60 GHz Indoor Networking Through Flexible Beams: A Link-Level Profiling

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The 1000x Challenge

- 1000x explosion of wireless traffic by 2020*
  - Uncompressed video streaming

  - Wireless data centers

  - Kiosk-to-mobile file sync

  - 5G mobile broadband access

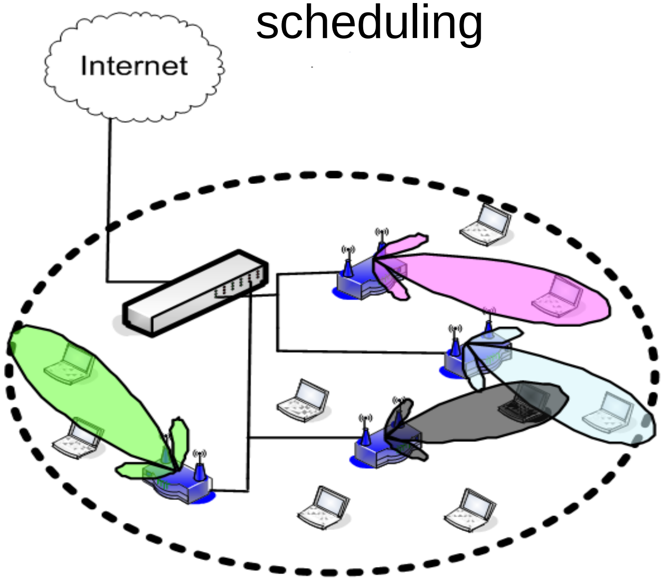
* Compared to 2012: www.qualcomm.com/1000x

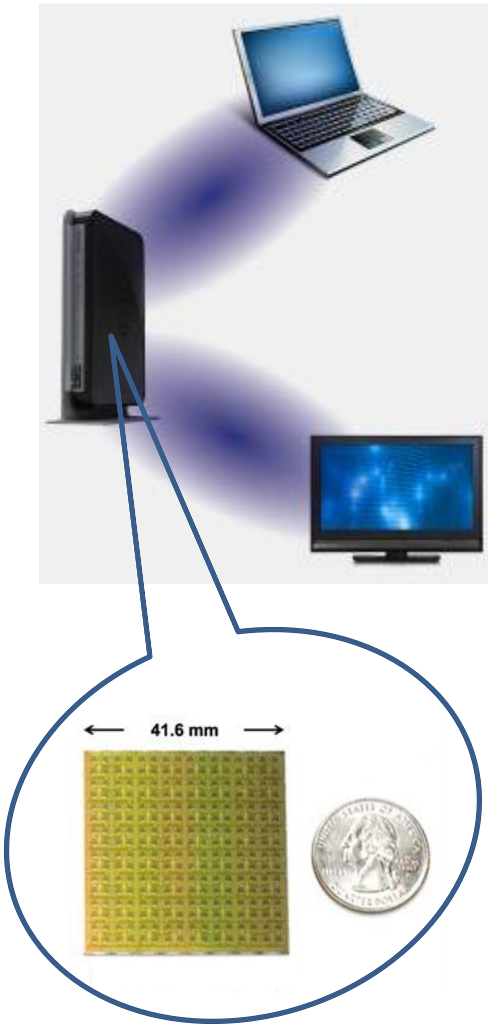
New Opportunity at 60 GHz

- Large unlicensed spectrum at 60 GHz millimeter-wave band
  - ~70x wider bandwidth compared to typical LTE
  - ~7Gbps of bit-rate
- Standardization activities
  - IEEE 802.11ad, IEEE 802.15.3c, ECMA-387
- Challenges:
  - Attenuation: 60 GHz link has 28 dB worse SNR than Wi-Fi link
  - Directionality: super-narrow beamwidth---new challenges in link establishment and maintenance

IEEE 802.11ad for 60 GHz Wireless LAN

- Enabling tech: flexible beams
  - Electronically steerable beams
  - Real-time beam-steering (latency < 40 ns)
  - Miniaturized phased-array antenna
- Hybrid MAC layer
  - Allows TDMA and contention-based scheduling





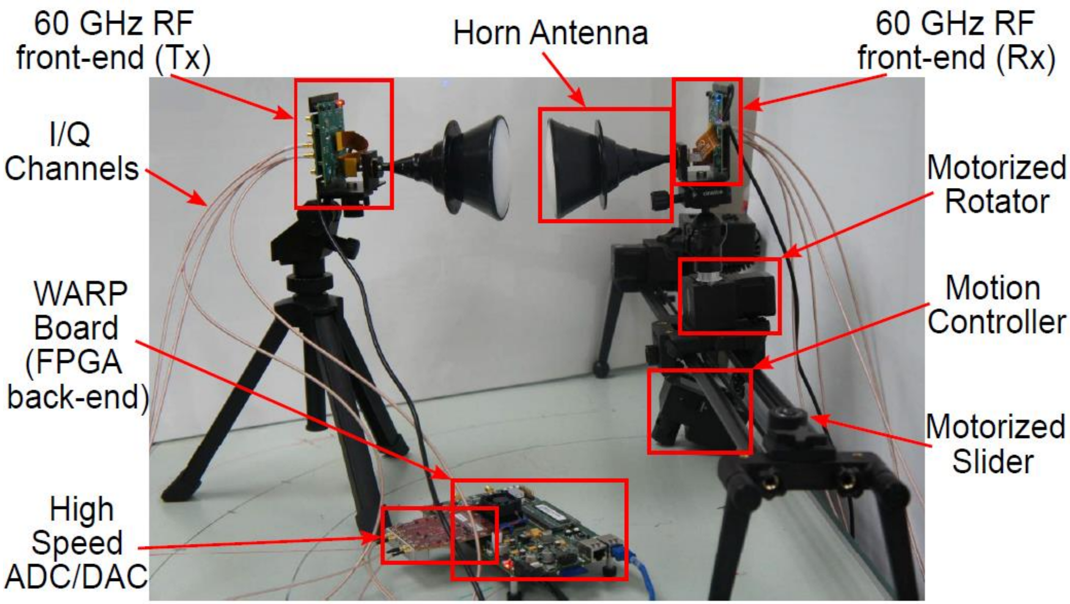
16x16 phased-array

Profiling Indoor 60 GHz Networks

- State-of-the-art measurement and modeling
  - Communications: simulation and analytical/empirical model
  - Networking: transport/application layer measurement using COTS 60 GHz devices
- Limitations
  - Does not capture sophisticated channel dynamics
  - Many open issues in MAC/PHY layers
- Our Contributions
  - Microscopic link-level measurement of 802.11ad-based 60 GHz indoor networks, using a custom-built 60 GHz software-radio
  - Clarifying open issues and unveiling new set of challenges
  - Hint towards new design principles for robust 60 GHz links

