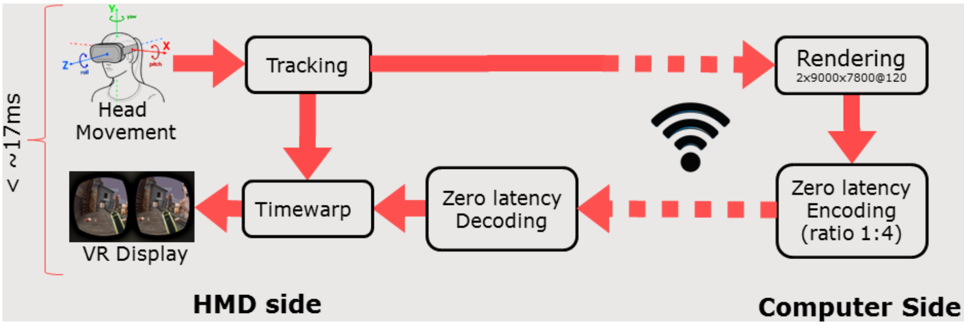


**Figure 9 - Wireless HMD example**

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 Economic environment

## 4.1 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. Furthermore, the need for wireless untethered VR is also currently being addressed as we saw earlier in Table 2.

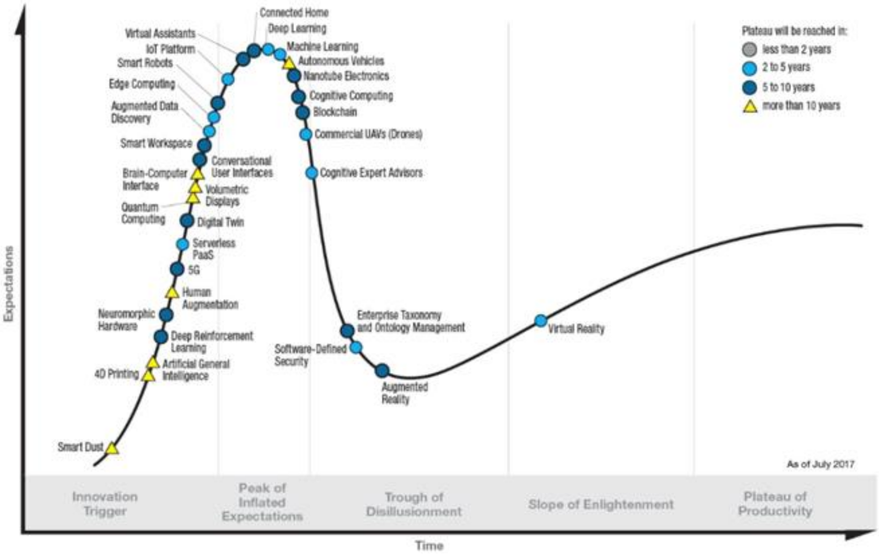


**Figure 10 - Gartner Hype Cycle for Emerging Technologies as of July 2017**

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].

