Millimeter Wave Networking Challenges

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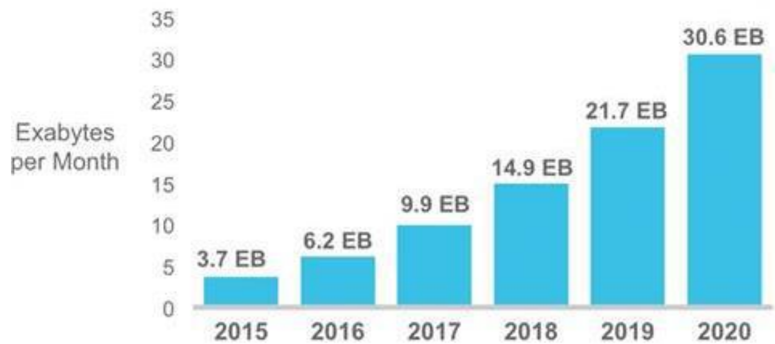
Developing the Science of Networks

Why Millimeter Wave?

- Continued rapid increase in wireless traffic volume



Cisco® Visual Networking Index (VNI)

- 100 X in user data rate
- 1000 X in number of devices
- 1000 X in data volume per area
- 1/10 X in energy consumption
- 1/5 X in end-to-end latency
- …

- Move to higher frequencies is inevitable in order to achieve multi-Gbit/s data rates per user
  - Spectrum is very crowded at current frequencies up to ~6 GHz
  - Link rates are already close to the theoretical capacity
- Many GHz of spectrum available at mm-wave frequencies (~30 - 300GHz)

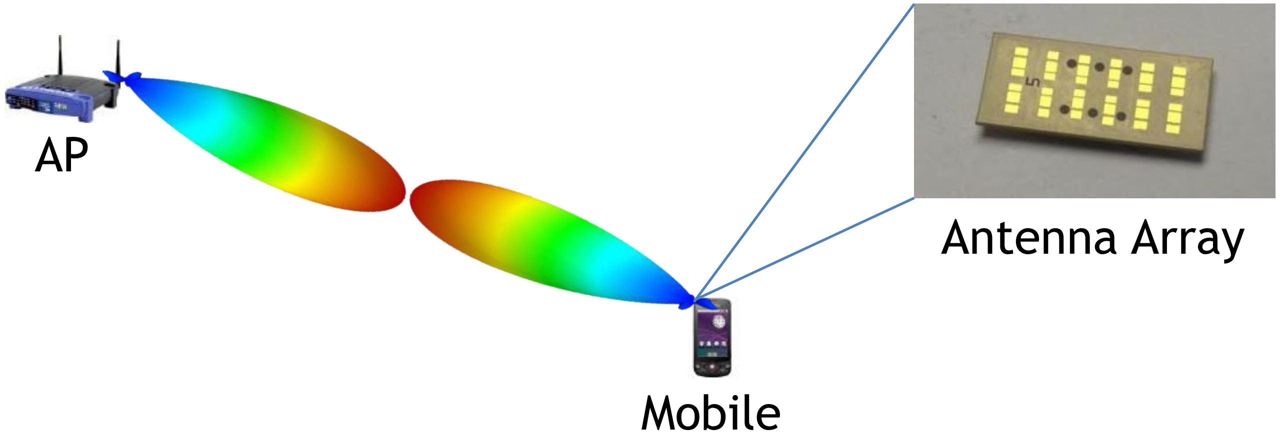
Millimeter Wave Challenges

Millimeter-wave communication is not easy

- High frequency related path loss
- Atmospheric absorption at very high frequencies
- More noise due to very wide bandwidth
- Most materials block the signal (also humans!)
- Communication primarily line-of-sight
- RF design much harder at these frequencies

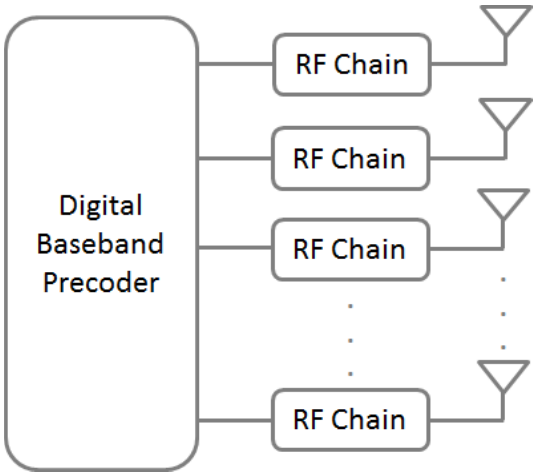
Mm-wave Communication

- Unacceptable communication range with omnidirectional antennas
- Use highly directional antennas
  - Increase gain at transmitter and receiver to overcome high path loss and absorption
- Antenna size directly related to wavelength → possible to integrate many antenna elements in a small form factor



How to Design Transceivers?