Methodology

- Custom-built 60 GHz software-radio
  - Reconfigurable transmitter/receiver and 60 GHz sniffer
  - Monitoring dynamic scenarios where link outage becomes norm
  - Programmable w.r.t. output power, beam patterns and signal waveforms



- Measuring 60 GHz links' performance
  - Emulating 802.11ad protocol stack with accurate timing parameters
  - Measuring RSS, bit-rate and throughput with adaptive beam pattern

Measurement Outline

- Profiling single static link
  - Key factors that affect link attenuation models
  - Coverage with directional beams, effect of FCC regulation
- Link behavior under environment dynamics
  - Overhead of beam-searching, discovery latency
  - Effectiveness of beam-switching under channel dynamics
- Multi-link spatial reuse
  - Spatial reuse between highly directional links

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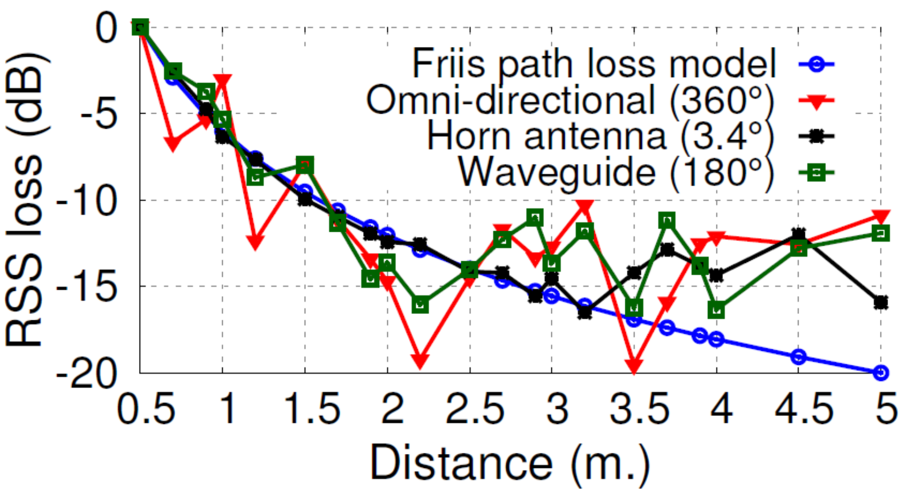
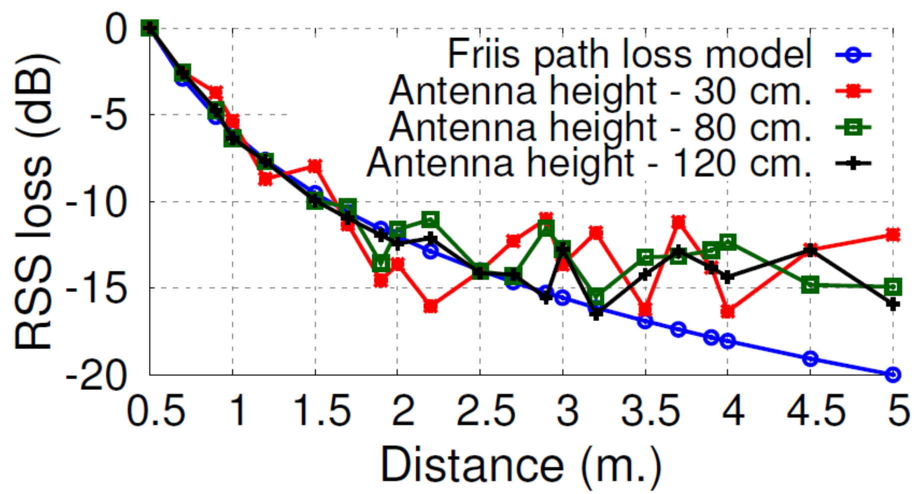
Profiling Single Static Link

- Line-of-Sight links
  - Theoretical attenuation model (Free-space model) is accurate under:
    - Short distance
    - High antenna deployment
    - Narrow beams

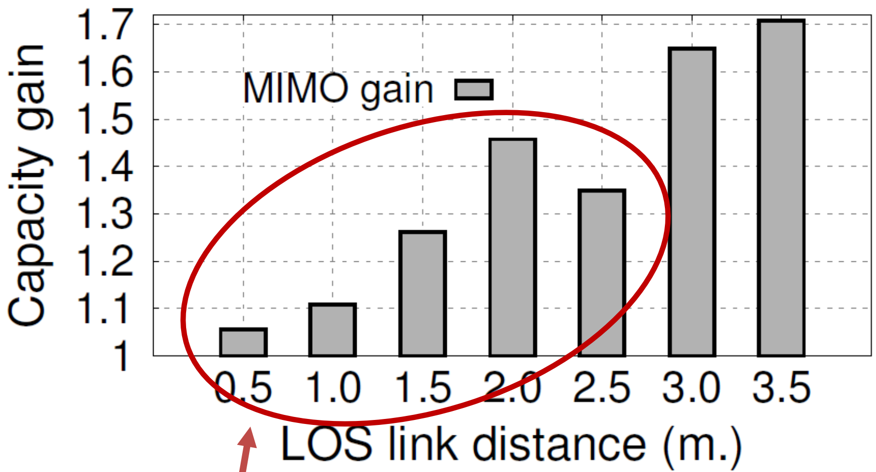
Less multipath!





Profiling Single Static Link

- Line-of-Sight links: MIMO link
  - Is 60 GHz MIMO link feasible?



