Mirror Mirror on the Ceiling: Flexible Wireless Links for Data Centers

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Data Centers are Everywhere

• No longer a luxury for tech companies

Retailers

Universities, hospitals

Governments
Today’s Data Centers

• Wiring is complex and costly
  – Planning, deploying, testing 10K+ fibers
  – Takes several weeks or even months

• Difficult to change wiring
  – High labor cost
  – Significant interruptions to operations

• Overprovisioning is difficult
  – Traffic demands unpredictable
  – Limited by hardware costs
Dealing with Traffic Hotspots

- Measurements show **sporadic congestion losses** caused by traffic hotspots
  - Traffic hotspots are unpredictable, can appear anywhere
  - Can double failure rate for some jobs

![Traffic Demands Heatmap]

Dealing with Traffic Hotspots

• Measurements show **sporadic congestion losses** caused by traffic hotspots
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• Hard to add bandwidth using wires
  😞 Do not know where to add capacity
  😞 Rewiring is complex, high labor cost
  😞 Interrupt current operation

Need alternative solutions!
Augmenting via Wireless Links

• Key benefit: **on-demand links**
  – Create links on-the-fly at congestion hotspots
  – Adapt to traffic dynamics

• **New wireless technology: 60 GHz beamforming**
  – Multi-Gbps data rate
  – Small interference footprint
Existing Work:
Connecting Neighboring Racks

- 60GHz flyways\(^1\) address local traffic hotspots by connecting neighboring racks wirelessly

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Our Goal: Any-to-any Communication

- Traffic hotspots can appear between any rack pair
  ➔ Connect any rack pair wirelessly

Hard to do using existing 60GHz beamforming!
Challenge #1: Link Blockage

- 60GHz transmissions are blocked by small obstacles (anything larger than 2.5mm!)

- Confirmed by our testbed measurements
  - Signal strength dropped by 10-30dB
  - Up to 15-90% throughput loss

Must use multi-hop forwarding
- Antenna rotation delay
- Reduce throughput by at least half
Challenge #2: Radio Interference

• Beam interferes with racks in its direction
  – Exacerbated by dense rack deployment
  – Signal leakage makes it worse

• Verified via testbed measurements
  – A single link causes 15-20dB drop in signal quality for 15 nearby links

😭 Links interfere with each other
  – Very few links can run concurrently
  – Put a hard limit on aggregate bandwidth
Outline

• Motivation

• Our solution: 3D beamforming

• Implications on data centers

• Deployment challenge
3D Beamforming

Connect racks by reflecting signal off the ceiling!
3D Beamforming

Connect racks by reflecting signal off the ceiling!

Key Benefits
- ✔ No more link blockage
- ✔ Much smaller interference

A

B

C

RX

RX

2D

3D
Simple Setup

Reuse existing hardware, low maintenance cost!

A

B

C

Reflector

Absorber
3D Beamforming Testbed

- Off-the-shelf 60GHz radio and horn antenna
  - HXI radio with 0dBm transmission power
  - 10° horn antenna from Flann Microwaves
Benchmark #1: Link Connectivity

Q1: Does reflection cause any energy loss?

Even cheap metal plate provides perfect reflection!

![Graph showing received signal strength vs. propagation path length](image.png)
Benchmark #1: Link Connectivity

Q2: How does longer propagation path impact data rate?

Negligible data rate loss
Benchmark #2: Interference Footprint

- A transmitter (0,0) communicates with a receiver (2,0)
- Measure the received energy at multiple locations
Benchmark #3: Robustness to Alignment Errors

- How does alignment accuracy impact signal strength?
- Fine grain experiment
  - Measure received signal when antennas perfectly tuned
  - Measure signal strength while introducing artificial alignment errors at $1^\circ$ increments

Today’s rotators: $0.006^\circ$ - $0.09^\circ$ accuracy
Benefits of 3D Beamforming

- Reflection overcomes link blockage

😊 Connect any rack pair w/ indirect LOS

- Bouncing the beam minimizes interference footprint

😊 Many links can run concurrently
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Link Concurrency in Data Centers

• Example data center scenario
  – Medium-sized data center: 250 racks in a 42m x 15m room
  – One 60GHz radio per rack
  – 125 randomly chosen bidirectional links w/ 5+Gbps data rate

Results

Connect any two racks via a single hop;
70% of links run concurrently w/ 5+Gbps rate!

Create a highly flexible network with data rates “close” to wired networks
Multiple Radios per Rack

- Each rack can talk to multiple racks concurrently
- Number of concurrent links increases **linearly** w/ the number of radios per rack!

![Graph showing the increase in concurrent links with the number of radios per rack]

- 250 racks
- 5+Gbps links
Impact of Ceiling Height

• How does ceiling height impact performance?
  – Higher ceiling increases signal arrival angle $\rightarrow$ smaller interference region
  – Also has longer propagation path $\rightarrow$ signal degradation

![Diagram showing impact of ceiling height on signal angle and number of concurrent links with a graph indicating a sweet spot at 3-4m]
Addressing Traffic Hotspots

• Large-scale data center simulations
  – 250 racks (5K servers), 8 radios/rack
  – Synthetic hotspot traffic based on popular workloads
  – Create 60GHz links for hotspots

• Result: Adding 3D beamforming links cuts completion time by half

Highly effective to address traffic hotspots
Deploying 3D Beamforming

• Need clearance between ceiling and top of rack
  – Raised floor to hide wires under racks
  – Cover wires by aluminum-plated ducts
  – Reuse wall or existing metal surface
Deploying 3D Beamforming

- Cost of 60GHz radios
  - Affordable thanks to the low-cost silicon implementation
  - A pair costs ~ $130 (25m+ LOS range)
  - Antenna arrays becoming the cheaper option
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