# Millimeter Wave Networking Challenges

## Visions for Future Communications Summit

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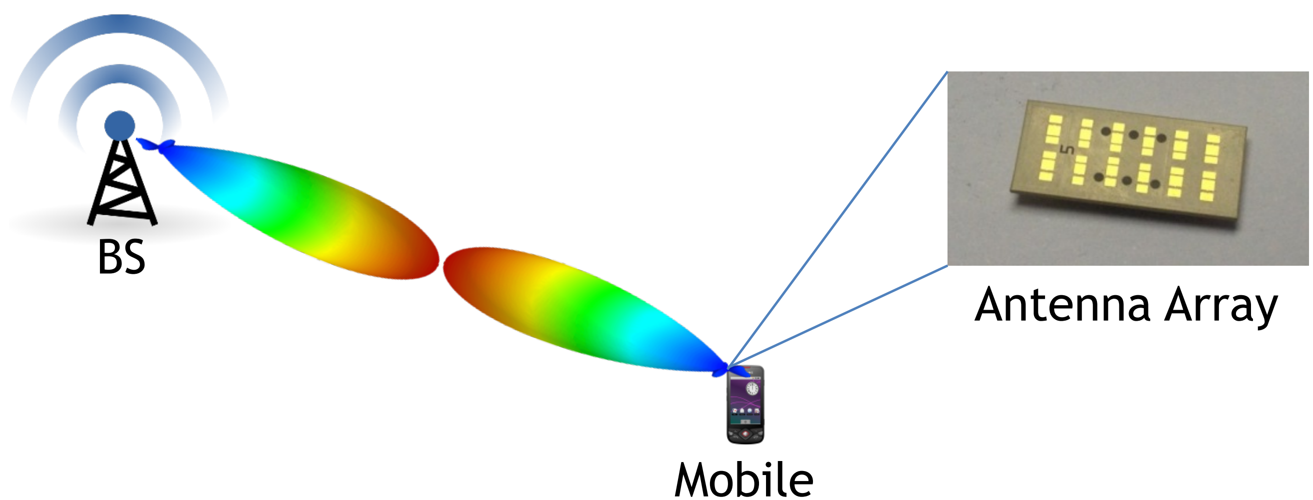
Developing the Science of Networks

# Mm-Wave Communication at a Glance

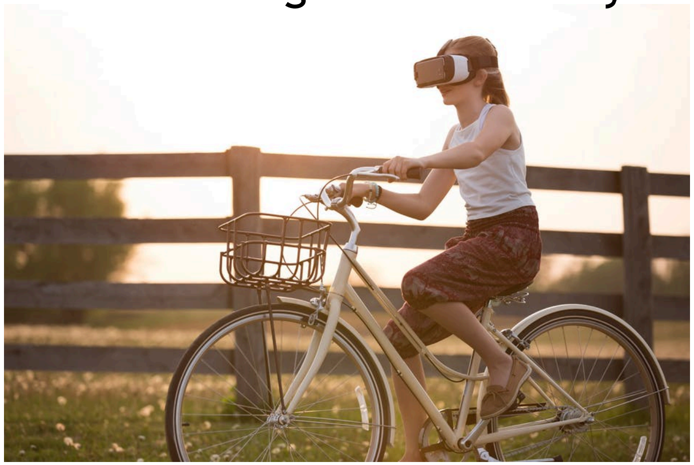
- Multi-Gbit/s per user to support rapid increase in wireless traffic
  - Many GHz of spectrum available at mm-wave frequencies (>6GHz)
- Very high levels of spatial reuse
  - Highly directly antenna arrays
  - Low interference (through side lobes)



# Challenging New Scenarios

V2X, autonomous vehicles
(drones, robots, …)

Virtual/augmented reality



Millimeter-wave *mobile* networks

# Mm-Wave Related Problems

**Millimeter-wave communication is not easy**

- High frequency related path loss
- Most materials block the signal
- Communication primarily line-of-sight
- Directional antennas need to be *aligned*
- RF design much harder at these frequencies

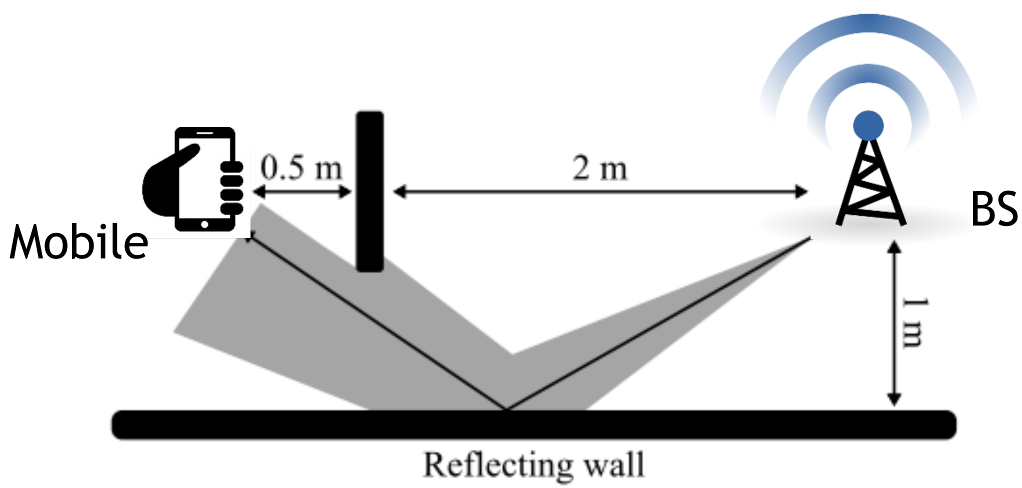
- Mm-wave links are brittle and break easily
- *How to design fast, reliable, low latency networks?*