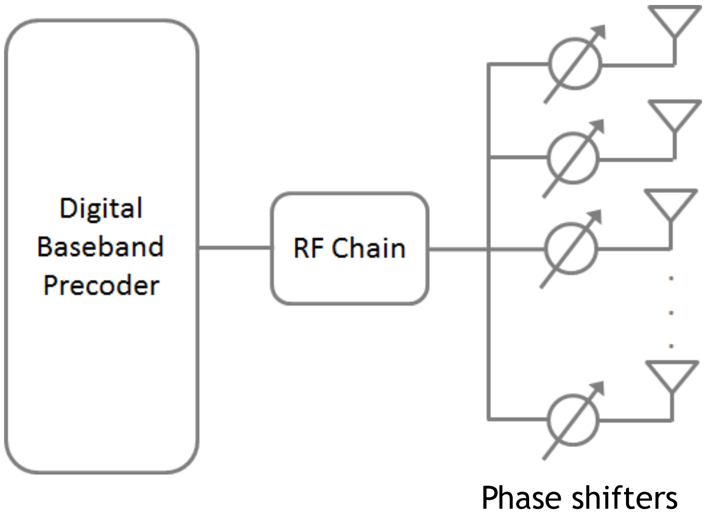
- Need electronically steerable antennas (for most applications)
- Digital beamforming (MIMO) as used for lower frequency systems
  - Capable of achieving multiplexing gains
  - Optimal beamforming because of precise amplitude/phase control
  - Each RF chain requires a (multi-GHz!) A/D converter, amplifier, …
  - Baseband processing requirements, overhead of channel estimation



- Too high complexity, cost, energy consumption → currently not practical for mm-wave

How to Design Transceivers?

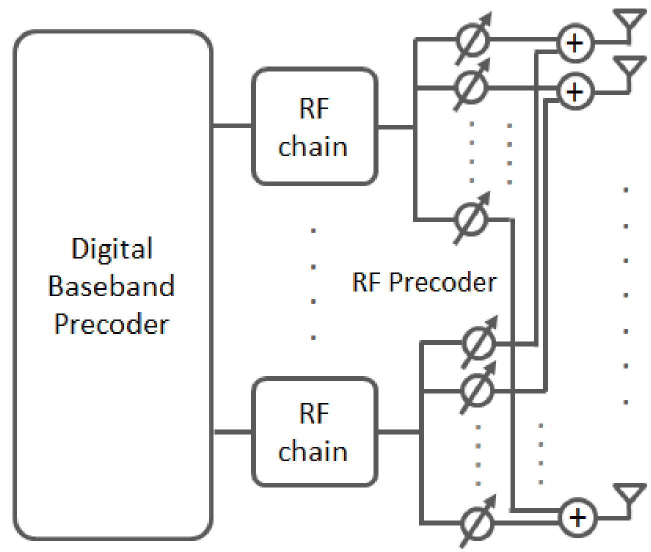
- Need electronically steerable antennas (for most applications)
- Digital beamforming (MIMO) as used for lower frequency systems
- Analog beamforming with one RF chain and analog phase shifters
  - Inexpensive, simple design
  - Sub-optimal beam shapes
  - Single stream, no multiplexing gains



- Implemented in today's off-the-shelf mm-wave devices

How to Design Transceivers?

- Need electronically steerable antennas (for most applications)
- Digital beamforming (MIMO) as used for lower frequency systems
- Analog beamforming with one RF chain and analog phase shifters
- Hybrid beamforming with multiple (but few) RF chains and analog phase shifters
  - Better beam shapes
  - Multiple streams
  - Somewhat higher device complexity
  - Need to understand what is a good design



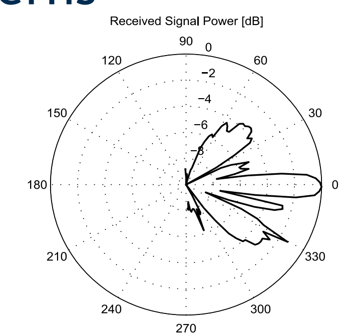
Phase shifters

- Active research area: interesting tradeoff providing a lot of the flexibility of MIMO with a moderate increase in complexity

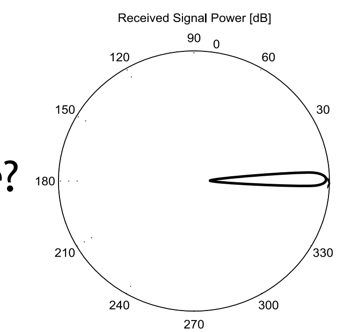
How to Design Transceivers?

