# Cutting the Cord in Virtual Reality

Omid Abari
PhD Advisor: Dina Katabi
Massachusetts Institute of Technology

**Abstract –**Today's virtual reality (VR) headsets require a cable connection to a PC or game console. This cable significantly limits the player's mobility and hence her VR experience. The high data rate requirement of this link (multiple Gbps) precludes its replacement by WiFi. In this paper, we focus on using mmWave technology to deliver multi Gbps wireless communication between VR headsets and their game consoles. The challenge, however, is that mmWave signals can be easily blocked by the player's hand or head motion. We describe a novel system design and algorithms that allow mmWave links to sustain high data rates even in the presence of blockage, enabling a high-quality untethered VR experience.

## 1. INTRODUCTION

The past few years have witnessed major advances in augmented reality and virtual reality (VR) systems, which have led to accelerated market growth. These devices are expected to soon dominate the gaming and entertainment industry, and they have found applications in manufacturing and healthcare [7, 8]. However, a key challenge prevents this technology from achieving its full potential. High-quality VR systems need to stream multiple Gbps of data from a data source (PC or game console) to the headset. As a result, these headsets have an HDMI cable snaking down the player's neck and hardwiring her to the PC, as shown in Fig 1. The cable not only limits the player's mobility and interferes with the VR experience, but also creates a tripping hazard since the headset covers the player's eyes. This has left the industry searching for untethered solutions that can deliver a high-quality VR experience without these limitations. Unfortunately, typical wireless systems such as WiFi cannot support the required data rates. Moreover, the strict latency constraints on VR systems preclude the use of compression/decompression to accommodate lower data rates [12]. This challenge has led to awkward products: Zotac has gone as far as stuffing a full PC in the player's backpack in the hope of delivering an untethered VR.

Ideally, one would like to replace the HDMI cable with a wireless link. In fact, multiple companies have advocated the use of mmWave for VR since mmWave has been specifically designed to deliver multi-Gbps data rates [1]. The 802.11ad standard operates in mmWave and can deliver up to 6.8 Gbps. However, using mmWave links for the VR application presents some difficulty because such high frequency signals require a line-of-sight between transmitter and receiver. mmWave radios must use highly directional antennas to focus their power and compensate for path loss. As a result,they do not work well through obstacles or reflections. Said differently, these links would work well when the receiver on the headset faces the transmitter and has a clear line-of-sight, but if the player turns her head to look around or if other people in the environment obstruct the receiver's view to the transmitter, the signal will be lost (see Fig. 2). In fact, if the player moves her hand in front of the headset, this motion will block the signal and cause a glitch in the data stream (shown in our empirical results in §3). While temporary outages are common in wireless communication, the VR data is non-elastic: it cannot tolerate any degradation in SNR and data rate.

**Figure 1—Virtual Reality experience:** The headset's cable not only limits the player's mobility, but also creates a tripping hazard.

We propose MoVR, a novel system for addressing the problem. MoVR is a configurable mmWave mirror. It has no transmit or receive capabilities (i.e., no transmit or receive baseband chains). It acts as a programmable mirror that detects the direction of the incoming mmWave signal and reconfigures itself to reflect it toward the receiver on the headset. MoVR reflects the signal without reduction in data rate in comparison to the direct line-of-sight. Furthermore, in contrast to a traditional mirror, MoVR does not require the angle of reflection to be equal to the angle of incidence. Both angles can be programmed so that our mirror can receive the signal from the mmWave transmitter at the data source and reflect it towards the player's headset, regardless of its direction.

MoVR's design overcomes multiple challenges. In particular, though it has no transmit or receive chains, MoVR needs to detect the direction of the signal from the PC and the direction of the headset so that it can set angles of incidence and reflection appropriately. Recall that mmWave signals are highly directional. Identifying the best signal direction between two nodes typically requires them to transmit and receive, yet MoVR can neither transmit nor receive; it can only reflect signals. In §4, we present a novel protocol that measures the direction along which a signal propagates using the backscatter principle, which works correctly even when one node has no transmit or receive capabilities.

Another challenge in designing MoVR stems from the leakage between the transmit and receive antennas. At a high level, MoVR works by capturing the RF signal on its receive antenna, amplifying it, and reflecting it using a transmit antenna. However, some of the signal reflected by MoVR is also received by its own receive antenna. This means that the output of the amplifier is fed back to the input of the amplifier. This creates a feedback loop that can cause the amplifier to saturate, thereby generating garbage signals. In §4, we explain how MoVR solve this challenge by adapting its amplification gain to maximize the SNR while avoiding saturation.

