Design of Mirror Assembly for a DMD-Based Data Center Interconnect

4 pages

1. INTRODUCTION

Free-space data center interconnects (wireless, optical) require a reflection mechanism to avoid obstacles/interference that can arise due concentrating signals in a plane consisting of source/destination nodes. A proper reflection mechanism above the communicating nodes (as in Fig. 1) enables a beam to depart the source, hit the reflector structure well above the source and destination, and head towards the desired destination by utilizing all three spatial dimensions. This technical report involves the design of a mirror assembly (i.e. reflector structure) for 3-D beam steering in data center networks that make use of the diffraction properties of Digital Micromirror Devices (DMDs).

The report is organized as follows. First, we examine the steering requirements with a flat structure that covers the the whole space between the source and destination points. Driven by the requirements of DMD, we try to complement the flat reflector surface with auxiliary mirrors. Then, we investigate the possibility of consolidating the flat ceiling reflector and the auxiliary reflectors for a unified mirror assembly design and propose an algorithm for realizing such a structure. Finally, we discuss other design options and fabrication considerations.

2. CEILING-WIDE FLAT REFLECTOR

In order to directly connect a pair of source and destination racks, we initially focus on a seemingly straightforward optical design based on a flat reflector surface, spanning the data center ceiling. In line with Fig. 1, we assume that the distance between the ceiling and the floor in the data center equals d. The floor and ceiling planes are denoted by $Z = 0$ and $Z = d$, respectively. We assume $A = (x_s, y_s, z_s)$ and $B = (x_d, y_d, z_d)$ to denote the light departure point on the source rack and light reception point on the destination rack, respectively. The light beam from the source rack is assumed to depart the rack at an elevation angle θ (i.e., the angle between the Z axis and the beam vector) and an azimuth angle ϕ (i.e., the angle between the X axis and the image of the beam vector in the XY plane). The reflection of the light from the ceiling (from point $C = (x_i, y_i, z_i)$) requires the normal to the ceiling and the incident beam to form a reflection plane that is perpendicular to the ceiling.

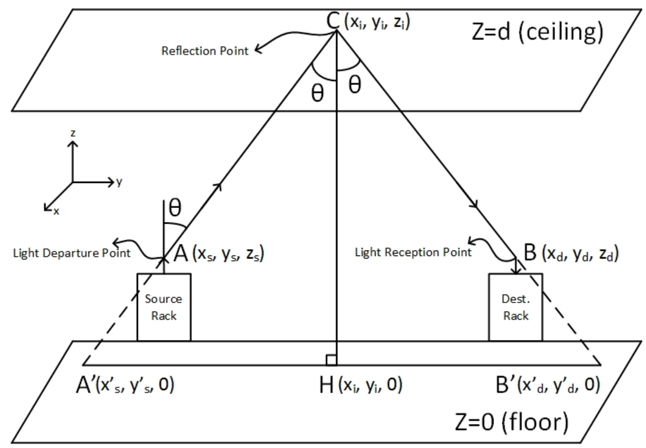


Figure 1: Beam propagation scenario with a horizontal reflector.

Let $A' = (x'_s, y'_s, z'_s)$ be the intersection of the line passing through points A and C with the floor plane as $Z = 0$. Also let $B' = (x'_d, y'_d, z'_d)$ be the intersection point of the line connecting points B and C with $Z = 0$. Points A', B', and C form an isosceles triangle that lies on a plane perpendicular to both $Z = 0$ and $Z = d$. The bisector of angle $A\hat{C}B$ would be the perpendicular bisector of side $A'B'$ (i.e., $A'H = HB'$). By finding the coordinates of A', C, and H as a function of the coordinates of points A and B, we calculate elevation and azimuth angles as follows.

$$tan\theta = \frac{A'H}{CH} = \frac{\sqrt{(x'_s - x_i)^2 + (y'_s - y_i)^2}}{d} \quad (1)$$

$$tan\phi = \frac{y_d - y_s}{x_d - x_s} \quad (2)$$

We can examine the beam steering requirements for free-space optical connectivity within a data center pod using DMD and a flat reflector structure. Fig. 2 provides the top view of a standard pod, including rack configuration along rows and columns. We focus on the beam originating from rack $R(1, 1)$, located at the bottom left corner of the pod. We assume the light originates from the center of the ToR