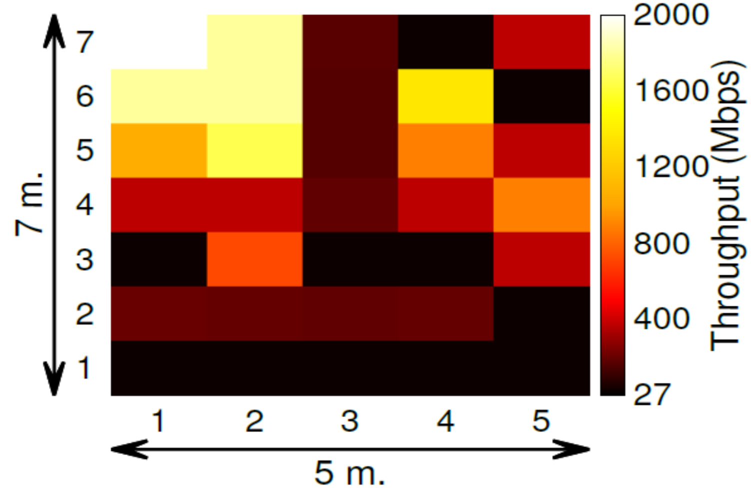
2x2 MIMO, ideal gain=2

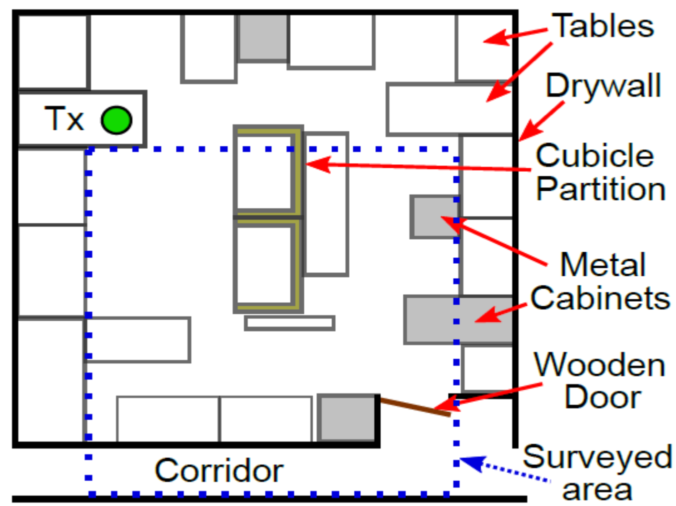
Marginal gain at short-distance

New challenge for 60 GHz MIMO!

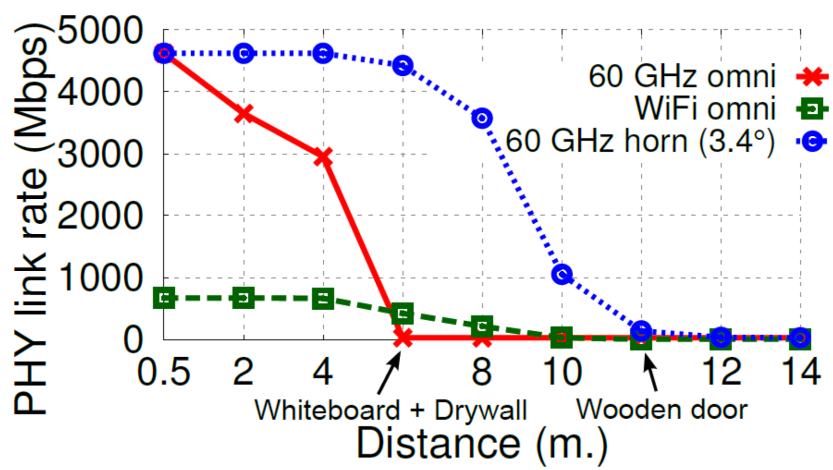
Profiling Single Static Link

- Non-Line-of-Sight links
  - Room-level coverage is feasible even with 180 degree beam





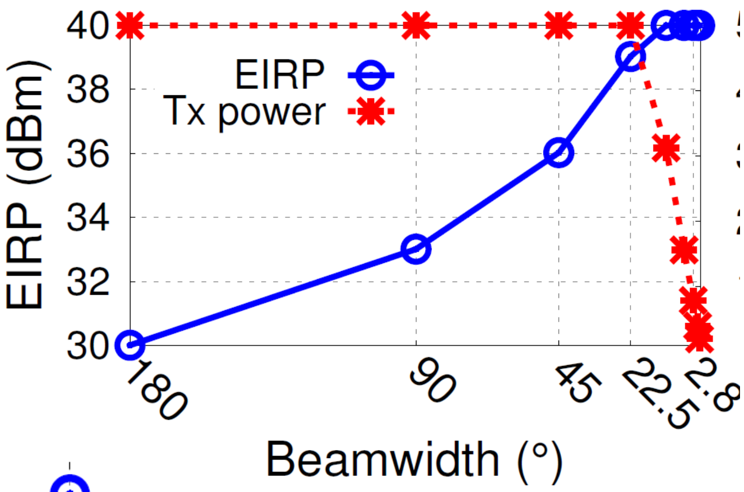
  - Beyond room-level coverage with narrow beam (3.4 degree) is comparable to Wi-Fi!

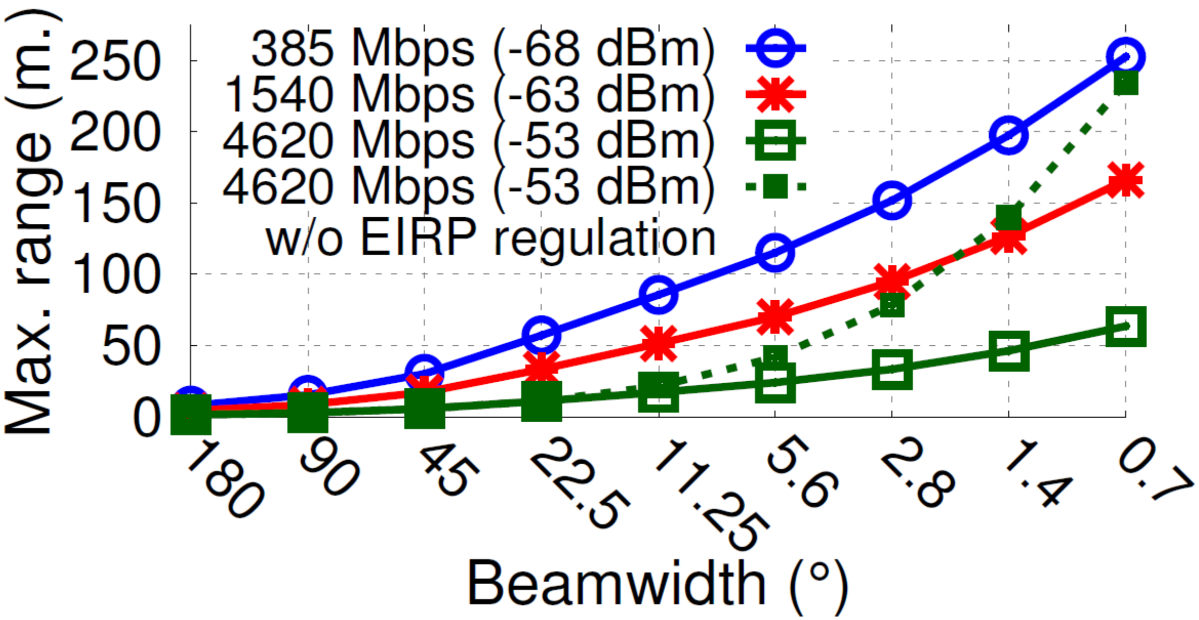


Coverage not so bad!

