Fast and Infuriating: Performance and Pitfalls of 60 GHz WLANs Based on Consumer-Grade Hardware

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60 GHz Wireless

- 7 GHz of unlicensed spectrum available around 60 GHz

- Standardized under 802.11ad, which uses 2.16 GHz wide channels

- 802.11ad is 350% faster than 802.11ac
Utilizing the 60 GHz Band: Challenges

**Short Range**

- **802.11 n/ac**
- **802.11 ad**

**Easily Blocked**

- **802.11 n/ac**
- **802.11 ad**
Increasing Range: Beamforming

• Using multiple antenna elements

• Codebook
  • Set of multiple pre-computed antenna weights (phase values)
  • Typically designed to cover wide sweep space
  • Device selects a beam from codebook in runtime
Directional Transmission

High frequency
Short/Limited Range

Directional Transmission
BEAMFORMING

Vulnerability to LOS Blockage
Non-resilience to Mobility

A lot of research efforts directed towards addressing these challenges

Most recent systems work is experimentally driven!
Current Choice of Measurement Platforms

- Software-Defined Radio (SDR)-based
- Used in conjunction with a 60 GHz up-converter
- Access to lower-layer PHY information
- Control over beam direction
- Deeper insights into link behavior
SDRs Vs. Commercial Off-the-Shelf (COTS) Hardware

A. Limited to few 100 MHz of bandwidth
B. Use mechanically steerable horn antennas

A. 802.11ad uses 2.16 GHz wide channels
B. 802.11ad COTS devices use phased-antenna arrays
802.11ad: Beamforming

Our COTS hardware does this procedure once every 10 frames OR On Loss of ACK
Experimental Setup: Devices (Access Point)

- **TP-Link TALON AD7200**
- First commercial 802.11ad router (rel. June 2016)
- QCA9008-SBD1 (QCA9500 chipset)
- Single carrier data rates up to 4.6 Gbps
- 32-element phased antenna array
- Includes only 1 G LAN interface
Experimental Setup: Devices (Access Point)

- *Netgear NIGHTHAWK* X10 Smart WiFi Router
- Released around October 2016
- Same chipset as the Talon
- 32-element phased antenna array
- Sports 10 G LAN SFP+ interface
- Actual throughput limited to around 2.3 Gbps
Experimental Setup: Devices (Client Laptop)

- **Acer Travelmate** P446-M
- Released in April 2016
- QCA9008-TBD1 (client version of the AP chipset)
- Fedora Linux (kernel 4.x)
- Open source wil6210 driver
- 32-element phased antenna array
Experimental Setup: Methodology

- Downlink TCP traffic generated using iperf3
- Additional Talon Router to sniff packets off air
- The devices use proprietary beam and rate adaptation mechanism
- In case of disconnection, radios automatically try to re-establish link through NLOS paths
- Collect link parameters:
  A. Tx and Rx MCS
  B. MAC Layer Throughput
  C. Signal Quality Indicator (SQI)
  D. Beamforming Status: OK/Failed/Retrying
  E. Sector (beam direction) used by AP and Client
Link Performance: Distance

<table>
<thead>
<tr>
<th></th>
<th>Outdoor &gt; 2 Gbps</th>
<th>Outdoor &gt; 1 Gbps</th>
<th>Lobby &gt; 2 Gbps</th>
<th>Lobby &gt; 1 Gbps</th>
<th>Corridor &gt; 2 Gbps</th>
<th>Corridor &gt; 1 Gbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nighthawk</td>
<td>23 ft</td>
<td>65 ft</td>
<td>55 ft</td>
<td>80 ft</td>
<td>140 ft</td>
<td>155 ft</td>
</tr>
<tr>
<td>Talon</td>
<td>-</td>
<td>-</td>
<td>80 ft</td>
<td>80 ft</td>
<td>155 ft</td>
<td>155 ft</td>
</tr>
</tbody>
</table>

Gbps range limited to around 65 ft.