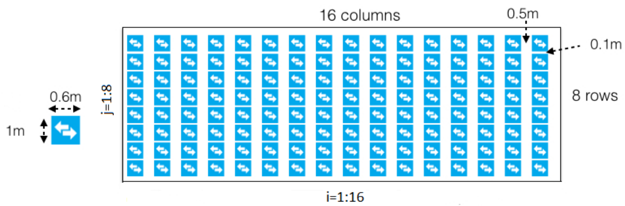


Figure 2: Organizing racks into a pod.

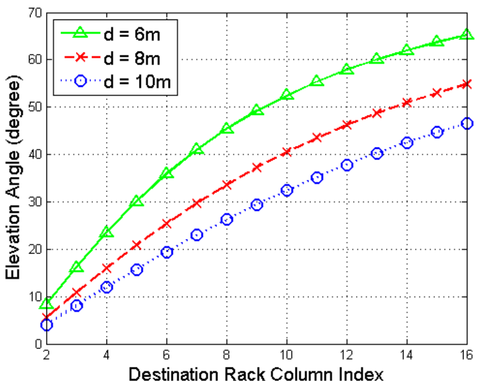


Figure 3: Elevation angle vs. destination index for racks within the same row.

module and is also delivered to the center of the destination ToR. Furthermore, we consider the optical transmitter and receiver to be mounted on a ToR without any vertical spacing. In other words, z_s and z_d in Fig. 1 are both equal to the rack height, H. We consider $H = 2.2m$ and study the impact of ceiling height (d) on beam angles. Fig. 3 depicts elevation angle versus destination rack column index for d =6, 8, and 10 m, respectively. For a ceiling height of $d = 6$, the elevation angle varies between 8.2° and 65.3°. These steering angles are much larger than the angles that can be realized by a DMD (about 3°). Hence, with a flat ceiling reflector, it becomes mandatory to envision a secondary reflection system for enhancing the DMD diffraction angles. Such a system can be mounted on ToR and can incorporate an array of miniature mirrors, where the light diffracted by the DMD is incident on an appropriate mirror so as to adjust the departure angle. Fig. 4 illustrates how a diffraction angle θ can be increased to $2\alpha - \theta$ by using a mirror with α degrees alignment with respect to the vertical axis.

3. ALIGNING THE CEILING REFLECTOR

Instead of using a flat reflector on the data center ceiling and secondary reflectors in close proximity to the DMD for enhancing the light departure angle, we investigate allocating an array of tiny mirrors per DMD on the ceiling so that the two reflection functions could be integrated. In this configuration, the diffracted beam out of the DMD is directed

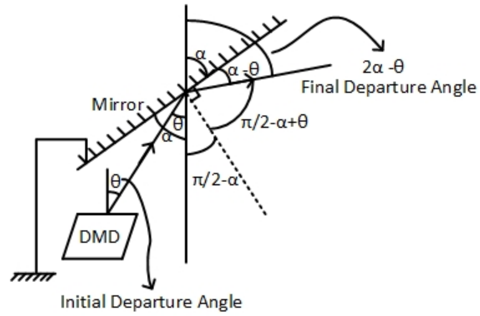


Figure 4: Elevation angle enhancement with ToR mirror.

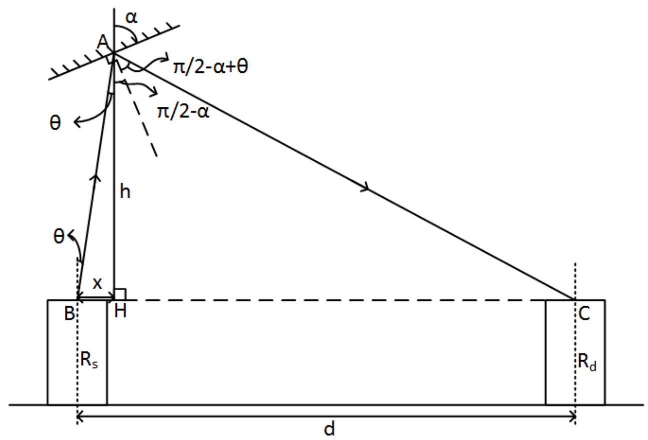


Figure 5: Mirror alignment for connecting source and destination racks.

