

FSO-VR: Steerable Free Space Optics link for Virtual Reality Headsets

Md. Shaifur Rahman
Stony Brook University
New York, USA
mdsrahman@cs.stonybrook.com

Kai Zheng
Stony Brook University
New York, USA
kai.zheng@stonybrook.edu

Himanshu Gupta
Stony Brook University
New York, USA
hgupta@cs.stonybrook.com

ABSTRACT

In near future, we expect the Virtual Reality (VR) headsets to be wireless and to be demanding data-rate up to Tbps, thus pushing RF technology to the limit. In this work, we explore the possibility of using steerable Free Space Optics (FSO) to create a wireless link between a wall-mounted static transceiver and a VR headset in motion with its user. We describe our architecture, develop a link emulator using off-the-shelf optical devices, analyze the response time of the system and its effect on tolerable motion of the VR headset. We describe an in-band feedback mechanism to track the laser beam between the transceivers in motion. We lay out additional challenges to tackle, so as to unleash the full potential of FSO communications for wearable devices like VR headset.

CCS CONCEPTS

• **Hardware** → *Photonic and optical interconnect; Emerging interfaces;*

KEYWORDS

Virtual Reality, Free Space Optics

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1 INTRODUCTION

Virtual Reality (VR) has recently become a popular medium of information consumption. It is expected that in near future, the VR headsets will render a life-like experience. Authors in [3] estimate that to unleash such a perfect illusion, the data transmission rate for a single VR headset can be up to 1 Tbps or even more considering frame rate, field of view, pixel density etc. Wireless connectivity to such a VR headset is highly desirable to let the user dip in immersive virtual reality “without any strings.” In near future, users congregating in amusement parks, theater halls etc. are expected to use such wireless VR headsets simultaneously. Providing so many

extremely high throughput wireless links to wandering users will push even mmWave technology to the limit. To this regard, we propose our system FSO-VR that uses steerable optical links in the air to achieve that goal.

Free Space Optics (FSO) communication is similar in principle to (wired) optical fiber communication except that in FSO, the beam travels in free space instead of being enclosed in an optical fiber. In general FSO link can provide very high bandwidth (up to 100 Gbps) over a long distance (tens of kilometers) [6]. However, FSO links are susceptible to outdoor effects such as weather, scintillation, beam-wandering etc. For indoor environment and short links (<100 meter), most of the challenges are manageable. Although static FSO links have been used for decades, steerable FSO has been proposed recently in the context of datacenters [1] and backhaul networks [4]. In those cases, the steering of the beam is controlled and pre-configured in the sense that, links are created among a set of transceivers. However, if one of the transceiver is in arbitrary motion (such as an user with head movements and wearing VR headset), the link maintenance becomes challenging. In this work, we explore the possibility of wireless links for VR headset using steerable FSO. There are many advantages of using FSO: (i) it uses a very narrow beam and thus has minimum co-channel interference compared to mmWave RF. We can virtually create thousands of links in the same arena as long as the line of sight between the corresponding transceivers are maintained. (ii) the transceivers are free of antennas and can have a very small-form factor, thus can seamlessly integrate with wearable gadgets. Therefore, for wearable gadgets that require high bandwidth wireless connection such wireless VR headset, FSO link is a natural choice. However, the benefits does come with some formidable challenges. In this work, we explore few of them.

We first describe terms and concepts related to steerable FSO communications:

- (1) *SFP/SFP+* : An SFP is a Small Form-factor Pluggable transceiver that has a dimension of an inch or two. It contains a laser source and a photo-diode for transmission and reception of optical signal respectively. In a wired optical link, the SFP modulates and transmits the incoming bits onto the laser and demodulates the signal received by the photo-detector.
- (2) *Collimator* : A collimator is a set of lenses that make the outgoing laser beam parallel to prevent dispersion or focus the incoming laser beam on the photo-detector to minimize signal loss. SFP with at least 10Gbps capacity is termed as SFP+.
- (3) *Galvo Mirror (GM)* : It is used for steering laser beams. It typically consists of a set two mirrors at right angles, each of which can be rotated independently. A laser beam can be