We built a prototype of MoVR and evaluated its performance empirically. Our results show that MoVR allows mmWave links to sustain high data rates even in the presence of blockage, enabling a high-quality untethered VR experience.

## 2. RELATED WORK

**(a) Virtual Reality:** Existing VR systems can be divided into PC-based VR like Occulus Rift and HTC Vive, and Gear VR like systems by Samsung and Visus [4, 9]. PC-based VR systems leverage their computational horsepower to generate rich graphics that look realistic and support fast head motion, but they require an HDMI cable to connect the PC to the headset. Gear VR slides a powerful smart phone into the headset, eliminating the need for an external cable. Their mobility, however, is limited by the inability to support rich graphics that react to motion; their imagery tends to blur with motion [2]. There is a huge interest in untethered PC-based VR systems. Sulon proposed to equip the headset with an integrated computer [5]. Unfortunately, this would make the headset much larger and heavier, interfering with the user experience. Zotac advertises a mobile VR system where the user carries the PC in a backpack. Finally, Google has recently announced that their next VR headset will be wireless, but has not provided any details of the design or the release date [10].

**(b) mmWave Communications:** Much past work on mmWave communication addresses *static links*, such as those inside a data center [16, 19, 14], where there is a line-of-sight path between the transmitter and receiver. Some past work looks at mobile links for cellular networks or wireless LANs [17, 20, 11]. Most of these solutions assume line-of-sight connectivity, though some of them do consider scenarios in which the line-of-sight between transmitter and receiver is blocked. However, since they target elastic applications, their solution switches the directional antenna to the best reflected path, which typically has a much lower SNR (see Fig. 3). In contrast, our VR application is non-elastic and cannot tolerate reduction in its SNR and data rate. Finally, the work in [19] has proposed a form of mmWave mirror to reflect an RF signal off the ceiling of a data center. Their approach, however, covers the ceiling with metal. Such a design is unsuitable for home applications and cannot deal with player mobility.

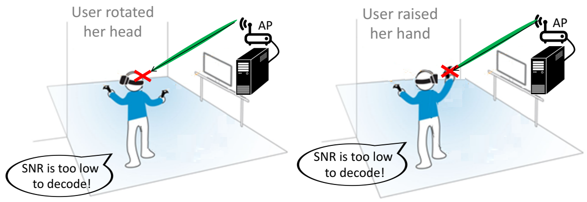

**Figure 2—Blockage Scenarios:** As the user moves her head or hand, the line-of-sight path between the AP and the headset's receiver can be blocked, resulting in a drop in SNR and data rate.

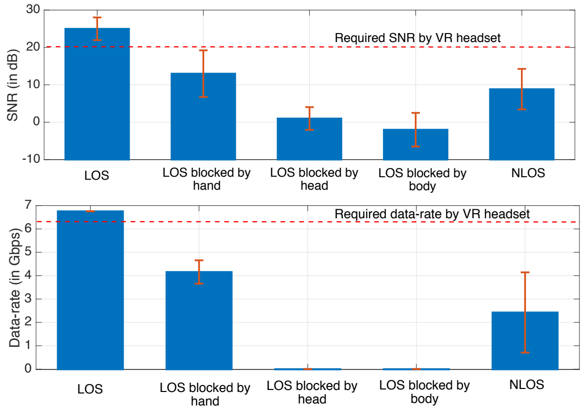

**Figure 3—Blockage impact on data rate.** The SNR and data rate for different scenarios: line-of-sight (LOS) without any blockage, LOS with different blockages, and non-line-of-sight (NLOS). Blocking the signal results in a significant drop in SNR and causes the system to fail to support the data rate required by VR.

## 3. BLOCKAGE PROBLEM

The key challenge in using mmWave links for VR applications is that they may be easily blocked by a small obstacle such as the player's hand. This is a side effect of highly directional antennas, which mmWave radios must use to focus their power and compensate for path loss. Below, we investigate the impact of blocking the direct line-of-sight on mmWave SNR and data rates. To do so, we attach a mmWave radio to an HTC PC-based VR system and another one to the headset (see §5 for hardware details). We conduct experiments in a $5m \times 5m$ office. We place the headset in a random location that has a line-of-sight to the transmitter, and measure the SNR at the headset receiver. We then block the line-of-sight and measure the SNR again. We consider different blocking scenarios: blocking with the player's hand, blocking with the player's head, and blocking by having another person walk between headset and the transmitter. We repeat these measurements for multiple different locations. Fig. 3 shows the results of this experiment, where the top graph shows the SNR and the bottom graph shows the data rate. The SNRs are measured empirically and the corresponding data rates are computed by substituting the SNRs measurements into standard rate tables based on the 802.11ad modulation and code rates [3, 6]. The first bar in Fig. 3 shows that, in the absence of blocking, the mean SNR is 25dB and the resulting data rate is almost 7 Gbps, which exceeds the needs of the our VR system. Bars 2, 3, and 4 in the figure correspond to different blocking scenarios. They show that even blocking the signal with one's hand degrades the SNR by more than 14 dB and causes the data rate to fail to support the VR application.