Profiling Single Static Link

- Scalability of rate and range with beamwidth
  - Radiation power is limited by FCC rules
  - Non-linear rate-range scaling in LOS with beamwidth due to power limitations





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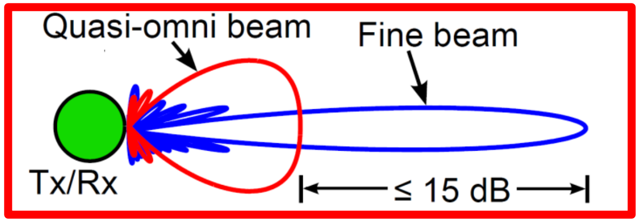
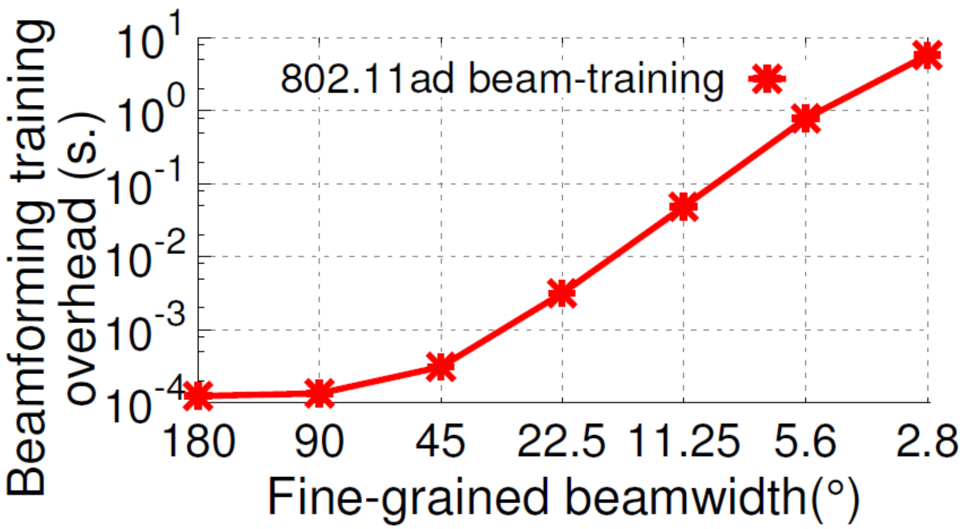
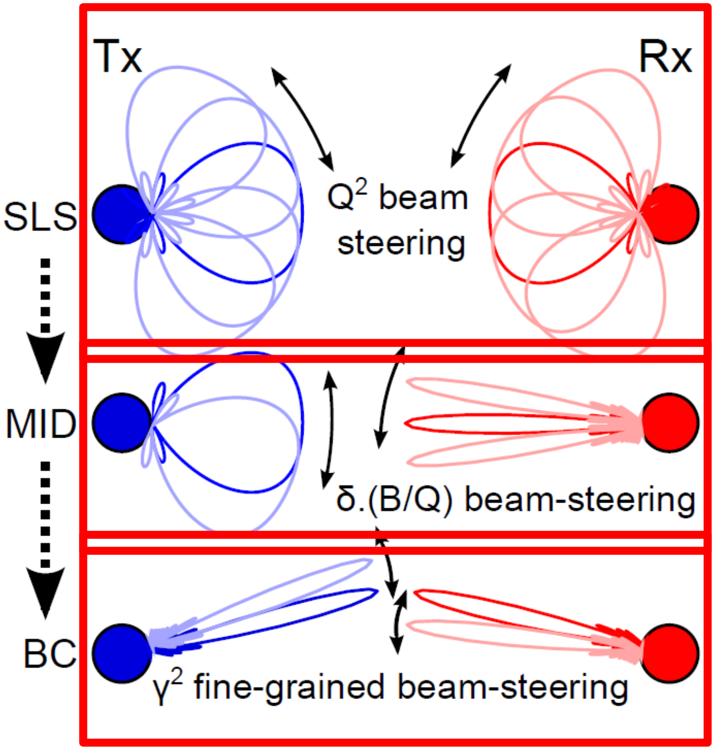
Impacts of Directional Beam-Searching

- Overhead of beam-searching
  - Beam-searching is a must
  - Beam-searching in 802.11ad comprises of 3 steps
  - Beam-searching overhead is still quadratic with # directions

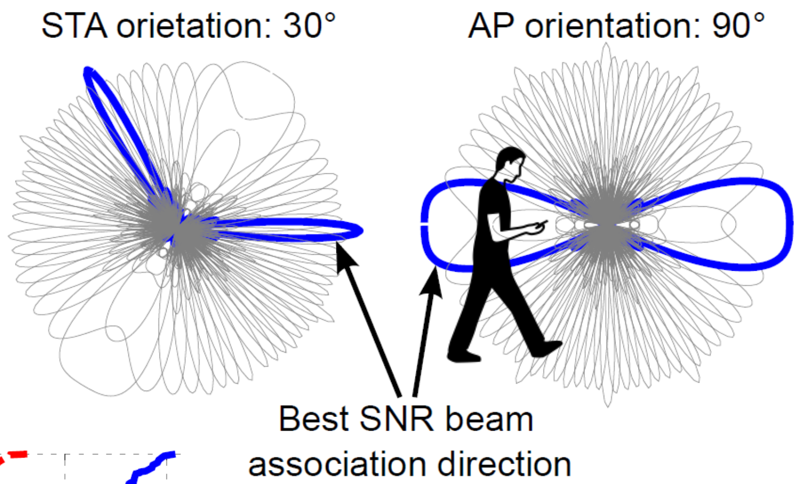


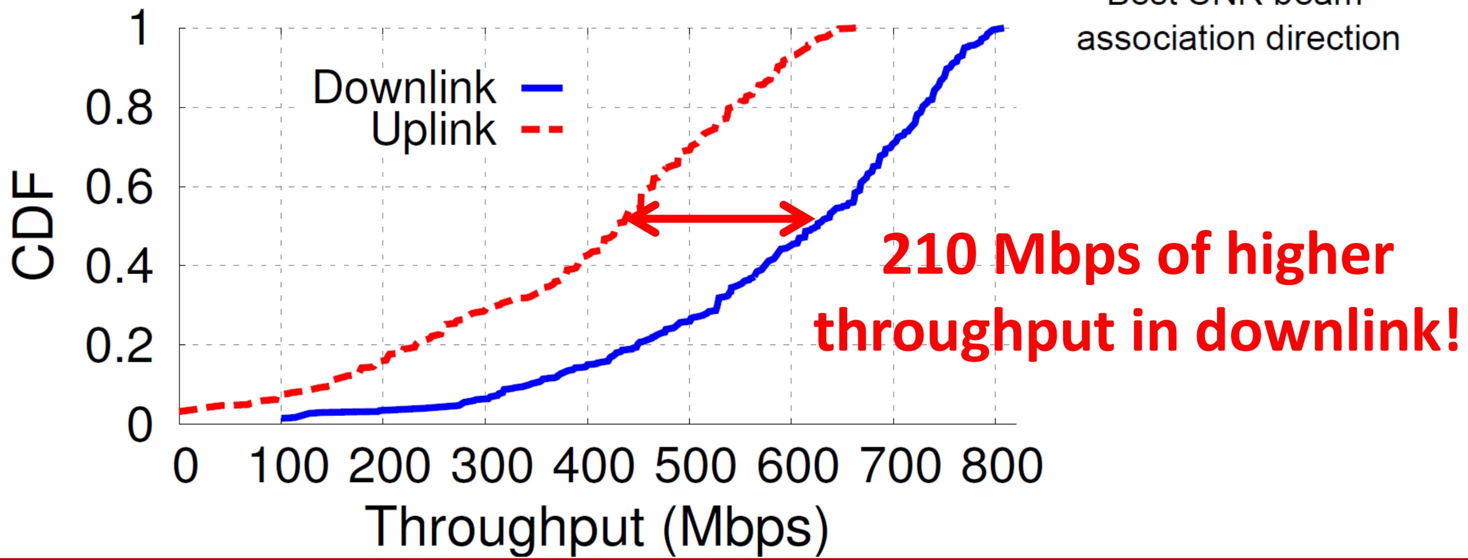




Impacts of Directional Beam-Searching

- Asymmetric link performance
  - Channel is reciprocal, but beams can be asymmetric
  - Large throughput asymmetry between down- and up-link in presence of human blockage and movement

