Millimeter-wave networks: what's done and what's missing

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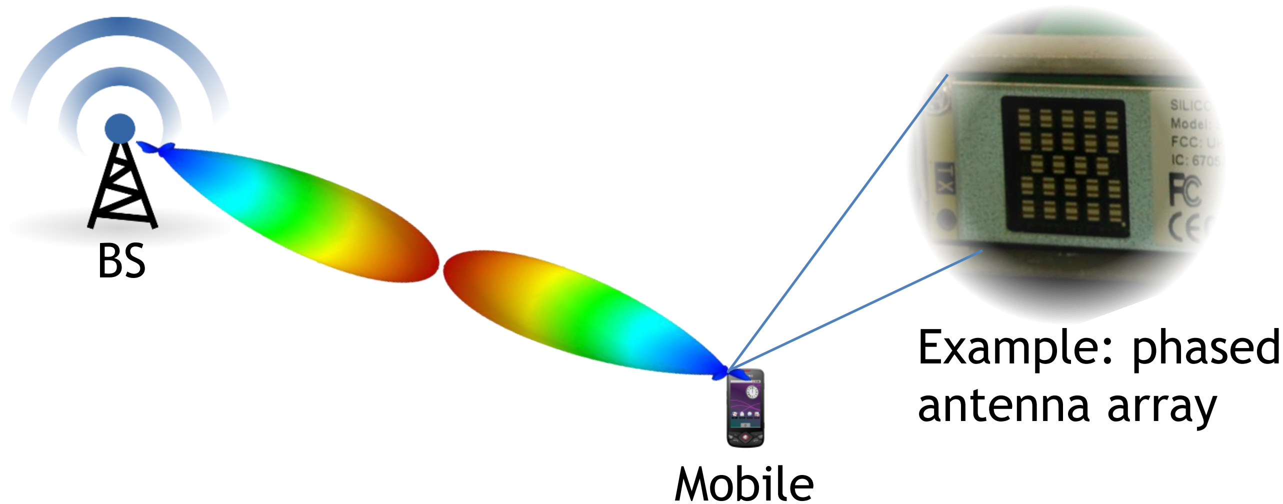
Developing the Science of Networks

Why Millimeter-Wave?

- Many GHz of spectrum available at mm-wave frequencies (multi-Gbit/s per user)
- Very high levels of spatial reuse through highly directional antennas

BUT:

- High path loss, most materials block the signal
- Communication via line-of-sight (or a strong reflector)
- Antennas need to be *aligned* (beam training)



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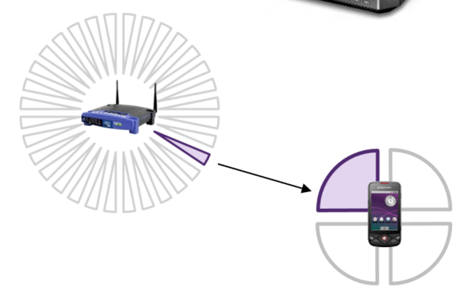
What’s Done?

- First generation hardware
  - Demonstrated feasibility (cost, hardware complexity, energy consumption, device integration, …)

- Single link beam-training works well (even for mobile scenarios)



- First deployment experience
  - Verizon 5G mm-wave
  - Facebook Terragraph

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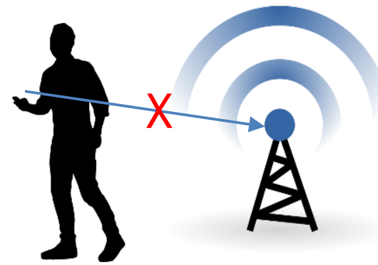
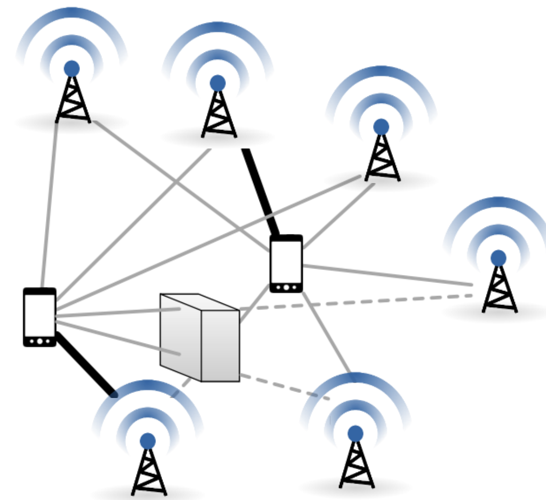
What's Missing

- Compelling uses cases

- Dealing with (self-) blockage



- Algorithms for large, ultra-dense large deployments



- Good hardware platforms for research and experimentation

- And more….

