3D Beamforming for Wireless Data Centers

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ABSTRACT

Contrary to prior assumptions, recent measurements show that data center traffic is not constrained by network bisection bandwidth, but is instead prone to congestion loss caused by short traffic bursts. Compared to the cost and complexity of modifying data center architectures, a much more attractive option is to augment wired links with flexible wireless links in the 60 GHz band. Current proposals, however, are severely constrained by two factors. First, 60 GHz wireless links are limited by line-of-sight, and can be blocked by even small obstacles between the endpoints. Second, even beamforming links leak power, and potential interference will severely limit concurrent transmissions in dense data centers. In this paper, we explore the feasibility of a new wireless primitive for data centers, *3D beamforming*. We explore the design space, and show how bouncing 60 GHz wireless links off reflective ceilings can address both link blockage and link interference, thus improving link range and number of current transmissions in the data center.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design

General Terms

Design, Performance

Keywords

Wireless data centers, beamforming

1. INTRODUCTION

To alleviate perceived changes in data center network traffic patterns due to distributed computing systems such as MapReduce and Dryad, recent work has proposed alternatives to the standard hierarchical data center network that increase pair-wise throughput capacity [6, 9, 12, 13, 14]. While each solution achieves full bisection bandwidth, each requires significant changes in data center hardware and the network stack.

More recently, traffic measurement studies have made surprising observations on the real traffic requirements of data center applications [10, 11, 16]. Specifically, these measurements show that current data workloads fall far short of full utilization on data center networks, and that congestion loss, when it occurs, is sporadic, difficult to predict, and often the result of short-lived bursts at links with relatively low utilization [10].

These results imply that instead of drastically altering the data center architectures, network managers are better served augmenting existing systems with flexible point-to-point links. One possibility is to utilize high-throughput, beamforming wireless links in the 60 GHz band. The 60 GHz band is unlicensed, provides multi-Gbps data rates, and can be implemented using relatively low-cost hardware. Finally, because 60 GHz signals attenuate quickly with distance, multiple wireless links can be deployed in a single data center.

Current work is exploring the effectiveness of 60 GHz links in data centers as easily reconfigurable links that can alleviate traffic hotspots [15, 17]. However, these systems have significant limitations. First, even beamforming directional links will experience *signal leakage*, and produce a cone of interference to any receivers near or behind the intended target receiver. This limits the number of links that can be active concurrently in densely occupied data centers, thus reducing the aggregate throughput offered by these wireless links.

Second, these links *require direct line-of-sight* between sender and receiver, and can be blocked by even small objects in the path. This limits the effective range of 60 GHz links to neighboring top-of-rack radios. Given that hotspots occur regularly at both edge and core links [10], augmenting core links would require multiple hops through a line-of-sight 60 GHz network. With the use of half-duplex, directional antennas, this leads to greater than 50% throughput drop, along with additional delays required to frequently adjust antenna orientation.

(a) Rack-based DC   (b) Container-based DC   (c) 2D Beamforming   (d) 3D Beamforming
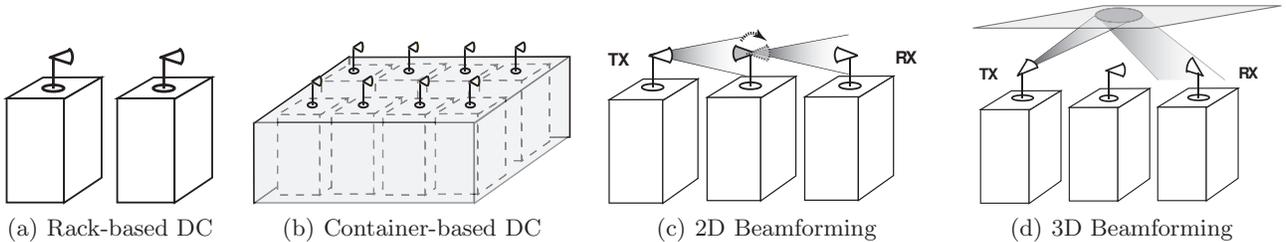
Figure 1: Radio transceivers are placed atop each rack (a) or container (b). Using 2D beamforming (c), transceivers communicate with neighboring racks directly, but forward traffic in multiple hops to non-neighboring racks. Using 3D beamforming (d), the ceiling reflects the signals from each sender to its desired receiver, avoiding multi-hop relays.