towards a small mirror on the ceiling that has been properly aligned to reach a destination. Here, the DMD is responsible for fine switching among tiny ceiling mirrors and ceiling mirrors are intended to route light to other racks in the data center. Fig. 5 illustrates one such scenario where source rack R_s and destination rack R_d, both along a data center row, get connected through a small mirror on the ceiling.

In Fig. 5, the beam departs R_s at an angle of θ relative to the normal to the surface of the ToR switch. This angle is realized by the proper hologram loaded on the DMD for reaching R_d and lies in $(0, \theta_{max})$, where θ_{max} is the maximum achievable diffraction angle. The mirror mounted above R_s to make communication with R_d possible is α radians aligned with respect to the vertical axis. We assume that the vertical distance between the incident point on the mirror, A, and the ToR, is h. Denoting the light departure point as B, light arrival point as C and the intersection between the normal from A to line BC as H, we let d represent distance BC and x represent BH. In triangle AHC:

$$tan(\pi - 2\alpha + \theta) = \frac{d - x}{h}. \tag{3}$$

In triangle AHB, on the other hand, x can be expressed as a function of θ.

$$tan\theta = \frac{x}{h} \Rightarrow x = h \times tan\theta \quad (4)$$

Combining (3) and (4) we have

$$tan(\pi - 2\alpha + \theta) = \frac{d - h \times tan\theta}{h} \quad (5)$$

which enables us to determine the required mirror alignment angle as follows:

$$\alpha = \frac{1}{2}\left[\pi + \theta - tan^{-1}\left(\frac{d - h \times tan\theta}{h}\right)\right] \quad (6)$$

We consider the range of mirror alignment angles required for connecting racks along a row within a data center pod (as depicted in Fig. 2). For our calculations, we set $h = 4m$. For a source rack $R_s = R(1,1)$, in order to communicate with rack $R(1,2)$, the DMD of R_s should realize the minimum diffraction angle ($\theta_{min} \simeq 0°$). Further, we assume that the diffraction angle for reaching the last rack along a pod row, $R(1,16)$, has its maximum possible value ($\theta_{max} \simeq 3°$). Based on these assumptions and the parameters in Fig. 2, α is equal to 82.3° for communication with rack $R(1,2)$ and 53.4° for communication with rack $R(1,16)$. In a data center network with hundreds of ToRs, such angled mirrors placed side-by-side would form a geometrical structure that we denote as mirror assembly. In the next section, we present a mechanism to realize a conical mirror assembly.

4. MIRROR ASSEMBLY LAYOUT

A mirror assembly is composed of many individual mirror *facets*. It resembles a patch panel made by these facets where each facet is aligned to help the transmitter reach a unique destination. The structure of the overall assembly and the angles of its facets depend on various factors such as distance from DMD, DMD's output angles, number of receivers, and alignment tolerance. Alignment tolerance refers to how far the actual location of the receiver can be relative to its assumed location (e.g., due to vibrations or micro-movements of the rack such as opening and closing). Here, we explain one possible method for constructing a proper mirror assembly based on the fundamental properties of optics and using a greedy algorithm.

Facet angle and size: We begin by explaining how to find the angle and the size of one facet (in 3-D space) that is meant to reach a particular receiver. Fig. 6 illustrates the required geometry to reflect light from a transmitter to receiver. Let S, D, and R denote light departure, light reception, and light reflection points, respectively. Given the (x,y,z) coordinates of these three points, we compute the coordinates of the vector $\vec{RH}$ that is the bisection of $\measuredangle SRD$ angle. Notice that $\vec{RH}$ is also perpendicular to the reflection plane P and hence it is the normal of this plane. Given the normal of a plane ($\vec{RH}$) and one point on the plane (R), we can calculate the coefficients a,b,c,d such that $aX + bY + cZ + d = 0$ defines P. This plane determines the angle at which the facet needs to be placed.