- Need electronically steerable antennas (for most applications)
- Digital beamforming (MIMO) as used for lower frequency systems
- Analog beamforming with one RF chain and analog phase shifters
- Hybrid beamforming with multiple (but few) RF chains and analog phase shifters
- Antenna patterns

Now: significant side lobes



Future?

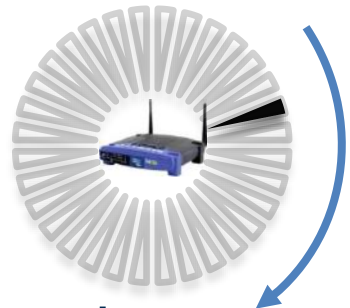


- A/D power consumption directly related to precision
  - Work on signal processing with one (or few) bit A/D converters
- …

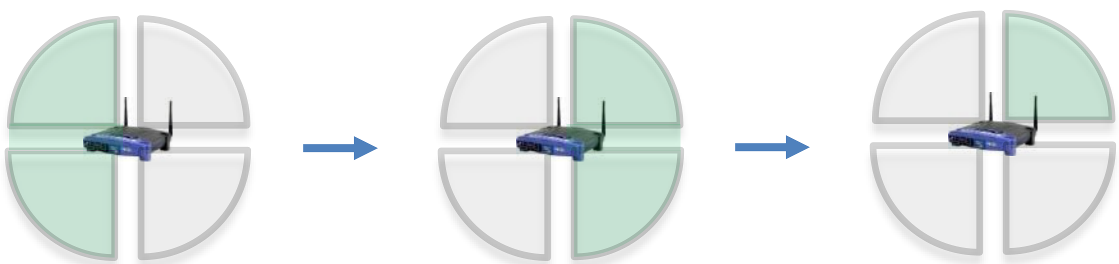
How to Align the Antenna Beams?

Beam training to set the right beam steering direction

- Brute force



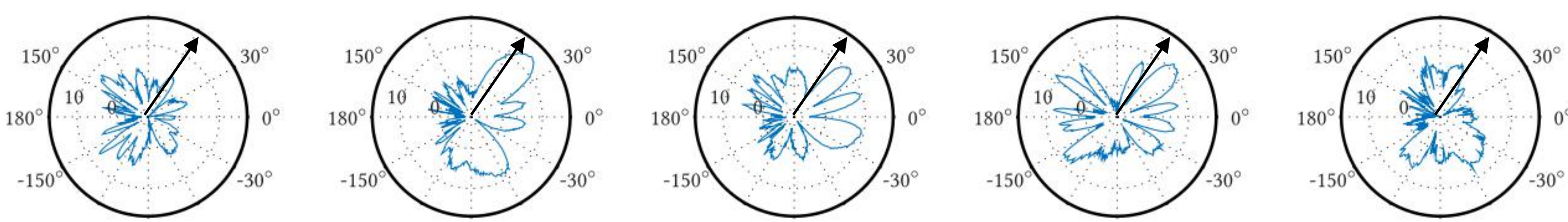
- Hierarchical approaches



  – Hybrid beamforming antennas can even listen in multiple directions at the same time
- Using past information (previous direction, rate of change, …)

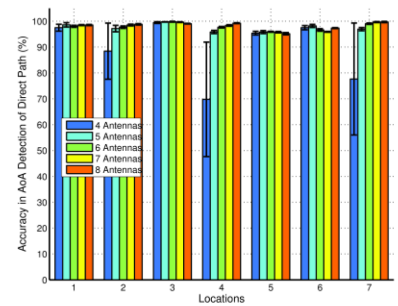
Compressive Beam Training

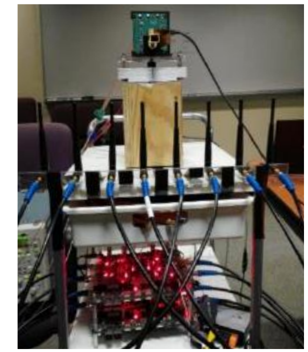
- Exploit sparseness of mm-wave multipath channel
  - Typically line-of-sight path and maybe a few reflected paths
- Compressive Beam Training
  - Sparse estimation problem, no need to train all possible directions
  - Multiply received signal strength values with corresponding beam patterns and add them up