Open Space
Minimal reflectors

Narrow
Walls on both sides

MUCH larger range
80/155 ft. (> 1Gbps)

Corridor > Lobby
(b) PHY data rate over distance in the Corridor.
Link Performance: Orientation (Setup)

50 ft. (Lobby)
Link Performance: Orientation (Rx)

- *Rx sector* (beam direction) *never* changes
- We tried extreme angles
- Gbps communication possible between [-75°, 75°] angles
- **Quasi-omni beam patterns**

\[
\text{Gbps rates are possible even without beamforming gains on Rx side}
\]
Link Performance: Orientation (Tx)

(a) Performance for different Tx angles with both routers.

- **NIGHTHAWK** maintains higher data rates between [-45, 30] deg.
- **TALON** maintains >1 Gbps rates almost at all angles.

(b) Loss due to suboptimal Tx sector with Talon for different Tx angles.

- **TALON** still selects mostly sub-optimal Tx sectors.
Coverage: Experiment Setup

Two Tx (AP) positions: Tx1 and Tx2

Two Rx (Laptop) orientations: Rx Or1 and Rx Or 2

(a) Lobby floorplan.
Coverage: Tx Orientation

(c) AP at Tx2, client orient. 1.

(a) Lobby floorplan.

(a) AP at Tx1, client orient. 1.
Coverage: Rx Orientation

(c) AP at Tx2, client orient. 1.

(a) Lobby floorplan.

(d) AP at Tx2, client orient. 2.
Access Point (AP) Placement

• Compare four placement options

A. Default (used in most measurements in the paper)
B. Table (Home WiFi Networks)
C. Wall-mounted (Enterprise WiFi Networks)
D. Ceiling-mounted (Dense Enterprise WiFi Networks)
Access Point (AP) Placement

**Table and Ceiling** performs best >2.3 Gbps (up to 60 ft.)

**Ceiling** performs better for < 60 ft. Default better over larger distances
AP Placement: NLOS Performance
TALON maintains >1.5 Gbps rates in ALL topologies

Outage time is upper bounded by 5% in ALL topologies
AP Placement: Communication through Walls

Variation in performance from 0 Mbps to 2.3 Gbps
Blockage: Mobile Client, Wall Blockage

Too many SLS failures makes the driver abandon re-connection.
Mobility: Away from the AP

TALON: >2.3 Gbps up to 67 ft.
NIGHTHAWK: >2.3 Gbps up to 37 ft.

TALON: >1 Gbps up to 180 ft.
NIGHTHAWK: >1 Gbps up to 135 ft.
Mobility: Away from the AP [Beamforming Failures]

SQI changes **falsely** trigger beam-adaptation

*Beamforming failures* hurt performance!
Mobility: Towards the AP

[Graphs and charts showing data rate variation with distance for different models, possibly Nighthawk and Talon, with error bars indicating variability.]

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Challenges: Summary

Non-critical Challenges

- Transient human blockage has minimal impact. 802.11ad COTS devices perform frequent sector sweeps.

- Sector sweeps take less than 1ms (blockage occurs at 100 ms timescale). Devices train only their Tx sectors and use quasi-omni Rx.

- Through-wall communication is feasible and can allow a single AP to serve multiple rooms.
Challenges: Summary

**Unexpected Challenges**

- Interaction between beam training and rate control critical
  Incorrect beam and rate severely hurt performance

- Beam steering accuracy strongly degrades beyond 60 degrees

- Placement of antenna inside AP dictates performance
  AP deployment should take AP form factor into consideration
Challenges: Summary

**Expected Challenges**

- Movement and rotation: Strong impact on performance

- Mobility scenarios cause link adaptation failures
  - Loss differentiation critical to solve this

- Rate control just based on link quality indicators which can be uncorrelated to the 60 GHz channel state
THANK YOU!

Questions?