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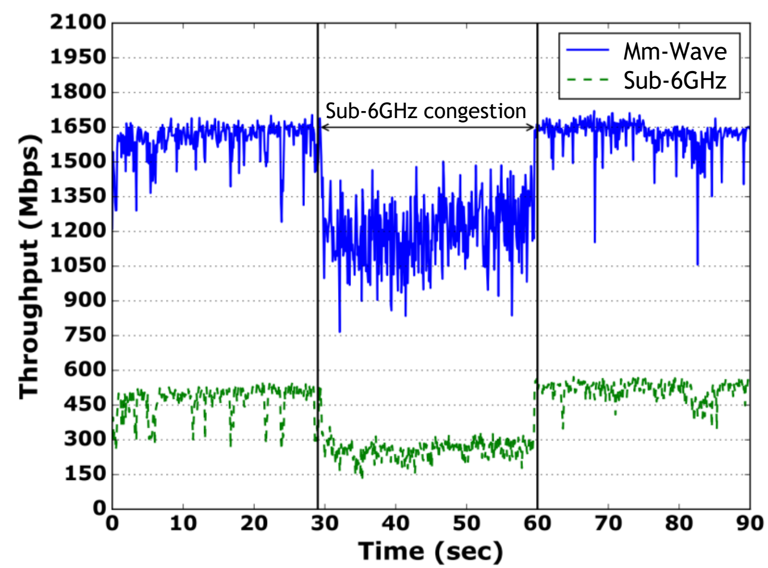
Network Resilience

- Combing mm-wave and sub-6GHz important for resilience (and speed)
  – 5G+ and WLAN devices will be multi-band
- MP-TCP promising since it is technology agnostic and avoids replicating reordering functionality at lower layers
  – But past work showed performance problems over mm-wave
  – Amount of reordering at the receiver *critically* affects performance

Example: reacting to sub-6GHz congestion



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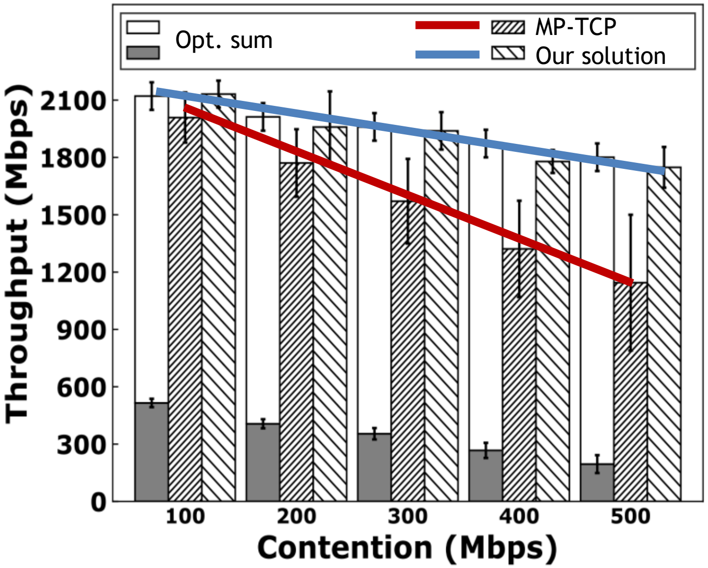
Multi-path TCP

- Designed MP-TCP scheduler that determines optimal assignment of packets to sub-flows
  - Probe for the correct packet assignment ratio for sub-flows
  - Take into account events such as blockage, network scans, …
  - Achieves close to opt. performance



- For low latency, this needs to be done within the mobile network rather than end-to-end
  - Ongoing work on multi-connectivity, but many issues remain (buffers at different layers, CloudRAN may help)
  - Estimation of per interface latencies to reduce reordering
  - Link quality prediction for proactive traffic steering