Note that one cannot solve the blockage problem by putting another antenna on the back of the headset, since both antennas may get blocked by the player's hands or body, or by people in the environment.

One naïve solution to overcome this challenge is to deploy multiple mmWave APs in the room to guarantee that there is always a line-of-sight between the transmitter and the headset receiver. Such a solution requires extending many HDMI cables in the environment to connect each AP to the PC. However, this defeats the purpose of a wireless design because it requires enormous cabling complexity. Further, requiring multiple full-fledged mmWave transceivers will significantly increase the cost of VR systems.

Another option would be to rely on non-line-of-sight paths –i.e., the signal reflections from walls or other objects in the environment. Specifically, both transmitter and headset receiver can direct their signal beams toward a wall and rely on the reflection from the wall. In fact, this is how current mmWave systems work. Unfortunately, non-line-of-sight paths typically have much higher attenuation than the line-of-sight path due to the fact that walls are not perfect reflectors and therefore scatter and attenuate the signal significantly.

To confirm, we repeat the measurements for all blocking scenarios, but instead of trying to receive the signal along the blocked direct path, we sweep the mmWave beam on the transmitter and receiver in all directions. We try every combination of beam angle for both transmitter and receiver antennas, with 1 degree increments. We ignore the direction of the line-of-sight and note maximum SNR across all non-line-of-sight paths. The last bar in Fig. 3 shows the results for this experiment. It shows that when transmitter and receiver have to use a non-line-of-sight path, the SNR drops by 16dB on average. The figure also shows that this reduction in SNR causes the data rate to fail to support the VR application.

## 4. MOVR

MoVR is a programmable mmWave mirror that can control both the angles of incidence and reflection. Fig. 4 shows a basic diagram of the circuit and a picture of our prototype. Specifically, each MoVR device consists of two directional antennas, connected via a variable-gain amplifier. Each antenna in MoVR is a phased-array. Because mmWave signals have very small wavelength, we can build a highly directional antenna by packing multiple antenna elements into an array, and controlling the phase of each element using an analog component called a phase shifter. The result is a small antenna (half the size of a credit card) that focuses the signal into a narrow beam, which we can steer in any direction by changing the control input of the phase shifters. This beam steering is done electronically in sub micro-seconds.

One or more MoVR mirrors can be installed in a room by sticking them to the walls. As shown in Fig. 5, each MoVR mirror focuses its receive beam (angle of incidence) on the mmWave radio connected to the PC, which we call the mmWave AP. MoVR focuses its transmit beam toward the mmWave radio on the headset. MoVR has a bluetooth link with the AP to exchange control information.

For MoVR to reflect the VR signal from the AP to the headset, it needs to address two key design questions: how does MoVR identify the correct direction to align its transmit and receive beams (i.e., its angles of incidence and reflection)? and how does MoVR chose the optimal amplification gain that maximizes the SNR at the headset? Below, we explain these two challenges and provide solutions.

### 4.1 How does MoVR find the correct angles of incidence and reflection?

To deliver the signal from the AP to the headset, MoVR needs to align its receive antenna beam towards the AP and its transmit antenna beam towards the headset. We will focus on estimating the direction along which signal propagates from the AP to the MoVR mirror – i.e., the angle of incidence. An analogous process can be used to estimate the direction from MoVR's mirror to the headset.

The mmWave literature has a few papers that propose techniques for finding the the best beam alignment between two nodes [18, 15]. Unfortunately, we cannot use these schemes since they require the both nodes to transmit and/or receive signals, while MoVR can neither transmit nor receive; it can only reflect signals.

Thus, MoVR delegates to the AP the task of measuring the best incidence angle, which the AP can then communicate to the MoVR mirror via bluetooth. During this estimation process, the AP transmits and MoVR tries to reflect the signal back to the AP itself (instead of reflecting it to the headset) to allow it to measure the best angle. MoVR, however, does not yet know the direction of the AP. So it has to try various angles and let the AP figure out the direction that maximizes the SNR.