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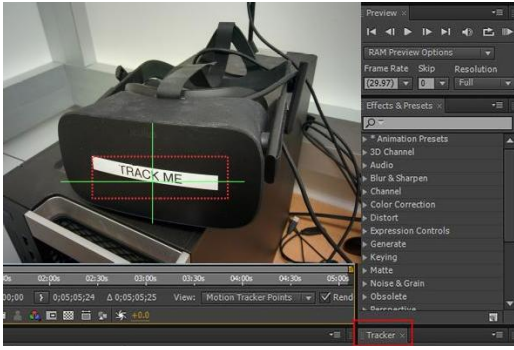


Figure 1: Calculating VR-headset motion for different VR contents using tracking software

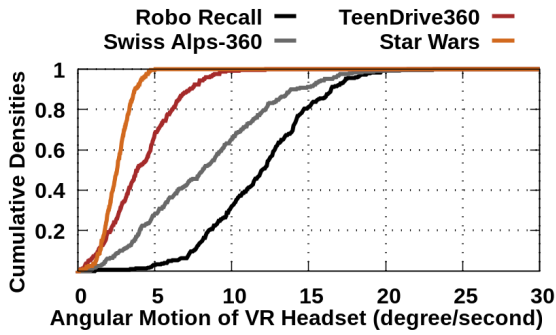


Figure 2: CDF of angular motions of VR headset for different VR contents, here maximum angular speed is 20 degree/second.

steered using a GM by reflecting off its mirrors. In effect, a GM can steer a beam towards any target within a predetermined rectangular angular cone called “coverage cone.” GM typically has response time of few milliseconds.

Note that, the infrared lasers (1550 nm wavelength) used in our testbed are class-I eye-safe and harmless to any entity. We start by presenting an experiment on the VR-headset movement.

2 VR HEADSET MOTION ESTIMATION

To determine the extent of the VR headset movement, we ran experiments using volunteers. We asked them to put on Oculus Rift [7] VR headset, one of the most popular ones currently in the market. We asked them to watch and interact for 4 types of contents for about 5 minutes each. Those include a VR movie (Star War: The Last Jedi), an educational software (Toyota’s TeenDrive360), a VR tour (Swiss Alps-360) and a VR game (Robo-recall). We did not constrain their movement, rather it was spontaneous and in response to the VR content. We tagged the front of the VR with a white paper-strip (for higher contrast on black gadget surface), as shown in Figure 1, and recorded their movement all along from the front using a camera. We used a motion-tracker software to track the movement of the white-strip frame-by-frame and estimate the angular and lateral speed of the VR headset from the 2D pixel-displacements on

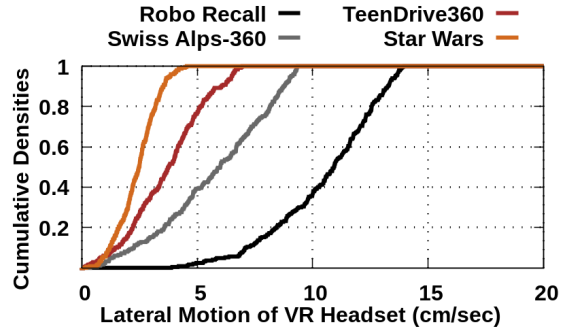


Figure 3: CDF of lateral motions of VR headset for different VR contents, here the maximum angular speed is 14 cm/second.

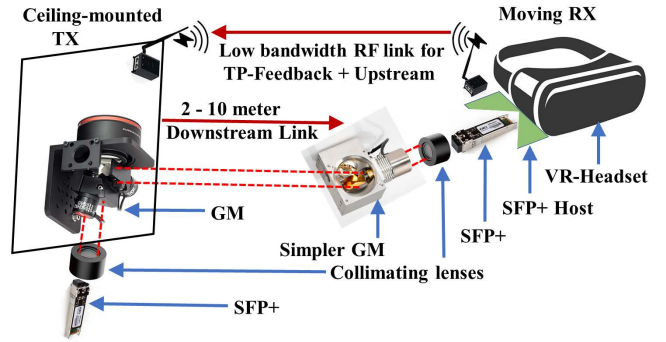


Figure 4: FSO-VR System Overview

the video-frame by scaling appropriately. We collected the angular speed in degree/second and the lateral speed in centimeter/second for all the users for each types of content and plotted the CDF in Figure 2 and 3 respectively. We observe that the angular speed is limited between 0 and 20 degree/second (Figure 2) and the lateral speed is limited between 0 and 14 cm/second (Figure 3). The VR video game required the highest movement and the movie required the least in both angular and lateral movement cases. With this estimate, we now present our FSO-VR system.