# Challenges

- Fast beam training
  – With many devices
- Quickly detect outage or blockage
- Support fast switching
  – Devices with multiple antenna arrays
  – Maintain multiple alternative mm-wave paths
  – Use multiple RF technologies (at different frequencies)
- *Without incurring excessive overhead!*
  – Many small cells, very frequent handovers between BS or technologies, Gbit/s streams, ms latency requirements

# Mm-Wave Channel is Highly "Geometric"

- Few available communication paths
- Position/movement of communication partner can be used to steer the antenna array
- Positions of obstacles allow to infer which paths are blocked
- Positions of obstacles/walls allow to infer which reflected paths are available

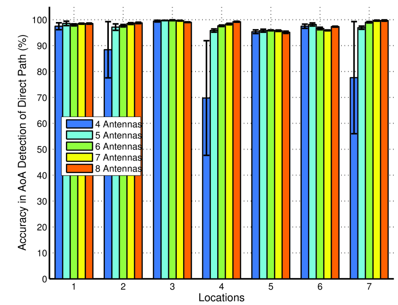


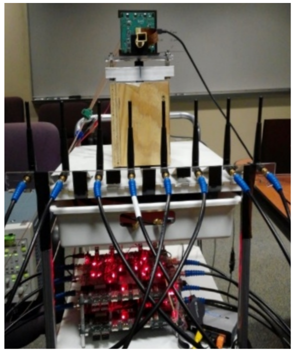
# Exploiting Side Information

- Use available sensor information (gyroscope, accelerometer, magnetometer, GPS, radar, …)
- Anticipatory networking
  - Network prediction and optimization under uncertainty
  - Machine learning to learn environment and movement patterns → determine good resource allocation decisions (handover, beam steering, …)
- Multi-band communication allows to use channel information from one band for communication at another

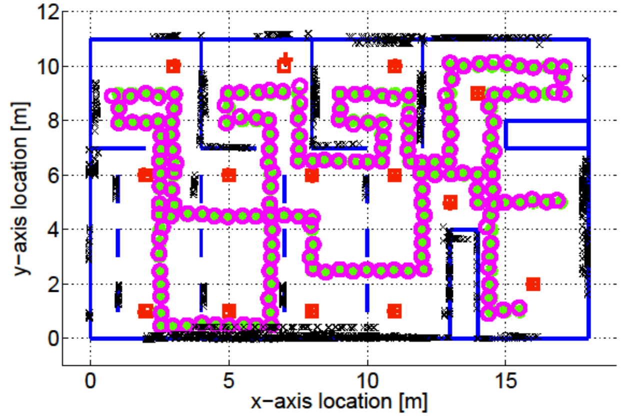
# Example: Beam Training Using Side Information

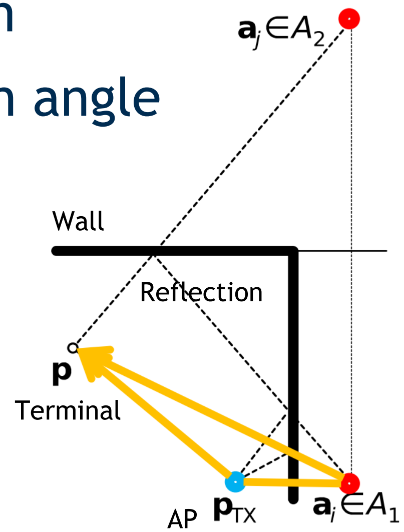
- Beam steering using angle-of-arrival estimation at low frequency band (for multi-band devices)



- Using a wireless location system directly allows to set the steering angle
  - Either using a lower frequency location system
  - Or build a mm-wave location system (based on angle information)



# Transport Related Issues

- Quickly switching Gbit/s streams between base stations and/or technologies is not trivial
  - Tight integration with C-RAN design can help
- Not as easy as running multi-path TCP over the multiple links or technologies
  - Need to quickly react to large rate variations; current transport protocols do not do this well
- Large buffers needed to support high data rates; small buffers desirable for low latency
  - Bufferbloat is an issue already at much lower rates
  - Note: also packet aggregation is very important

# Summary

- Single millimeter-wave links more or less well understood
- Dynamic networks remain a huge challenge
  - Efficient, low overhead orchestration of multiple links, technologies
- Exploiting Side Information
  - Anticipatory networking
  - Machine learning
- Integration with backhaul and C-RAN is important
- THz and VLC systems bring even further challenges

# THANK YOU !

# Challenges at all Levels of the Protocol Stack

- Difficult RF design → non-typical transceiver architecture
- Very directive signal → align the beams and keep them aligned (mobile! network)
- Short range → frequent handovers (or multi-hop routes)
- Many access points → efficient network management and control, energy efficiency
- Blockage → relaying, fall back to lower frequency
- Little interference → encourage parallel transmissions
- No omni-directional control signals for coordination → new initial access and MAC layer paradigms
- High rate variations → requires flexible transport protocol
- Typical packet size too small for Gbit/s rates → extreme packet aggregation (100s or 1000s of packets)
- … and many many more