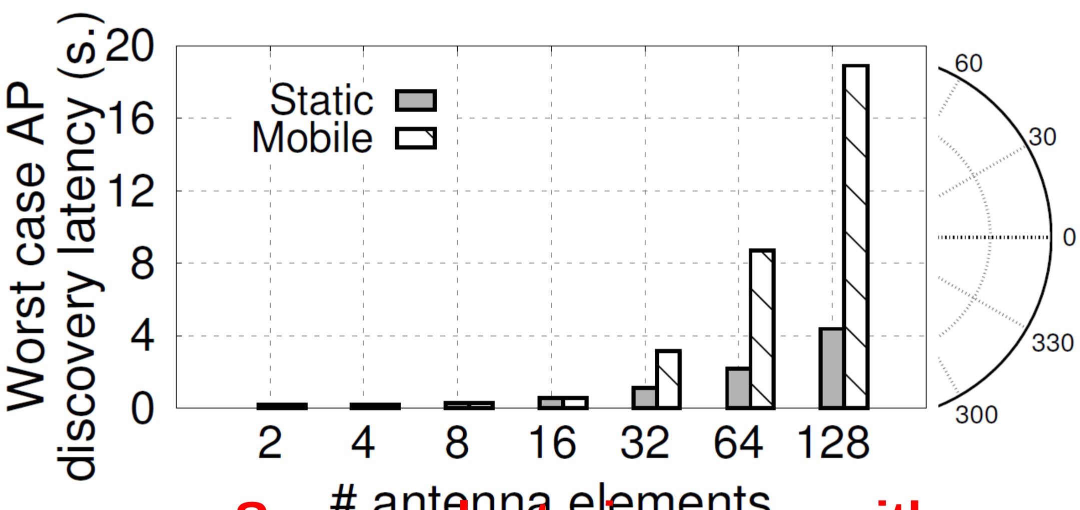




A consequence of interaction between phased-array beamforming and environment dynamics.

Impacts of Directional Beam-Searching

- AP discovery using quasi-omni beams
  - AP transmits beacons through quasi-omni beams to improve coverage and reduce beaconing overhead
  - Sparsity of 60 GHz signals in indoor environment renders it ineffective

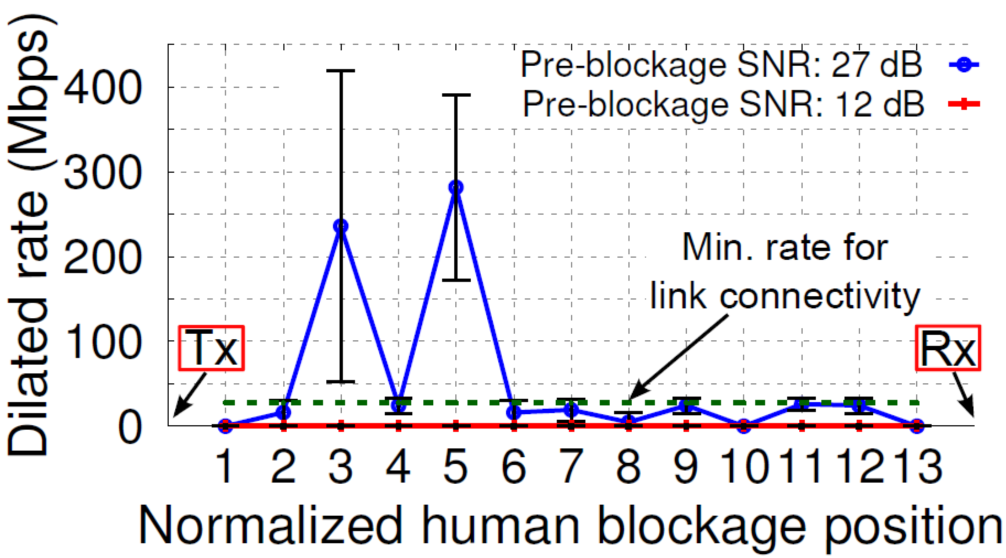


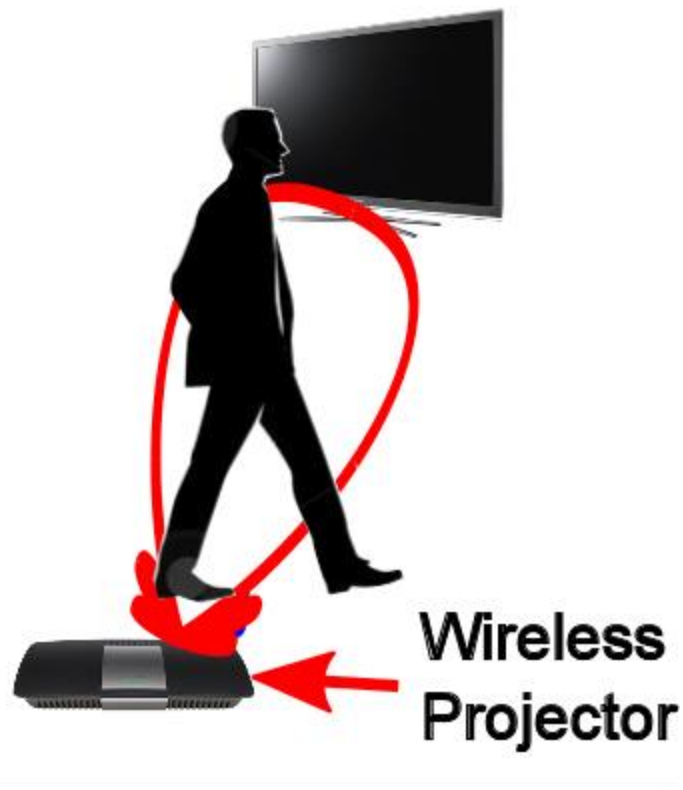
Sparse clustering even with omni transmitter

Sparse channel and mobility causes long AP discovery latency.