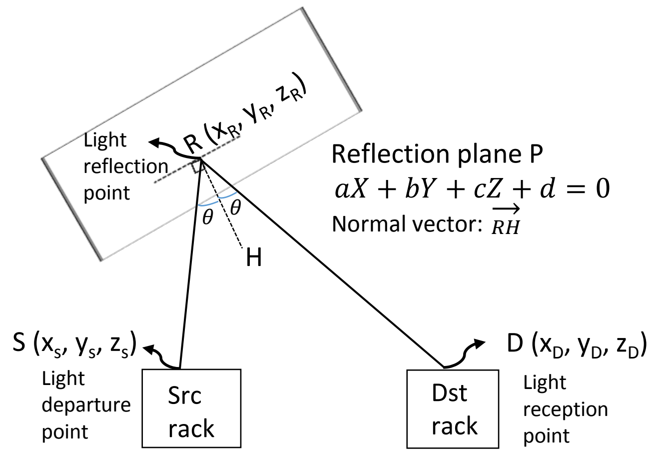


Figure 6: Alignment of one facet.

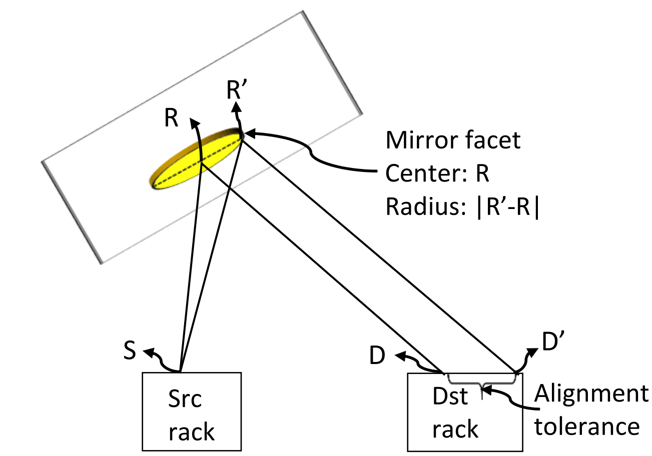
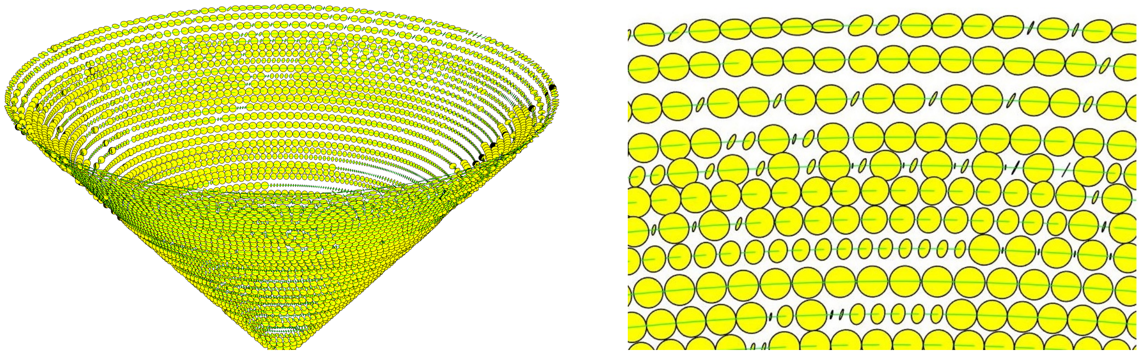


Figure 7: The facet radius and alignment tolerance.

After finding the reflection plane, the size of the facet needs to be determined, which depends on the desired alignment tolerance. As shown in Fig. 7, point R' is a point on plane P such that the reflected beam from R' on the destination rack (D') is equal to the alignment tolerance. We then create a circular facet with its center positioned at R and its radius equal to the distance between R' and R.