To address these issues, we investigate the feasibility of 60 GHz 3D beamforming as a novel and flexible wireless primitive for use in data centers. In 3D wireless beamforming, a top-of-rack directional antenna forms a wireless link by reflecting a focused beam off the ceiling towards the receiver. This allows it to reduce its interference footprint, avoid blocking obstacles, and provides an indirect line-of-sight path for reliable communication. To implement such a system, we only need beamforming radios readily available today, and simple flat metal plates can provide near perfect reflection when mounted on the ceiling of a data center.

3D beamforming has several distinctive advantages over prior "2D" approaches. First, bouncing the beam off the ceiling allows links to extend the reach of radio signals by avoiding blocking obstacles. Second, the 3D direction of the beam significantly reduces its interference range, thus allowing more nearby flows to transmit concurrently. The reduced interference also extends the effective range of each link, allowing our system to connect any two racks using a single hop, and mitigating the need for multihop links.

In this paper, we propose a 3D beamforming system for 60 GHz wireless transmissions in data centers. We describe a detailed design, and use detailed simulations to understand the design tradeoffs of such a system. We quantify the short-term implications of 3D versus 2D beamforming, and discuss key challenges remaining before widespread adoption of this technology. 60 GHz links are a promising tool to augment current data centers with flexible, point-to-point wireless capacity, and we believe this work is an advancement that eliminates some of the obstacles en route to its wide adoption.

2. WIRELESS DATA CENTERS

Wireless links can address the cabling complexity in data centers [15, 17, 18, 23, 26]. As shown in Figure 1(a)-(b), wireless radios can be placed on the top of each rack or shipping container, connecting the top-of-rack (ToR) switches wirelessly. Despite the potential to enable flexible network configurations and efficient cooling, data center managers are still skeptical on deploying wireless interconnects in practice [1]. In this section, we first describe existing wireless designs for data centers, and then outline their key limitations.

2.1 60 GHz Wireless

Existing designs [15, 17, 18, 26] adopt 60 GHz wireless technologies because of two reasons. *First*, the 7GHz available spectrum offers ample opportunity to achieve multi-Gbps data rates required by data centers. *Second*, operating at a high carrier frequency, 60 GHz links generate limited interference [29], which is highly beneficial to data centers with dense rack deployments.

To enhance link rate and further suppress interference, 60 GHz links use beamforming [15, 18], a physical layer technique to concentrate transmission energy in desired directions. Recent advances in radio design make 60 GHz beamforming radios readily available and affordable, either as directional (horn) antennas [15] or antenna arrays [4]. They can adjust beam direction in fine-grain [15, 27], either mechanically or electronically.

2.2 Limitations

Despite the advances in radio designs, the use of wireless still imposes limitations in data center networking.

Link Blockage. As shown in Figure 1(c), existing designs and their prototypes only directly connect neighboring racks due to link blockage [15, 18]. Because 60 GHz link has a wavelength of 5 mm, any object larger than 2.5 mm can effectively block radio signals [25]. Hence for today's grid-based rack placement, radio transceivers can easily block each other's signals. These transceivers can also reflect signals, resulting in multipath fading that severely degrades transmission rate [25]. One can reduce link blockage locally by placing racks in hexagons [28]. This, however, leads to inefficient space use and cooling problems, and still cannot solve the general link blockage problem.