3 FSO-VR SYSTEM

3.1 System Overview

In Figure 4, the overview of FSO-VR is presented. Here, we assume that a content server sends data-packets to the untethered VR headset. We term the direction from the server to the receiver (RX) headset as “downstream” and the opposite of it as “upstream.” We observe that the downstream link requirement can be Tbps [3] since it carries data-packets for high resolution immersive 360⁰ video. However, the upstream link data-rate can be very low [7] since it only carries control information such as headset orientation, pressed button signals etc. from the headset to the server. As such, we consider the downstream link to be steerable FSO link whereas a low bandwidth RF link suffices for the upstream link.

The transmitter (TX) end of the server side is mounted on a fixed location such as wall. However, we assume that it is preferably mounted on the ceiling for continuous line of sight with the RX. We assume the assembly to be in an indoor environment and the distance between RX and TX to be 2–10 meter which is a typical height of the ceiling. The collimation lens is located at each side to collimate (at TX) or focus (at RX) the laser beam. To demonstrate feasibility of a form-factor manageable and cost-effective FSO link, we propose to build our prototype using commodity optical SFP+ transceivers, as in prior works [1, 4, 5].

To keep the link operational in presence of (lateral and angular) movement of RX, we need a correction mechanism called “Tracking and Pointing (TP)” to keep the laser beam aligned between the TX and RX. This requires a Galvo Mirror (GM) [8] on both TX and RX ends; as the system is not very sensitive to RX angular movement, we can use a less sophisticated (and hence with a smaller form-factor) GM [2] at the RX end (on the headset). The system also requires a feedback loop from the RX to the TX via the RF link. In particular, an SFP+ host board such as [9] is connected to the SFP+ of the RX; this SFP+ host board essentially measures the received power via the Received Signal Strength Indicator (RSSI) value in the SFP+ and reports it back to the TP system, which initiates an appropriate correction at the GM(s). Overall, the optical path can be traced as follows:

- (1) The TX SFP+ is connected to the server network card and modulates the Tbps signal into a laser beam.
- (2) The beam then passes through collimation lens and possibly, other optical elements as required.
- (3) The collimated laser beam then bounces off the X and Y mirrors of the TX GM and is steered towards the mirrors of the RX GM
- (4) The received beam then bounces off the X and Y mirrors of the RX GM, passes through the optical elements (e.g., collimating lens) on the RX end and finally reaches the RX SFP+ which demodulates the optical signal and the data-packets are recovered to generate the VR content.
- (5) The SFP+ host board continuously generates the RSSI value and sends it as a feedback to the TP mechanism which corrects the link via an appropriate voltage signal to the GM(s) at TX and/or RX.
- (6) All the control signals from the VR headset are sent to the server via the RF uplink.

In Figure 5, the testbed is shown. To simulate the VR headset movement, the receiver emulating the VR-end is mounted on a precision angular translator stage. The GM-end is placed at a distance of few meters. In Figure 6, the Timbercon SFP+ host used in the testbed is shown. Once, the GM-controller receives the RSSI value less than a certain threshold, it must decide how much to re-orient the X and Y mirrors. We validated our TP mechanism using this testbed.