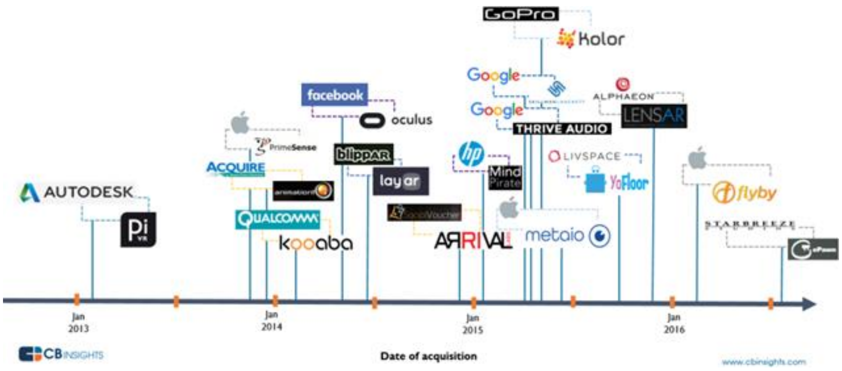


**Figure 11- VR/AR's Major Acquisitions as of 2017**

## 4.2 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].

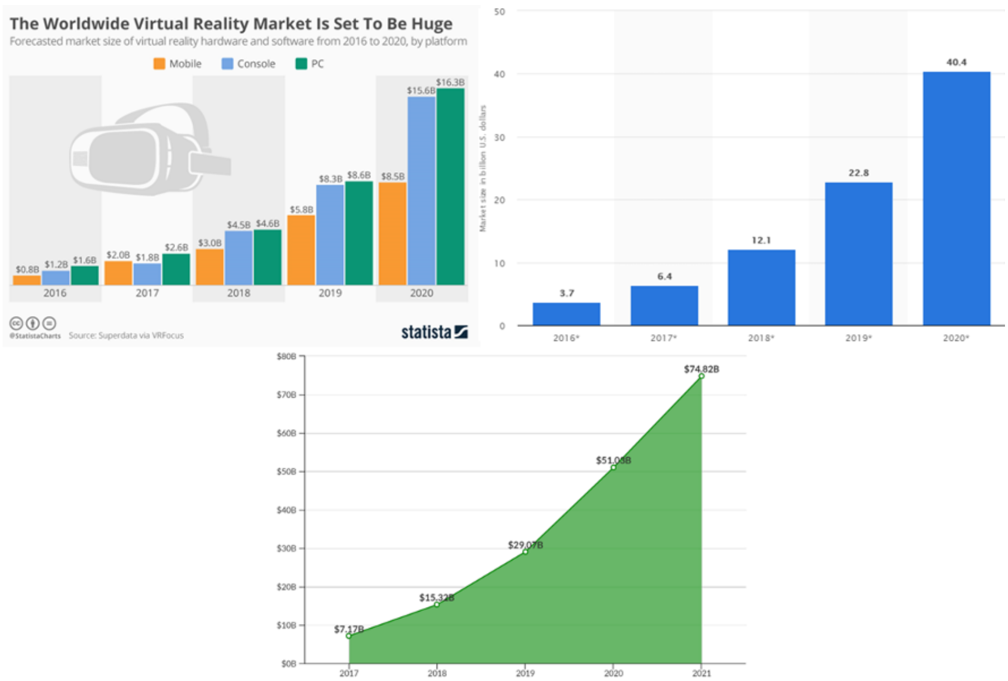


**Figure 12 - VR Market projections**

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

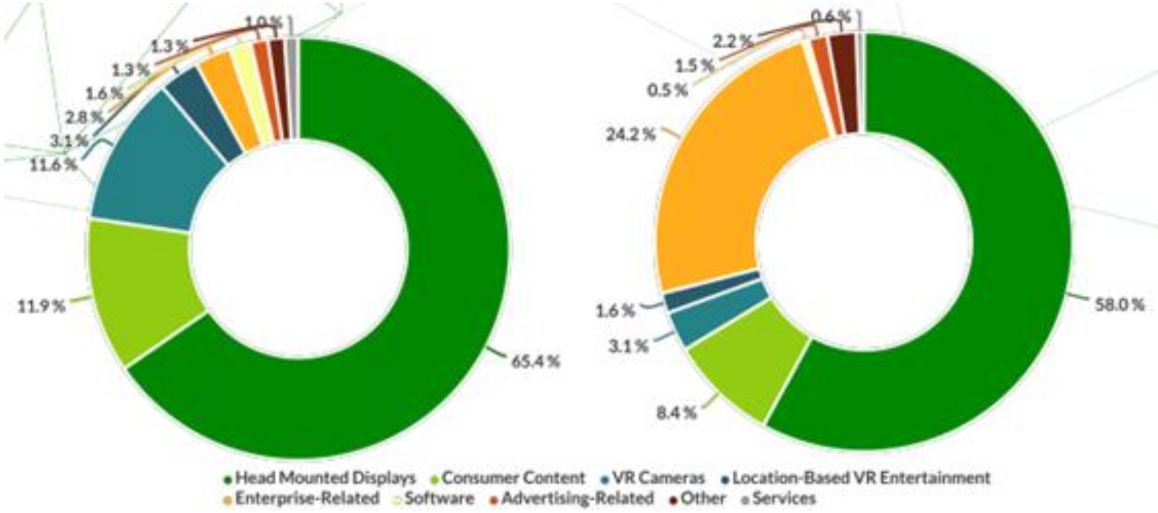


**Figure 13 - Total revenues by category 2017 (left) vs. 2021(right)**

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.

## 4.3 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.

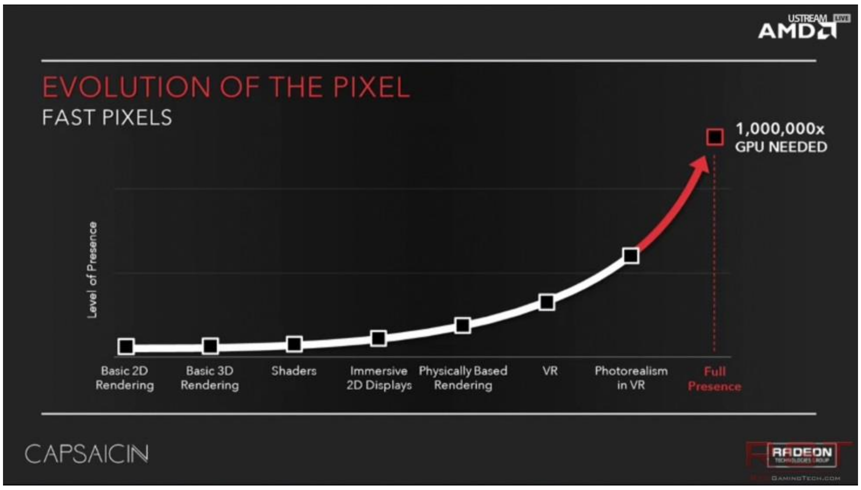


**Figure 14 - Evolution of the GPU computing power for full VR presence**

# 5 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 | Star VR | Pimax 8K | N/A |
| Resolution | 5120x1440 (5K) | 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 | 14.8Gbps | 55.62Gbps | 210.88Gbps |
| DL Traffic Density | 148.3Gbps / 100m² (1.48Tbps / km²) | 556.2Gbps / 100m² (5.56Tbps/km²) | 2.06Tbps / 100m² (20.6Tbps/km²) |
| Low latency video compression bandwidth for 10 users (4:1) | 37Gbps | 139Gbps | 527.2Gbps |
| Video Stream Latency | <2ms | <2ms | <2ms |

**Table 4 - 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.

# 6 References

[1] Virtual Reality Society, “History Of Virtual Reality,” 2016. [Online]. Available: https://www.vrs.org.uk/virtual-reality/history.html.

[2] P. Fuchs, G. Moreau and P. Guitton, Virtual Reality: Concepts and Technologies, CRC Press, 2011.

[3] A. Kulik, A. Kunert, S. Beck, R. Reichel, R. Blacj, A. Zink and B. Froehlich, “C1x6: a stereoscopic six-user display for co-located collaboration in shared virtual environments,” *ACM Transactions on Graphics (TOG) - Proceedings of ACM SIGGRAPH Asia 2011,* vol. 30, no. 6, 2011.

[4] Haptical, “The latest virtual reality headset sales numbers we know so far,” March 2017. [Online]. Available: https://haptic.al/latest-virtual-reality-headset-sales-so-far-9553e42f60b5.

[5] VRNISH, “VR location-based entertainment: the catalyst of VR?,” September 2017.