Restricting wireless connections to neighboring racks means that any extended connection must go through multiple hops. This increases end-to-end delay, reduces throughput, and produces bottlenecks at certain racks that must forward a significant amount of traffic.
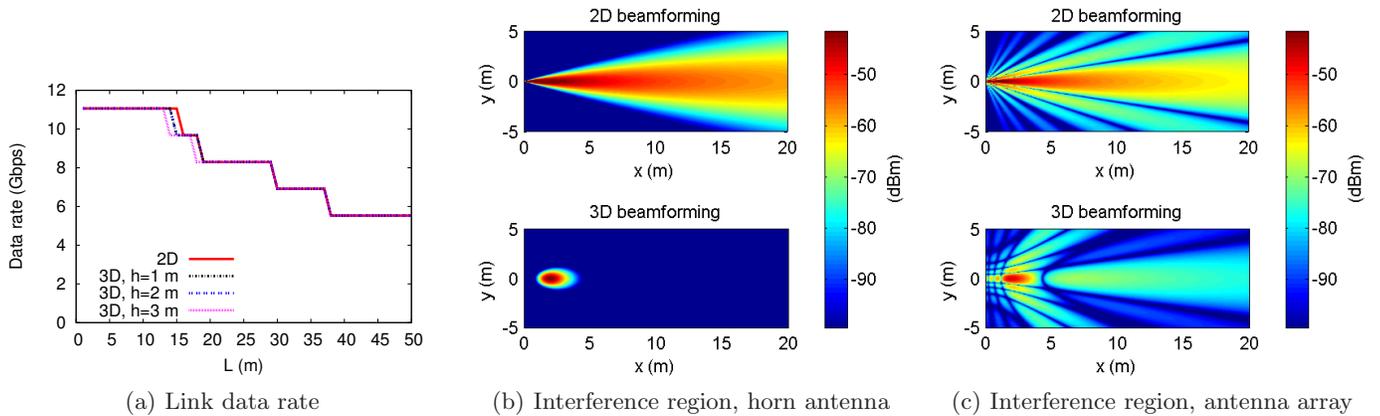
Figure 2: **Key properties of 3D Beamforming. (a) Data rate vs link distance L. (b)-(c) 2D and 3D beamforming signal maps using both horn antenna and antenna arrays. The transmitter is at (0m,0m) and the receiver is at (2m,0m).**

Radio Interference. While beamforming can bound the transmission energy in a "narrow" direction, it still creates interference at some receivers. Furthermore, radio design artifacts lead to signal leaked outside of the intended direction [20, 27]. These factors, together with the dense rack deployment, create harmful interference for concurrent links. For example, consider a link using a typical horn antenna with 10° beam width and 10dBm transmit power. A single link can interfere[1] with up to 27 racks in a typical deployment with 160 racks in a 11m×33m area [17].

Radio interference constrains the number of concurrent links, and thus also network throughput. Separating links in the frequency domain limits link capacity. Alternatively, increasing spacing between racks leads to inefficient space usage.

3. 3D BEAMFORMING

To address the above limitations, we propose *3D beamforming*, a new beamforming approach that leverages ceiling reflections to connect racks wirelessly. As shown in Figure 1(d), each sender points its beam towards a point on the ceiling, which reflects the signal to the desired receiver. This creates an indirect line-of-sight (LOS) path between the sender and receiver, bypassing obstacles[2] and reducing interference footprint. Next we discuss the feasibility of 3D beamforming, and show how it addresses the limitations of 2D beamforming.

3.1 Feasibility

3D beamforming requires three hardware components:
- *Beamforming Radios*: We reuse today's beamforming radios [4, 15] and adjust beam directions in both azimuth and elevation either electronically or using

rotators. Existing rotators can achieve an accuracy of 0.09^o [3], sufficient for our needs.
- *Ceiling Reflectors*: We mount microwave reflectors on the ceiling such that they act as *specular mirrors* to reflect signals. These reflectors can be flat metal plates, which have been shown experimentally to offer perfect specular reflection without degrading energy or changing path loss characteristics [7, 24]. In practice, simple aluminum plates are sufficient, and require no power and little maintenance.
- *Electromagnetic Absorbers*: We place electromagnetic absorbers [7] on the top of the racks or containers to prevent any local reflection and scattering around the receiving antenna. These absorbers are widely available and require no maintenance.

To form a link, two endpoints point their antennas at the ceiling point halfway between them.

3.2 Key Properties

Extended Link Connectivity. Using ceiling reflection, 3D beamforming bypasses obstacles in the horizontal plane, eliminating the antenna blockage problem of its 2D counterpart. Since ceiling reflectors introduce no loss [7, 24], and oxygen absorption is negligible for indoor 60 GHz LOS links [22], the resulting indirect LOS path can be modeled by the free-space propagation model, verified by experiment studies [15, 22]:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 (L^2 + 4h^2)}, \qquad (1)$$

where P_t and P_r are the transmit and receive power, G_t and G_r are the transmit and receive beamforming antenna gains, λ is the radio wavelength, L is the distance between the sender and receiver, and h is the distance from the antenna to the ceiling.