Is Beam-Switching Effective during Blockage?

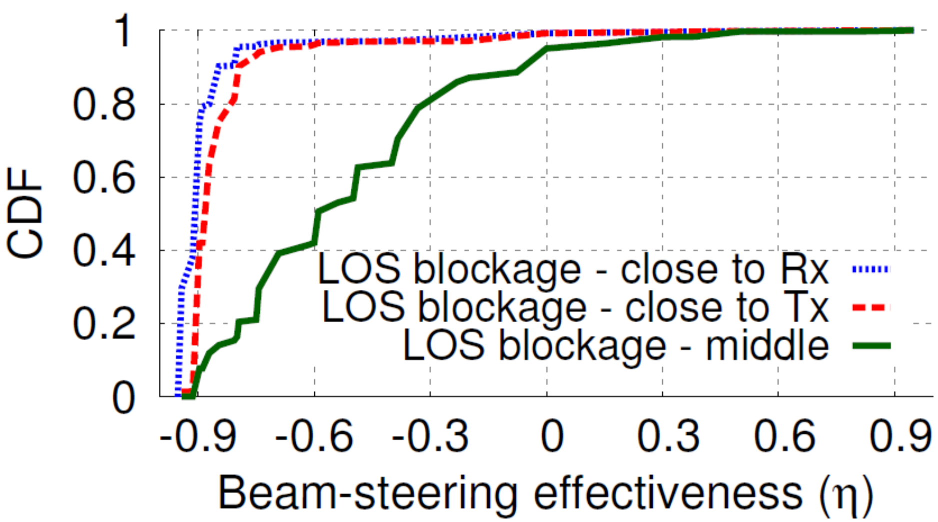
- Switching between beamwidths
  - Switching to quasi-omni beam when blocked and to narrow beam when blockage disappears
  - Experiment with 3.4-degree narrow beam and 19.2-degree quasi-omni beam



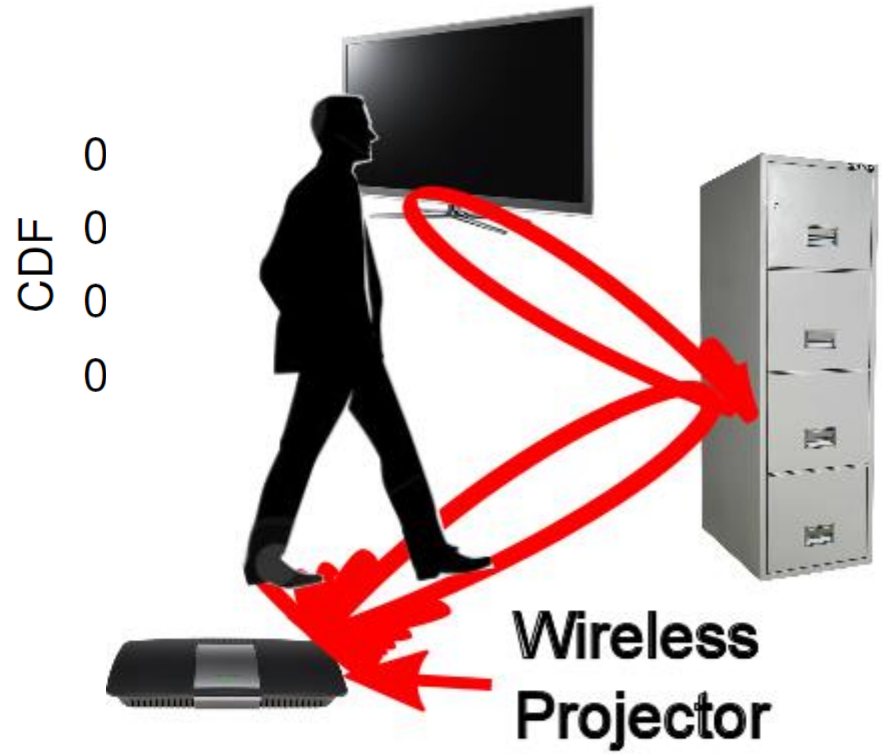


Is Beam-Switching Effective during Blockage?

- Steering beam directions
  - Effectiveness is measured in terms of normalized change in throughput before and after blockage



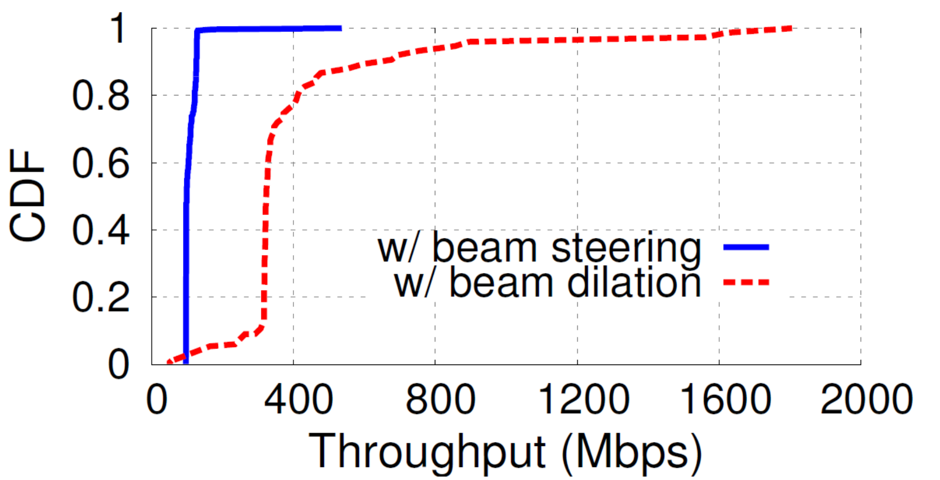
(c) Under human blockage at different positions (Beamwidth: 22.5°)

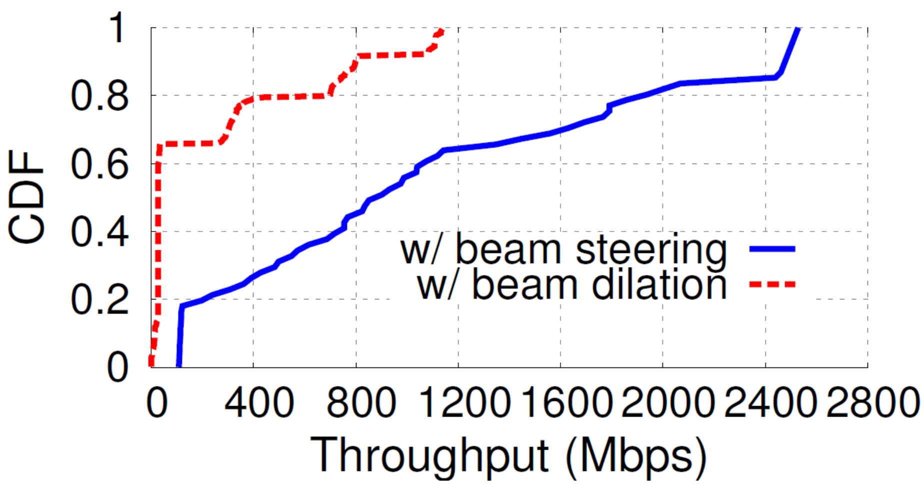


Steering effectiveness depends on environment types, blockage position and operating beamwidth

Beam-switching during blockage and motion

- One solution does not fit for all dynamics
  - Beamwidth adaptation is more effective during device motion
  - Beam-steering performed better during human blockage





Hint for robust 60 GHz link design: **Sense** the link dynamics and **adapt** beams accordingly.