3.2 TP Mechanism

In our system, the transmitter (TX) is ceiling-mounted and hence fixed, but the receiver (RX) VR headset can incur a lateral and/or angular movement. This is in contrast to previous works [4, 5] wherein the RX is fixed while the TX may move due to vibrations. In Section 2, we have shown two kinds of movements of the VR

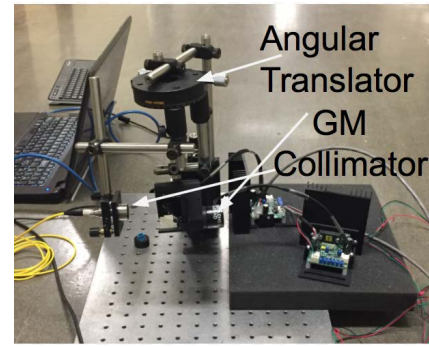


Figure 5: FSO-VR Emulated Testbed

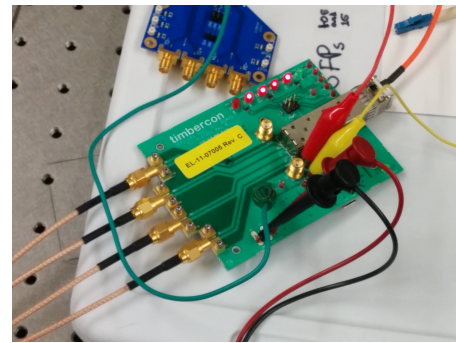


Figure 6: Timbercon Device connected to the receiver

headset i.e. i) lateral and ii) angular¹. The measurements are shown in Figure 3 and 2 respectively. Here, for “tracking” the beam, we use the received power as measured by an SFP+ host board, and use multiple “probes” as in [5] to infer the position of the beam or in effect, the movement of the RX assembly. A detailed description of the tracking algorithm is presented in Section 3.3. At a high-level, the correction mechanisms to handle lateral and angular motion of RX is as follows:

- (1) **Lateral Motion of RX:** Here, RX moves back and forth along its lateral axis. The way to correct alignment is to tilt the TX via TX-GM so as to follow the RX. For this correction mechanism to be effective: (i) the overall latency of the mechanism must be low enough (in our case, the latency is expected to be around 20 msecs [5]), (ii) the RX lateral speed must not be very high, and (iii) the link must have sufficient “intrinsic” angular tolerance. As discussed in Section 4, the angular tolerance requirement can also be formulated in terms of the TP latency, RX-movement speed, and link range.
- (2) **Angular Motion of RX:** This can be handled via the GM at the RX end, in a similar way as above.

Overall, the TP mechanism keeps the beam aligned and thus the link operational, even in face of the lateral and angular motion of the RX.

¹Even though the compound movement involving both angular and lateral movement is possible too, but we are considering both the movements separately for simplicity

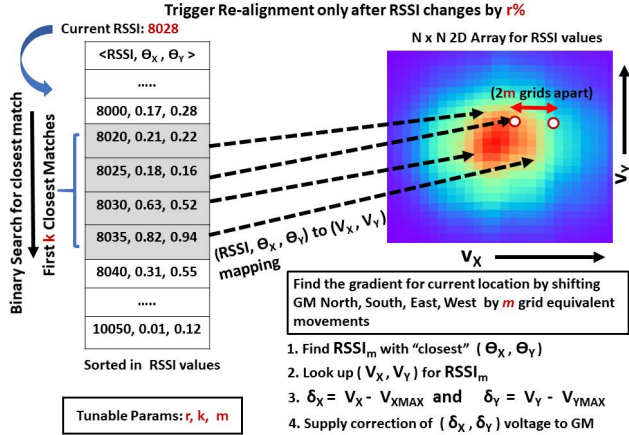


Figure 7: Beam-tracking method

3.3 Tracking Algorithm

To accurately apply required voltages to the X and Y -mirror controllers to steer the GM mirrors, we first build a map of received RSSI values over the feedback link by applying voltages from minimum $-V$ to maximum $+V$ volt in step of ΔV to both X and Y mirror controllers. The result is a $N \times N$ grid map of RSSI values as function of X and Y mirror voltages V_X and V_Y respectively. Here, $N = 2V/\Delta V$. For each grid point C on this map, we consider East, West, North and South grids that are each m grids away from C . We then find the gradient at C as a pair of angles θ_X and θ_Y using East-West and North-South RSSI values respectively. We generate a lookup table where each entry contains a tuple $(RSSI, \theta_X, \theta_Y)$ sorted by the non-decreasing value of RSSI. Each entry is also mapped to the corresponding mirror voltages V_X and V_Y , which is illustrated in Figure 7.