Thus, our algorithm works as follows. It first sets the mirror's receive and transmit beams to the same direction, say $\theta_1$, and sets the AP's receive and transmit beams to the same direction, say $\theta_2$. Then it tries every possible combination of $\theta_1$ and $\theta_2$ while the AP is transmitting a signal and measuring the power of reflected signal (from the MoVR mirror). The $\theta_1$ and $\theta_2$ combination which gives the highest reflected power corresponds to the angles for best alignment of the AP's transmit beam and the mirror's receive beam. Note that the angle of incidence is measured once at installation. The angle of reflection is first measured once at start-up. Then during use, the headset tracks the SNR and can trigger a new measurement if the SNR begins to degrade. However, MoVR does not need to repeat the full angle measurement process. Because the VR system constantly tracks the headset's po-

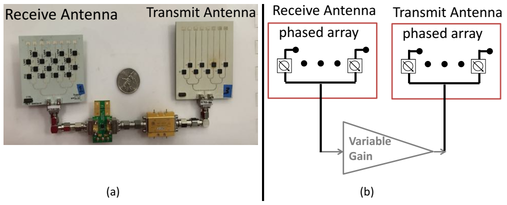

**Figure 4—MoVR programmable mmWave mirror:** (a) the implementation and (b) the block diagram of the MoVR mirror.

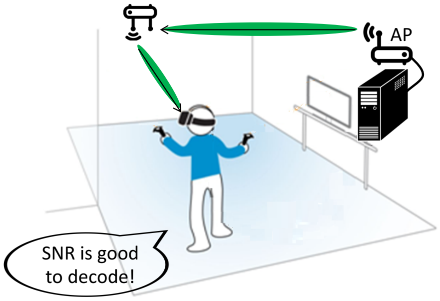

**Figure 5—MoVR's setup:** The PC is connected to a mmWave AP and the headset is equipped with a mmWave receiver. In the case of a blockage (ex. user turns her head), the AP steers its beam towards the MoVR mirror. The mirror amplifies the signal and reflects it toward the headset.

sition, we can simply leverage this information to determine the best angle.

### 4.2 How does MoVR find the optimal amplifier gain?

To achieve the best performance, MoVR needs to chose the amplifier gain that maximizes the SNR it delivers to the headset. On one hand, we would like to amplify the signal a lot, but on the other hand, the amplification gain cannot be more than the leakage from mirror's transmit antenna to its receive antenna. This limitation stems from the fact that if the amplification gain goes higher than the leakage, the amplifier will become saturated and generate garbage signals at its output.

To avoid this saturation, the mirror needs to measure the leakage and then set the amplification gain lower than the leakage. The leakage, however, varies as the directions of the transmit and receive beams change at the mirror. Our Results show that the leakage variation can be as high as 20dB.

The variation of the leakage, and the fact that the amplifier gain must always be set lower than the leakage, creates a need for an adaptive algorithm that reacts to the leakage in real time and adjusts the amplifier gain accordingly.

Our solution exploits a key characteristic of amplifiers: amplifiers draw significantly higher current (from a DC power supply) as they get close to saturation mode, compared to during normal operation [13]. Therefore, we can detect if the amplifier is getting close to saturation mode by monitoring the current consumption from the power supply. Thus, our gain control algorithm works as follows. It sets the amplifier gain to the minimum, then increases the gain, step by step, while monitoring the amplifier's current consumption. The algorithm continues increasing the gain until the current consumption suddenly goes high. This indicates that the amplifier is entering saturation mode. The algorithm keeps the amplification gain just below this point.

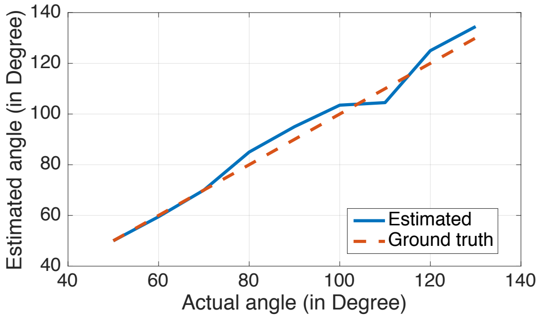

**Figure 6—Beam Alignment Accuracy:** The angle estimated by MoVR (blue) versus the ground truth angle (red).

## 5. EMPIRICAL EVALUATION

We have built a prototype of MoVR using off-the-shelf components as shown in Fig. 4. We equip the HTC VIVE VR headset with a mmWave receiver, and the VR PC with a mmWave AP. We evaluate MoVR in a $5m \times 5m$ room with standard furniture, in both line-of-sight and non-line-of sight scenarios.