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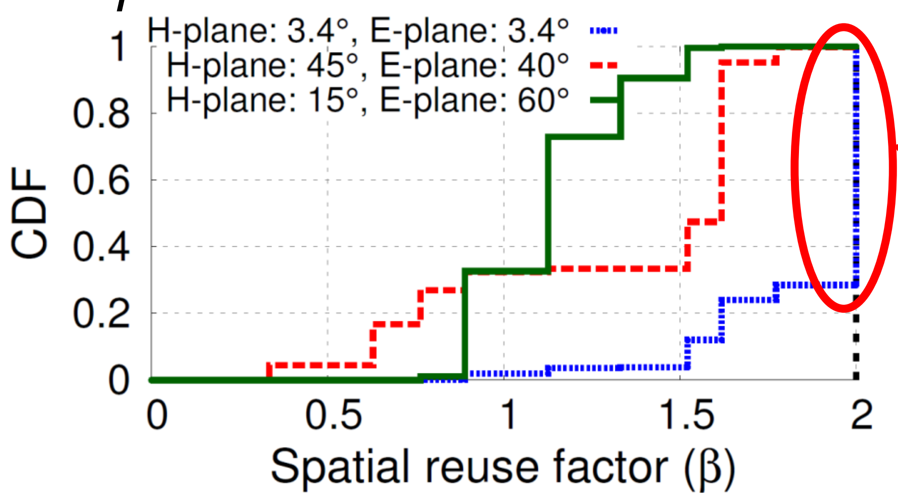
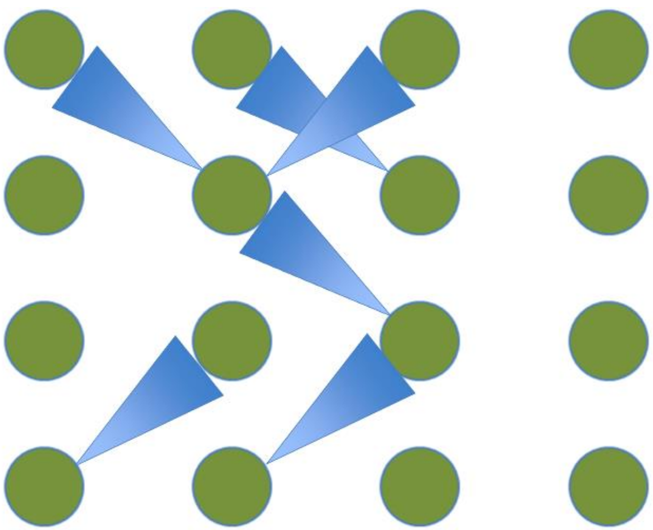
Spatial Reuse Between Static Links

- Spatial reuse factor
  - A metric to evaluate how many number of concurrent links can be packed in a given area

$$\beta = \frac{\text{Sum rate of concurrent links}}{\text{Average rate of isolated links}}$$

  - Ideally narrow beams should enable $\beta \approx 2$



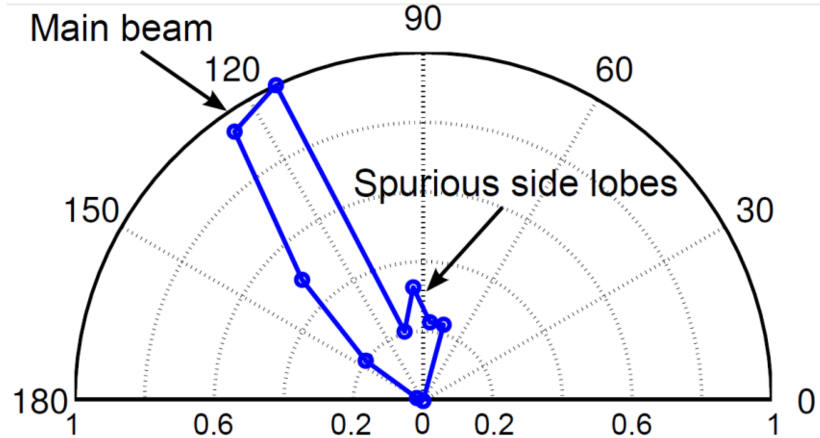


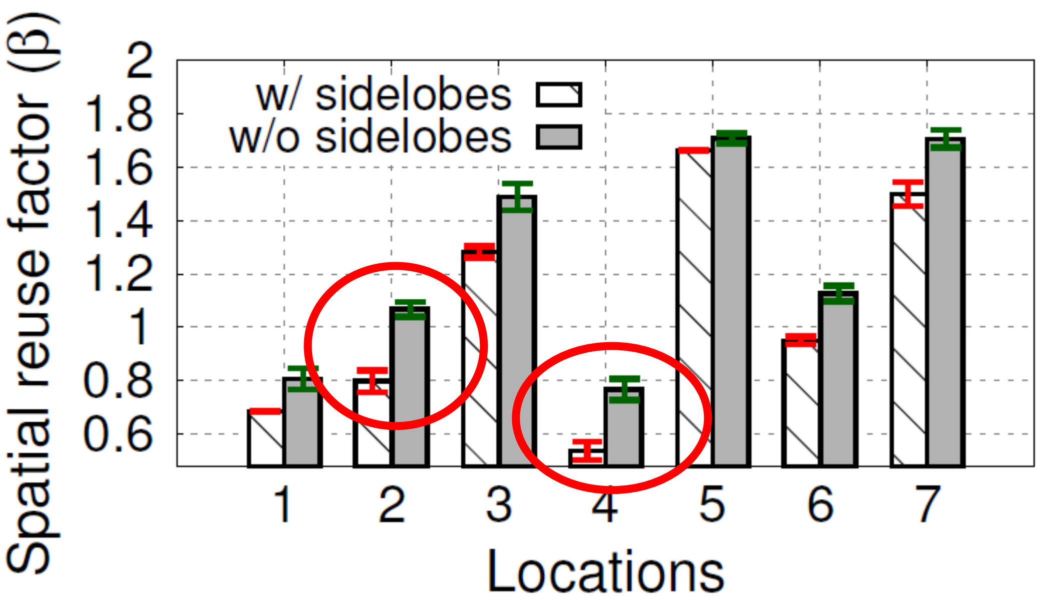
Result: only 80% of the cases $\beta = 2$

High directionality doesn’t mean interference free!