Following this model and the configurations defined by the 802.11ad standard [2], we study link throughput via detailed simulations. We consider links using typical horn antennas with 10° beam width [19, 20], transmitting over a channel of 2.16GHz. We conservatively

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[1] We define a rack as interfered with if its perceived interference power is greater than -71 dBm, the noise level defined by the IEEE 802.11ad standard [2].

[2] Here we assume that there are no obstacles between top of racks (or containers) and the ceiling.

Antenna Type	Design	Interference Area (m²)			
		L=2m	L=4m	L=6m	L=10m
Horn Antenna	2D	707	707	707	707
	3D	2	14	32	134
Antenna Array	2D	374	374	374	374
	3D	18	133	301	351

Table 1: Size of the interference region (interference power > -71 dBm) vs. link length L, for h=1m.

DC Topo	# of Hops	Occurrence (%) vs. L_{max}			
		10m	20m	30m	40m
Rack based	> 1	63	22	3	0
	> 2	22	0	0	0
Container based	> 1	83	46	24	8
	> 2	56	9	0	0

Table 2: The percentage of transceiver pairs that requires multiple hops to connect.

compute the link throughput as the *uncoded* modulation rate that guarantees a 1% packet error rate (PER) defined by the 802.11ad standard [2, 15]. Our result also takes into account the 36% overhead from guard band and pilot [2]. Figure 2(a) shows that 3D beamforming can maintain very high link rates up to 11Gbps[3]. Even with a link distance of 50m, it still offers 5.53Gbps. Furthermore, compared to 2D beamforming, 3D beamforming achieves similar throughput despite having a longer propagation path (Eq. (1)). This is an artifact of limiting the modulation rate to 256QAM. But even without this restriction, the difference is still < 12%.

Reduced Radio Interference. 3D beamforming reduces the interference footprint to the minimum. Figure 2(b)-(c) show the signal energy maps for both 2D and 3D beamforming using today's horn antenna and antenna array with 10° beam width and the 802.11ad configurations. The sender and receiver are placed at position (0m, 0m) and (2m, 0m) on the map, respectively. For 2D beamforming, the directional wave still propagates freely in its beam direction, affecting other receivers along the path. The signal leakage also exacerbates the level of interference. In contrast, 3D beamforming bounds the interference region to a much smaller area and limits the impact of signal leakage.

In Table 1, we compare the size of the interference regions of the two beamforming designs while varying the distance between the sender and receiver. We define the interference region as the area whose received interference power is above -71dBm, the noise floor defined by the 802.11ad standard. We see that 3D beamforming effectively reduces the interference region for both antenna types. The gain is most significant for shorter links, and for horn antennas due to its smaller signal leakage.

4. IMPLICATIONS FOR DATA CENTERS

Based on the key properties offered by 3D beamforming, we now discuss its short- and long-term implications.

4.1 Immediate Benefits

By extending transmission range while suppressing interference, 3D beamforming allows us to augment existing data center networks with flexible point-to-point

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[3]The throughput is bounded by 11Gbps because we limit the modulation rate to 256QAM. Without this restriction, rates can go up to 18Gbps.

wireless links. We illustrate this benefit by computing the number of concurrent wireless links supported in simulations of two known data center layouts.

- *Rack-based*: This is the topology used in [15]. Racks are grouped into 4×4 clusters, and each cluster is a row of 10 racks with no inter-spacing. Racks are of 0.6m×1.2m in size and aisles separating the clusters are 3m (between columns) and 2.4m (between rows) wide. In total, the data center is 11m×33m and contains 160 racks.

- *Container-based*: Offered by Sun Microsystems [5], this data center consists of 2×2 container clusters. Each cluster has 8 containers in a row with an inter-spacing of 0.61m. Each container is of 6.1m×2.4m in size, containing 8 racks laid out in two rows. Container clusters are separated by 3.7m (between columns) and 6.7m (between rows). The entire data center is 15m×50m and contains 256 racks.