### 5.1 Beam Alignment Accuracy

In this experiment, we aim to evaluate MoVR's ability to find the best beam alignment between the AP and the mirror. We place the AP next to the PC in our testbed. We then place the MoVR mirror at a random location and orientation in our testbed and estimate the angle which provides the best beam alignment between it and the AP using the method described in §4. We repeat the experiment for 100 runs, changing the mirror's location and orientation for each. We compare this to the ground truth angle, calculated from the locations of the AP and mirror. We use a Bosch GLM50 laser distance measurement tool to measure these locations to within a few millimeters.

Fig. 6 plots the estimated angle versus the actual angle. The figure shows that MoVR's algorithm estimates the angle of arrival of the signal (i.e. incident angle) to within 2 degrees of the actual angle. Note that since the beam-width of our phased array is ~10 degrees, such small error in estimating the angle results in a negligible loss in SNR.

### 5.2 SNR Performance

A key promise of MoVR is that it can address the blockage problem. To verify this, we place the AP in one corner of the room and the mirror in the opposite corner. We place the headset at a random location and orientation. The AP transmits packets consisting of OFDM symbols and the headset's receiver receives these packets and computes the SNR. We perform the experiment for 20 runs, changing the location and orientation of the headset for each. We repeat each run for three scenarios:

- *No-Blockage:* In this scenario, there is a clear, direct path between the AP and the headset receiver. The AP and

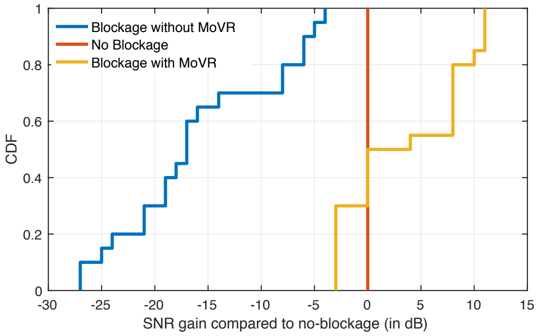

**Figure 7—MoVR's mirror performance:** Figure shows SNR gain compared to the *No-Blockage* in all three scenarios: *No-Blockage*, *Blockage-without-MoVR* and *Blockage-with-MoVR*.

headset have aligned their beams along this path.

- *Blockage-without-MoVR:* In this scenario, the direct path from the AP is blocked. In the absence of a MoVR mirror, the best approach is to try to reflect the signal off of a wall or some other object in the environment. Thus, to find the best SNR possible without a mirror, we make the AP and the headset try all possible beam directions and pick the one that maximizes the SNR.

- *Blockage-with-MoVR:* Here, we have the same blockage as in the previous scenario, but the system is allowed to use the MoVR mirror to reflect the signal as described in the earlier sections.

Fig. 7 compares the SNRs in all three scenarios. The figure plots the CDF of the SNR Gain relative to the SNR without blockage, defined as follows:

$$SNR\ Gain\ [dB] = SNR_{Scenario}[dB] - SNR_{No\ Blockage}[dB].$$

The figure shows that, in the absence of a MoVR mirror, a blockage drops the SNR by as much as 27dB, and the average SNR reduction is 17dB. As shown in §3, such high reduction in SNR prevents the link from supporting the required VR data rate. Thus, simply relying on indirect reflections in the environment to address blockage is ineffective.

The figure also shows that, for most cases, the SNR delivered using MoVR's mirror is higher than the SNR delivered over the direct line-of-sight path with no blockage. This is because, in those cases, the AP's distance to the mirror is shorter than its distance to the headset's receiver. Thus, the presence of MoVR's mirror along the path, and the fact that it amplifies the signal, counters the SNR reduction due to the longer distances to the headset. The figure further shows that, in some cases, MoVR performs 3dB worse than the no blockage scenario. This loss does not affect the data rate because, in these cases, the headset is very close to the AP, which provides a very high SNR (30dB) at the headset's receiver. This SNR is much higher than the 20dB needed for the maximum data rate. This experiment shows that MoVR's mirror enables a high data rate link between a VR headset and a PC even in the presence of blockage.

## 6. CONCLUSION

This paper presents MoVR, a system that enables a reliable and high-quality untethered VR experience via mmWave links. It provides a sustainable, high data rate wireless link to the VR headset even in the presence of blockage. In particular, it overcomes blockage of the mmWave link by introducing a smart and simple mmWave mirror that can reconfigure itself and adapt its angles of incidence and reflection.

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