Spatial Reuse Between Static Links

- Impact of side lobes of phased-array beams
  - Side-lobes: generated by phased-array
  - Existing modeling use fan-shape to represent beams: over-estimation of spatial reuse



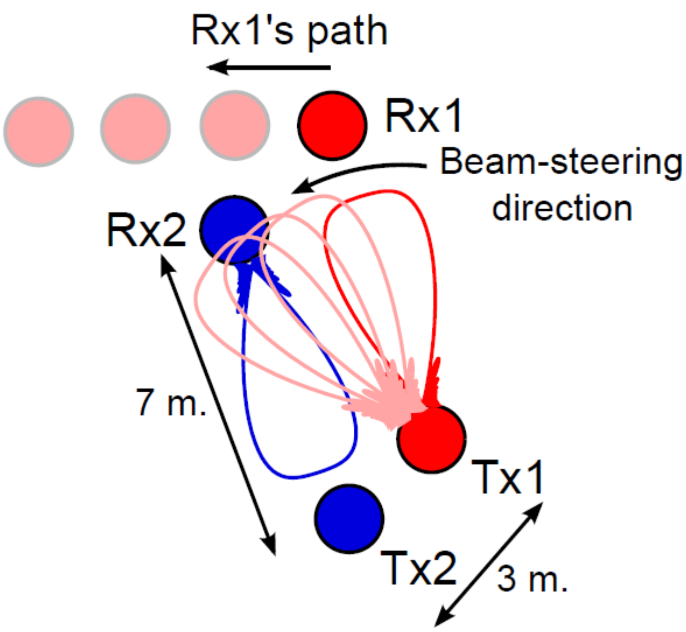


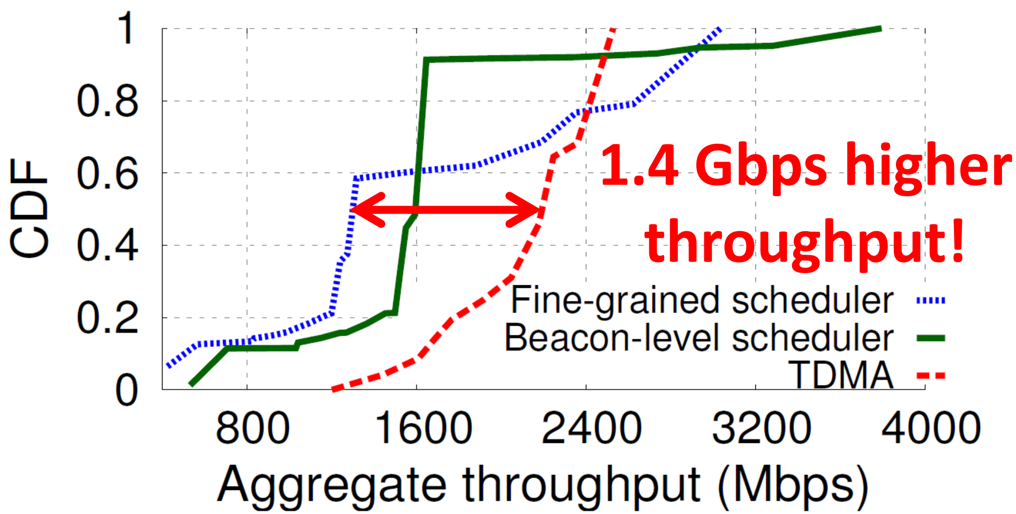
  - Experimented links using 30 degree beamwidth w/ and w/o sidelobes
  - Reuse factor can degrade by 6 ~ 25% resulting in 250 Mbps to 700 Mbps throughput drop!

Phased-array directionality is imperfect!

Spatial Reuse Between Dynamic Links

- Performance of interference-aware scheduler
  - 802.11ad AP builds conflict graphs to help multi-link scheduling and spatial reuse
  - Dynamic links cause frequent conflict graph change, and huge scheduling overhead





Better isolate mobile links in MAC scheduling!

Summary

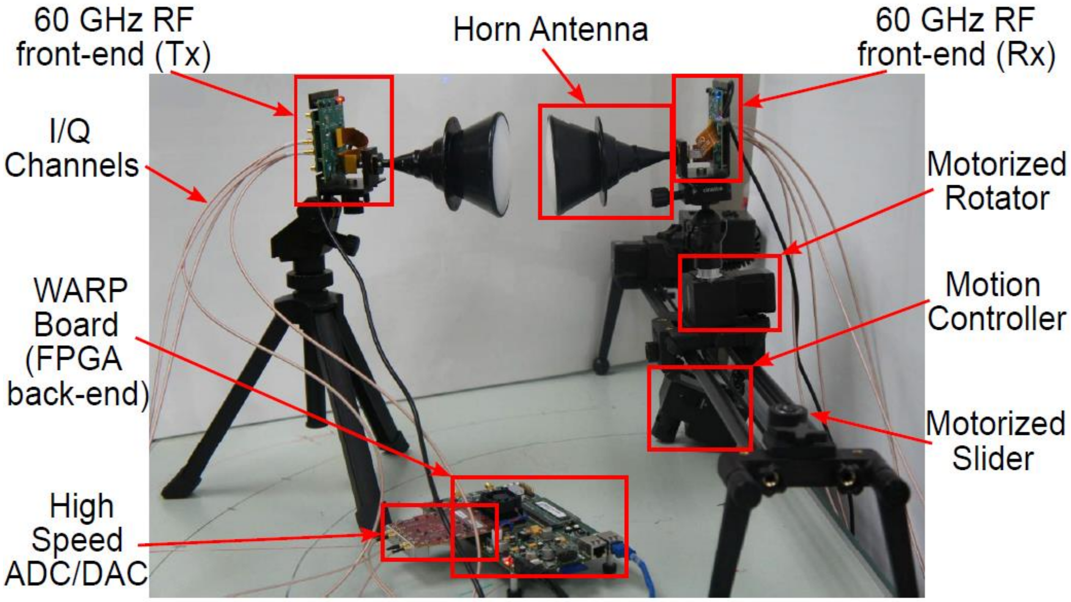
- A microscopic evaluation of flexible-beam based 60 GHz indoor networking unveiled many new challenges overlooked by previous measurement studies

- A robust 60 GHz indoor networking requires new design principle that are unavailable in current standards

- Open issues in 60 GHz wireless networking
  - Efficient beam-searching algorithm
  - Efficient AP discovery
  - Spatial reuse via beam scheduling/adaptation
  - Mitigate human blockage and device motion issues for robust indoor 60 GHz

Wisconsin Millimeter-wave Software Radio (WiMi)

http://xyzhang,ece.wisc.edu/wimi



Thank you!

Backup slides