We configure wireless links as follows. We assign one radio transceiver per rack and allow each transceiver to associate with one link. We build *bi-directional* links by randomly selecting transceiver pairs, forming arbitrary rack communication. Each receiver antenna also points to its sender. The maximum number of links for the two topologies are $N = 80$ and 128, respectively. For each group of N transceiver pairs, we determine the number of concurrent links as follows. We admit links one by one in a random order, compute their *cumulative* interference to each other, and only admit a link if all links after admission achieve a minimal rate of 5.53Gbps in the presence of interference. We consider both cases where all the links operate on a single 2.16GHz channel, and cases where three 2.16GHz channels (for the US 60 GHz band) are available.

To examine the impact of link lengths, we bound the distance between each link's two endpoints by L_{max}. Let D_{max} represent the maximum separation between two transceivers in each topology, 34.7m and 52.4m, respectively. We vary L_{max} between $[D_{max}/10, D_{max}]$. When $L_{max} = D_{max}$, every pair of transceivers can connect in one-hop. When $L_{max} < D_{max}$, some transceiver pairs require multiple hops. Table 2 lists the percentage of transceiver pairs who require more than 1 or 2 hops.

Due to space limitations, we only show the results with horn antennas, in terms of the number of concurrent links (Figure 3(a)-(b)) and the link rate distribution (Figure 3(c)). We make three key observations.
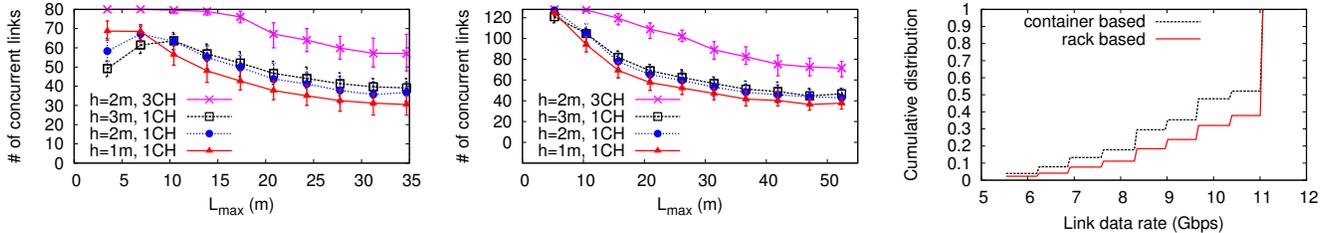
(a) # of concurrent links, rack-based (b) # of concurrent links, container-based (c) CDF of link data rate

Figure 3: (a) (b) The number of concurrent links supported as a function of L_{max}, for the rack-based and container-based topologies, using 1 channel (1CH) or 3 channels (3CH). (c) CDF of link data rate for $h = 1m$ and $L_{max} = D_{max}$.

Observation 1: 3D beamforming creates wire-like point to point wireless links. Consider the case where $L_{max} = D_{max}$ thus every transceiver pair connects in 1-hop. Our results show that on average, 30-45 randomly formed links can operate simultaneously on a single channel for h=1-3m. When using three channels, about 75% and 60% links can operate simultaneously for the two topologies respectively[4]. This result shows that we can simultaneously connect the majority of rack pairs wirelessly, using a wire-like connection of rate 5.53+Gbps. Figure 3(c) plots the cumulative distribution of link throughput for this scenario: 50% of links even support data rate higher than 10Gbps!

In total, this adds 0.35-0.4Tbps (1 channel) or 0.54-0.67Tbps (3 channels) of additional flexible bandwidth to the two data centers. We also compare the performance of 3D and 2D beamforming, assuming there is no link blockage for the latter. We observe a gain of 1.48-2.10. We omit the figure for brevity.

Observation 2: Shorter Links lead to more concurrent links. Figure 3(a)-(b) shows that the number of concurrent links increases with a smaller L_{max}. If we set $L_{max} = D_{max}/2$, the number of concurrent links supported by three channels increases to 94% and 87% for the two topologies. This is because a smaller L_{max} increases the receive power, making links more resistant to interference. More importantly, each directed beam arrives at its receiver in a larger elevation angle, producing a smaller interference region. The only exception is the rack-based topology, where the performance of $L_{max} = 3.4m$ is worse than that of $L_{max} = 6.8m$. This is because $L_{max} = 3.4m$ limits transceiver pairs to those within the same cluster, *i.e.* a row of racks with no spacing. The dense topology exacerbates the impact of interference.