When the RSSI value falls below a certain threshold such as $r\%$ of the peak value, the correction mechanism is triggered. The current RSSI value is noted and the GM is voluntarily moved East, West, North and South by applying voltage equivalent to m grid movement and the current gradient (θ_X, θ_Y) is calculated. The above generated table is then looked up using binary search to find the a value $RSSI_m$ corresponding to the "closest"² match of the current gradient and the corresponding voltages are retrieved. The difference between these voltages and peak RSSI voltages are applied to the X and Y mirror controller for the correction. However, due to the inherent latency of about 5 milliseconds in the SFP+ host-board, the latency of determining the gradient at current location is $4 \times 5 = 20$ milliseconds. We observed that the table lookup takes few hundred microseconds and is negligible compared to the RSSI feedback latency.

4 SIMULATIONS

It is out of scope of this preliminary work to demonstrate a working FSO link prototype with an effective tracking and pointing (TP) mechanism that can tolerate the expected (lateral and angular)

²Due to noise, up to k tuples around the binary searched match are tested to find the closest match.

movements of the RX assembly. Instead, here we show via an optical design simulator and analysis that the desired performance requirements can indeed be achieved with an appropriate link and optical design. Instead, we model an FSO link in Zemax [10], an optical design software platform, based on appropriate optical elements, and estimate link's signal loss for various relevant link settings (TX and RX movements, and link ranges). Similar simulations were done in [4] for longer ($> 100m$) links. Zemax is widely used by optical engineers to analyze, simulate and optimize optical systems.

RX Lateral Movement. We start with noting that, in a link of range d meters, to handle RX's lateral movement at y m/sec using our designed TP mechanism with latency of z seconds, the link must roughly have an "intrinsic TX-angular tolerance" of at least $2(yz/d)$ radians. Here, the *intrinsic TX-angular tolerance* is the maximum amount by which the TX assembly can be tilted without losing the link. The term (yz) comes from the fact that the link should be tolerant to the RX's lateral movement possible during the TP latency; this term of (yz) lateral movement at RX is "equivalent" to (yz/d) radians of TX's angular movement, and a factor of 2 is applied to account for the fact that the TP mechanism kicks in only after some initial displacement. Similar analysis was done in [4] for a 100m FSO link prototype, and is validated by results in [4, 5]. Thus, for our TP mechanism which is expected to have a latency of 20 msec, to handle RX lateral movement of up to 14 cm/sec (§2), the FSO-VR link should have a TX-angular tolerance of 2.8 mrad for 2m, 1.12 mrad for 5m and 0.56 mrad for 10m link.

RX Angular Movement. Similar to the above analysis, we can show that, to handle RX-angular speed of y rad/sec using a TP with latency of z sec, we need a link with intrinsic RX-angular tolerance of $2zy$ radians (irrespective of the link range). Thus, to handle RX-angular speed of 20 degrees/sec, we need a link that has an RX-angular tolerance of 14 mrad.

Link Simulation in Zemax. The above analysis suggests that we need to design an FSO link with intrinsic angular tolerances of 0.56-2.8 mrad at TX and 14 mrad at RX, for a range of 2 to 10m. A unidirectional link is generally very tolerant to RX angular movement, and in our link model in Zemax, we measured RX-angular tolerance of up to 70 mrad (assuming a 30dB link budget). Thus, achieving 14 mrad RX-angular tolerance is rather straight-forward. On the other hand, FSO links are very sensitive to TX angular movement [4, 5], especially for longer links. In our case, we were able to achieve required TX-angular tolerances by using a multi-mode coupling fiber at RX in conjunction with an appropriately design collimator.