[6] smartVR, “Les Salles d'Arcade en Réalité Virtuelle,” September 2017.

[7] J. M. O'Brien, “The Race to Make Virtual Reality an Actual (Business) Reality,” Fortune, 2016. [Online]. Available: http://fortune.com/virtual-reality-business/.

[8] The Verge, “Dream Park: From giant robots to haptic spiders, the real future of virtual worlds,” July 2016. [Online]. Available: https://www.theverge.com/2016/7/1/12058614/vr-theme-parks-disney-six-flags-the-void-ghostbusters-virtual-reality.

[9] TPCast, “TP Cast,” [Online]. Available: https://www.tpcastvr.com/product.

[10] Red Digital Cinema, “Human Eyesight & 4K Viewing,” 2017. [Online]. Available: http://www.red.com/learn/red-101/eyesight-4k-resolution-viewing.

[11] Steam VR, “Base Station Forecasting Request,” October 2017. [Online]. Available: http://steamcommunity.com/games/steamvrtracking/announcements/detail/1462966590052827478.

[12] Microsoft, “Introducing Windows Mixed Reality,” 2017. [Online]. Available: https://www.microsoft.com/en-us/windows/windows-mixed-reality.

[13] R. Munday, “The Moving Image,” 03 07 2014. [Online]. Available: http://visual-memory.co.uk/daniel/Modules/FM21820/visper08.html.

[14] M. Abrash, “Why virtual isn’t real to your brain: judder,” 20 June 2013. [Online]. Available: http://blogs.valvesoftware.com/abrash/why-virtual-isnt-real-to-your-brain-judder/.

[15] M. Abrash, “Latency – the sine qua non of AR and VR,” 29 December 2012. [Online]. Available: http://blogs.valvesoftware.com/abrash/latency-the-sine-qua-non-of-ar-and-vr/.

[16] O. Kreylos, “Lighthouse tracking examined,” 25 May 2016. [Online]. Available: http://doc-ok.org/?p=1478.

[17] N. Young, “Music Downloads...and why they make no sense,” 1 March 2012. [Online]. Available: https://people.xiph.org/~xiphmont/demo/neil-young.html.

[18] Gartner, “Top Trends in the Gartner Hype Cycle for Emerging Technologies, 2017,” 15 August 2017. [Online]. Available: https://www.gartner.com/smarterwithgartner/top-trends-in-the-gartner-hype-cycle-for-emerging-technologies-2017/.

[19] CB Insights, “AR/VR M&A Timeline: Facebook, GoPro, HP, Apple Begin To Grab Startups,” July 2016. [Online]. Available: https://www.cbinsights.com/research/top-acquirers-ar-vr-ma-timeline/.

[20] Digi-Capital, “Mainstream VCs’ bigger checks drive record AR/VR investment,” [Online]. Available: https://www.digi-capital.com/news/2016/10/mainstream-vcs-bigger-checks-drive-record-arvr-investment/#.WgxlkFtSxaR.

[21] Statista, “The Worldwide Virtual Reality Market Is Set To Be Huge,” 11 November 2016. [Online]. Available: https://www.statista.com/chart/6677/the-worldwide-virtual-reality-market-is-set-to-be-huge/.

[22] Statista, “Virtual reality software and hardware market size worldwide from 2016 to 2020 (in billion U.S. dollars),” 2017. [Online]. Available: https://www.statista.com/statistics/528779/virtual-reality-market-size-worldwide/.

[23] Variety, “Virtual Reality Projected to Become a $7 Billion Business This Year,” 11 April 2017. [Online]. Available: http://variety.com/2017/digital/news/virtual-reality-industry-revenue-2017-1202027920/.

[24] Red Gaming Tech, “AMD’s Radeon Polaris | Performance Per Dollar & The Immersive Era,” 15 March 2016. [Online]. Available: http://www.redgamingtech.com/amds-radeon-polaris-performance-per-dollar-the-immersive-era/.