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

Sanjib Sur, Vignesh Venkateswaran, Xinyu Zhang, Parmesh Ramanathan

University of Wisconsin - Madison
http://xyzhang.ece.wisc.edu
xyzhang@ece.wisc.edu
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](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
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 MACPHY 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
Measurement Outline

- Profiling single static link
  - Key factors that affects link attenuation models
  - Coverage with directional beams, effect of FCC rules

- Link behavior under environment dynamics
  - Overhead of beam-searching, discovery latency, link asymmetry
  - Effectiveness of beam-switching in presence of dynamics

- Multi-link spatial reuse
  - Spatial reuse between highly directional links
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!

---

![Graphs showing RSS loss vs. distance for different antenna types and heights.](image-url)
Profiling Single Static Link

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

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
Measurement Outline

- Profiling single static link
  - Key factors that affects link attenuation models
  - Coverage with directional beams, effect of FCC rules

- Link behavior under environment dynamics
  - Overhead of beam-searching, discovery latency, link asymmetry
  - Effectiveness of beam-switching in presence of dynamics

- Multi-link spatial reuse
  - Spatial reuse between highly directional links
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

![Diagram showing beamforming training overhead vs. fine-grained beamwidth](image)
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.

210 Mbps of higher throughput in downlink!
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 causes long AP discovery latency.
Is Beam-Switching Effective during Blockage?

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

![Graph and diagram showing the effectiveness of beam-switching during blockage.](image)
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.
Measurement Outline

- Profiling single static link
  - Key factors that affects link attenuation models
  - Coverage with directional beams, effect of FCC rules

- Link behavior under environment dynamics
  - Overhead of beam-searching, discovery latency, link asymmetry
  - Effectiveness of beam-switching in presence of dynamics

- Multi-link spatial reuse
  - Spatial reuse between highly directional links
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
Thank you!

Wisconsin Millimeter-wave Software Radio (WiMi)
http://xyzhang.ece.wisc.edu/wimi
Backup slides