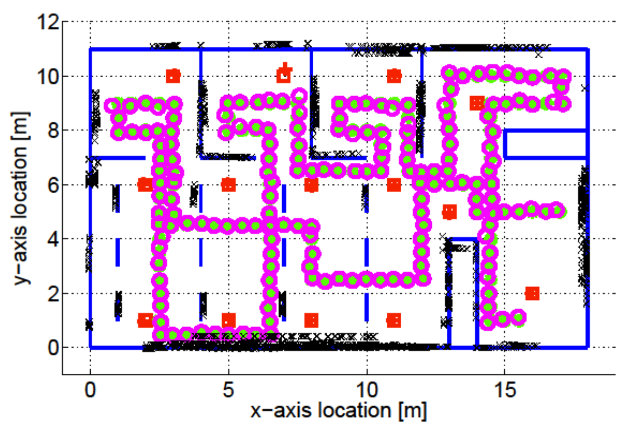
Beam Training Using Side Information

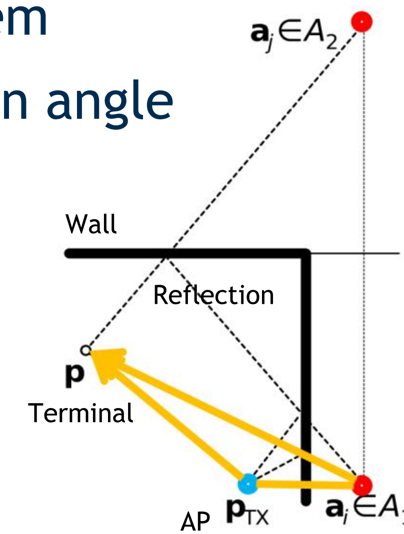
- Beam steering using angle-of-arrival estimation at low frequency band (for multi-band devices)





- Using a wireless location system directly allows to set the right steering angle
  - Either from a conventional Wifi location system
  - Or build a mm-wave location system (based on angle information)





MAC/Network Implications

- High spatial reuse possible, depending on antenna quality
- Very little interference, unless hit by main or side-lobe of another transmitter (→ adapt schedule)
- Use reflections, handover, relaying to establish or recover a communication path
  - Fall back to lower frequency if needed
  - Make before break; try to predict blockage, loss of signal, etc.
  - Again, a location system or learning approach help a lot
- CSMA/CA not ideal: imperfect carrier sensing!
- TDMA or polling are a good match
- Packet aggregation is critical to achieve good efficiency (1KB at 4GBit/s takes only 2μs)

Transport over Mm-Wave Links

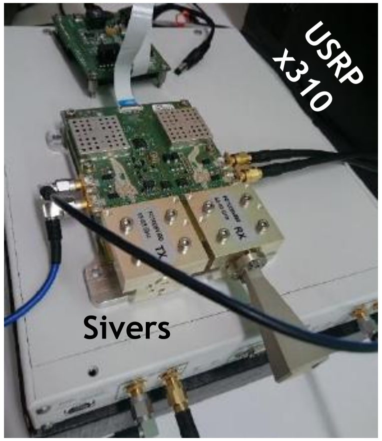
Fragile but very high rate network:

- Human blockage and beam retraining due to device mobility will create short-term outages
- Even when recovering through fall back to a lower frequency system there are orders of magnitude rate variations

- Very difficult for TCP to achieve and maintain Gbit/s rates under such conditions
- Using a large buffer at the helps, but this increases end-to-end latency
- Bufferbloat is an issue already at lower rate systems

Testbed Approaches

- Full bandwidth SDR based platforms
  - Powerful but very complex and costly
- Narrowband SDR based platforms (with upconverters to mm-wave)
  - Inexpensive, but not standard compliant, only mechanical beam steering
- Off-the-shelf devices
  - No configurability
- Lack of flexible and inexpensive experimental platform



Dell D5000 Wireless Dock

Testbed Approaches

- "Open" off-the-shelf devices often boosted research, e.g., Linksys WRT54G with OpenWRT, MadWifi hacks, …
- Currently undertaking similar effort for Talon TP-Link Talon AD7200 Router (with TU Darmstadt)
- Ported OpenWRT/LEDE to Talon router and hacked the firmware of the 802.11ad mm-wave interface
  - Full access to the embedded Linux
  - AP, client, and monitor mode
  - Access full beam training information
  - Modified beam steering algorithm (select sector for communication)
  - Working on custom beam designs (modify phase shifts)
  - Implemented compressed beam training
  - Will be made publicly available

Full 802.11ad PHY & MAC
USD 350

Conclusions

- Extremely promising area, data rates of tens of Gbit/s
  - In the future: >100 GHz to THz systems
- Conventional wireless network paradigms don’t work well
  - Very directional, little interference, high levels of spatial reuse
  - Fragile links, very high network dynamics (especially for mobile networks)
- Requires close collaboration of PHY layer and network layer researchers
- Mm-wave-communication will become an integral part of wireless networking

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

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