Assembling the structure: Each <transmitter, receiver> pair requires one facet on the mirror assembly for communication. We outline a greedy algorithm to fashion multiple facets into a mirror assembly. Fig. 8 (a) illustrates the overall mirror assembly shape that our algorithm produces; this illustration has thousands of little facets. As shown, the assembly consists of several *rings* that together form a conical shape. Each ring hosts several facets that direct light towards their corresponding receivers. The radius of each ring depends on its height and the DMD angles used to reach its facets. The top most ring is close to the ceiling and uses the



(a) Mirror assembly with 18,432 facets, (b) Zoomed in view of facets.

Figure 8: Mirror assembly based on greedy placement.

highest angular values (we assume this to be $\pm 3^{\circ}$ in each direction).

Our algorithm begins by ranking receivers based on their distance from the sender. It then starts with the top most ring and greedily places facets on an empty spot on the ring such that the facet does not overlap with any other facets on the same ring and it does not block the light for any facets on the higher rings. The algorithm continues filling up each ring before creating a new ring. The height of each ring is determined based on the largest facet placed on the ring to avoid overlap among facets on side-by-side rings. Fig. 8 (b) shows a zoomed in view of the mirror assembly in Fig. 8 (a).

For typical values of data centers—rack size as 0.6 m$\times 1$ m, ceiling height from top of rack as 2 m, inter-rack separation of 0.5 m, 48 photodetectors spread across the top of rack, and alignment tolerance of 5 mm—we find that we can construct mirror assemblies that can reach tens of thousands of receivers. Our greedy algorithm is able to fit 18,432 facets on a mirror assembly with 46 layers where the radius of the outer layer is 10.5 cm. As mirror assemblies in the data center could preserve the same shape due to the periodic disposition of server racks, they can be mass produced using the Diamond Turning Machine (DTM) technology.

5. DISCUSSION

As illustrated in the previous sections, the engineering of the mirror assembly requires careful considerations and several designs could be feasible. For example instead of using circular mirrors and a conical geometry, it is possible to arrange rectangular mirrors such that a pyramid with 4 sides is achieved (Fig. 9). This CAD structure has been built based on the same reflection principles described in the previous section and enables each side to cover a quadrant within the data center.

It is also feasible to build flat mirror assemblies so that several of them can be placed side by side without significant blocking. A flat structure of static holograms where all reflectors are aligned and mounted on a flat surface could be a solution. Millimeter-sized static holograms are already available in the market and can diffract light with negligible loss. These static hologram gratings can provide angular reflection of as large as 80°. In such a design, instead of angled mirrors, a 2-D flat surface consisting of multiple static holograms is placed on the ceiling to provide the same angular requirements as with a 3-D mirror assembly. In using the static holograms, there is no need to physically angle them since their flat surface is grated and provides the desired angle. This relaxes the spatial limitations of forming angled mirrors and is inexpensive at mass-scale.

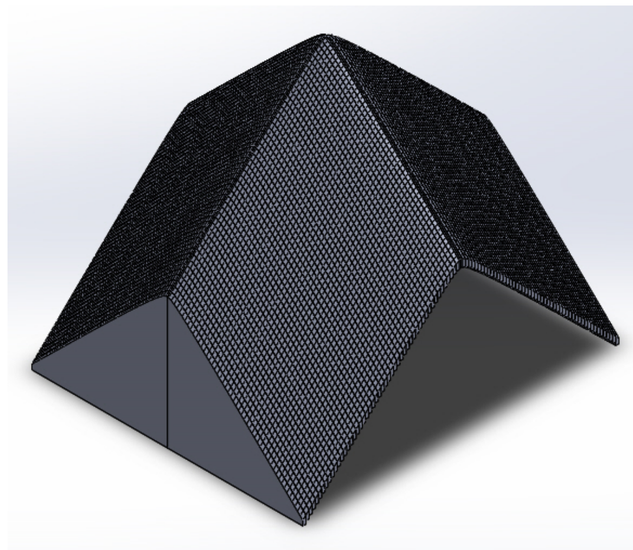


Figure 9: A mirror assembly of pyramid shape with 10,000 facets.

Finally one should consider the feasibility of variable mirror size in the design of the mirror assembly. Different mirror sizes can be used to optimize performance in terms of light blocking characteristics. This is an open question that requires further investigation.