Observation 3: Increasing ceiling height helps. In Figure 3(a)-(b) we also compare the performance for h=1-3m, where increasing h leads to more concurrent links. This is because a larger h produces a larger eleva-

tion angle when directive beams reach their receivers, effectively reducing the interference region. However, the benefit quickly plateaus at $h = 3m$.

4.2 Long Term Implications

The advantages of 3D beamforming also lead to several long-term implications for data center networking.

Flexible Traffic Scheduling. With the ability to form point-to-point links at multi-Gbps rates, a data center now can schedule jobs with full flexibility, rather than be restricted by configurations defined by physical cables and aggregation routers.

Easy Rack Movement/Replacement. Data center managers can upgrade or move racks without any physical constraints, and quickly calibrate the beam configuration based on rack locations.

Moving Towards a Full Wireless Data Center. The extended connectivity and reduced interference address the major concerns of wireless data centers. This can potentially lead to widespread adoption of wireless links in data centers as replacements for wired cables.

5. DEPLOYMENT CHALLENGES

In this section, we briefly discuss the key challenges of deploying 3D beamforming in data centers.

Connection Management. Managing 3D beamforming links faces three challenges. First, to establish a link, two transceivers must choose a mutual data channel and steer their antennas to the right direction. This requires a reliable control path. One can implement the control channel using existing wired connections. A central controller can schedule rack communications by assigning each transceiver pair with their beam directions and channel usage. The second challenge is to assign 60 GHz channels among links to maximize frequency reuse. This requires both accurate characterizations of interference conditions across active links and efficient allocation algorithms. Finally, the mixture of wired and wireless links creates additional challenges in network fault diagnosis and recovery.

Real-time Antenna Rotation. To communicate with different racks, each transceiver must adjust its

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[4]The number of concurrent links does not grow proportionally with the number of channels because interference patterns are not uniform across links. This negative effect should gradually diminish for increasingly large data centers.

beam direction in both azimuth and elevation. The rotation delay is 50ns [27] for antenna arrays and a few seconds for horn antennae using rotators [3]. Such delays must be accounted for in traffic scheduling.

Physical Rack/Reflector Placement. 3D beamforming performs the best when there are no obstacles between the top of rack/container and the ceiling. When physically arranging racks/containers as well as ceiling reflectors, data center managers should avoid obstacles such as cables and cooling pipes. This is a non-issue for container based data centers, because nothing is placed on top of the containers [5]. For other data centers, raised floors can be used to house cables and pipes in the ground; and data centers using suspended cable trays can conceal them within aluminum-plated ducts, essentially lowering the reflection point from the ceiling. When unavoidable, one can also plan multi-hop transmissions or reflect off walls to route around obstacles. An open question is whether physical rack and reflector placement can be jointly optimized with network communication patterns.

6. RELATED WORK

Data Center Networks. Most prior work is on addressing traffic congestion via network architecture design and scheduling [6, 8, 9, 12, 13, 14], or modeling network traffic characteristics [10, 11, 16]. Wireless data center was first proposed in [23]. Recent proposals use wireless links to augment [15, 17] or replace [26] wired links. In this work, we identify two practical issues of existing approaches, and propose a new beamforming paradigm to deploy better wireless interconnects. While prior work has applied the principle of reflection to connect NLOS links [23] or to reduce WiFi interference [21], we generalize it to 60 GHz links. Our key contribution is to use ceiling reflection in the data center context to extend connectivity and suppress interference.

60 GHz Technology. Prior work on 60 GHz also addressed radio design issues, including modeling propagation and reflection characteristics [7, 24, 25, 29] and antenna design [4, 27]. Our work leverages readily available hardware, and focuses on designing new wireless interconnects explicitly for data centers.

7. CONCLUSION

60 GHz wireless links are an ideal solution to address bursty traffic in the data center. To address link blockage and interference problems in today's approaches, we propose a 3D beamforming technique that extends the reach of wireless links by avoiding obstacles, while increasing the number of available concurrent transmissions by reducing interference. Using two popular data center configurations, we show that a 3D beamforming link can connect any two racks using a single hop, eliminating the need for multihop wireless links. Finally, we identify next steps in building 3D beamforming systems to augment next generation data center designs.

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