In Figure 8, we plot the signal path loss as observed in the optical simulator for our link design for varying TX and RX angular displacements. In particular, in Figure 8(a), we observe that the total path loss remains well within the optical budget for TX angular movement of upto 0.7 mrad for a 10m link, 1.6 mrad for a 5m link, and 3.5 for a 2m link – which are well above the desired TX-angular tolerances. Similarly, in Figure 8(b), we observe that the total path loss remains relatively unchanged for RX angular movements of upto few tens of mrad—which is well above the required RX-angular tolerance of 14 mrad for our context. Thus, based on the above analysis, we expect our TP system to be able to keep the link fully operational (at full data rate of 10Gbps of SFP+)

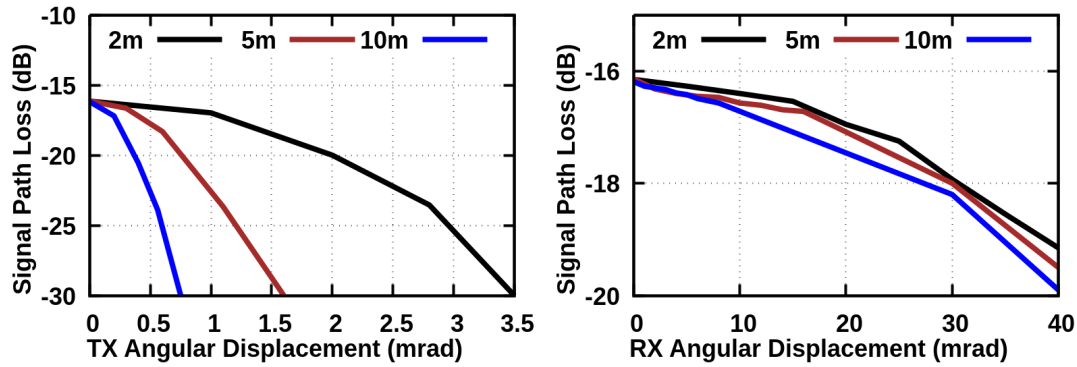


Figure 8: (a) Loss for varying TX Angular Displacements (b) Loss for varying RX Angular Displacements

while correcting for anticipated RX lateral and angular movements of speeds upto 14 cm/sec and 20 degrees/sec respectively.

We note that our above analysis and results are preliminary—in particular, it ignores simultaneous lateral and angular movement of the RX, noise, additional vibration of the deployment platforms etc. However, link’s design can be easily improved to increase angular tolerance by a combination of increased optical budget (e.g., via use of an amplifier), more robust optical design (e.g., use of a wider beam), improved TP design and latency, etc.

5 CONCLUSION

In this work, we presented the preliminary findings on using steerable free space optics for wireless VR headsets. In principle, the proposed system can work with any other mobile devices or gadgets for short distance (<10 m) communications without weather effects. Nevertheless, VR headsets have the highest bandwidth requirement compared to any other wearable devices. Using custom high-performance optical instruments, the tolerable motion can be increased from 20 degree/second to 45 degree/second or higher, and the throughput can be increased from 10 Gbps to 40 Gbps or higher. To our knowledge, this work is the first to explore FSO communications for wearable devices with (angular) motion. There are lot of challenges still remaining. We can outline the ongoing/future works as follows:

- (1) *Adding automatic pointing capability:* currently we assume that the GM-transceiver and VR-transceiver are previously paired in the sense that the link is already established. However, steering the beam from the GM-transceiver to find the receiver VR headset anywhere in the room is a non-trivial task. We are exploring automatic pointing mechanism for our system. This is also required when the line-of-sight is blocked temporarily and the link has to be re-established.
- (2) *Increasing angular movement tolerance:* SFP+ host board constrain the angular motion tolerance of our system. We are exploring different in-band and out-of-band feedback mechanisms to improve the movement tolerance.
- (3) *Increasing Throughput:* Currently 40Gbps throughput for a single bi-directional link are easily achieved for FSO links in the datacenters. However, those transceivers are perfectly aligned and remain so without disruption or motion. In our

use case, the angular motion poses extra challenges. We are exploring better instrumentations to increase the throughput withstanding the motion.

We believe the outcome of FSO-VR will foster interest in steerable FSO links for high bandwidth communications for wearable devices, VR headset in particular.

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