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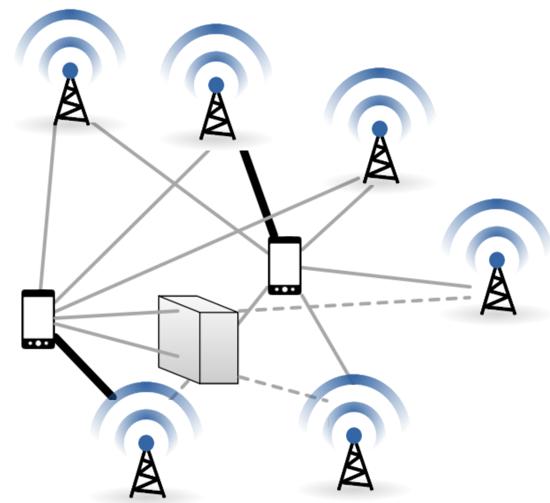
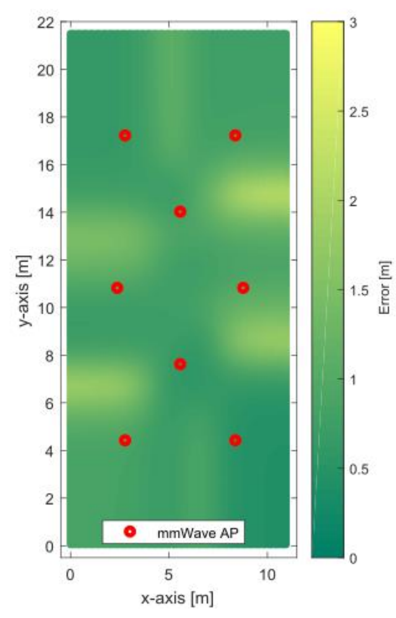
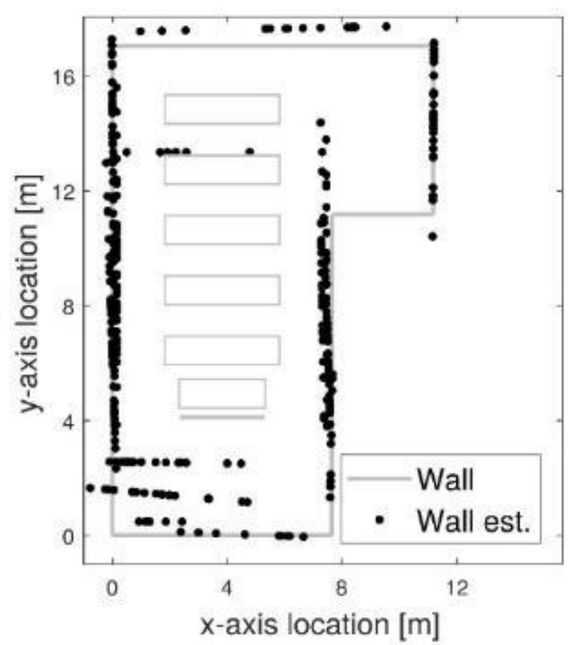
Large Scale Dense Deployments

- With many BSs and UEs, association and handover become combinatorial
  - Impossible to beam train all BS/UE combinations before making a decision



- Mm-wave location systems and environment mapping
  - Beam-steering driven by UE location
  - Handover and blockage prediction





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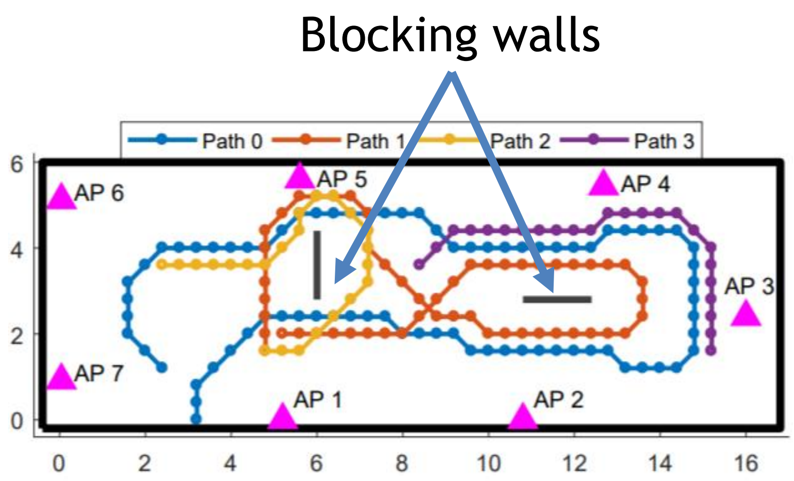
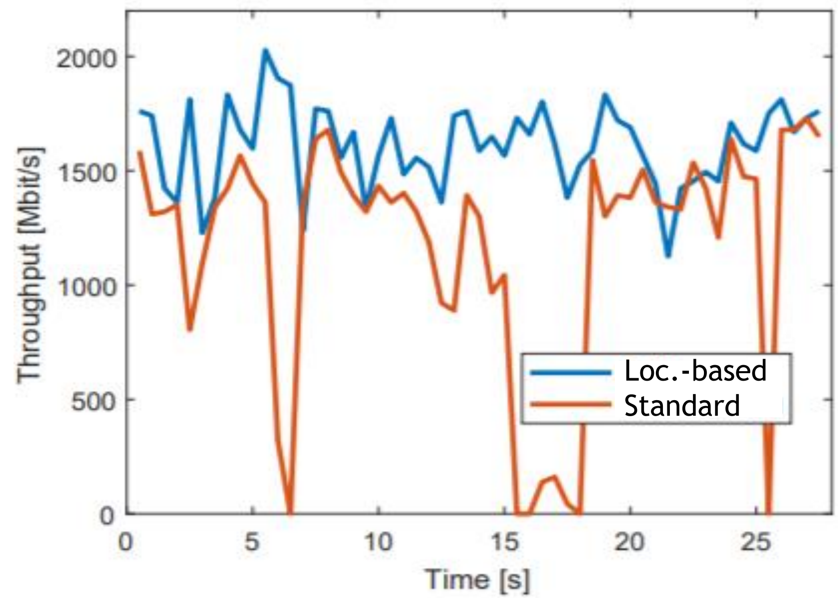
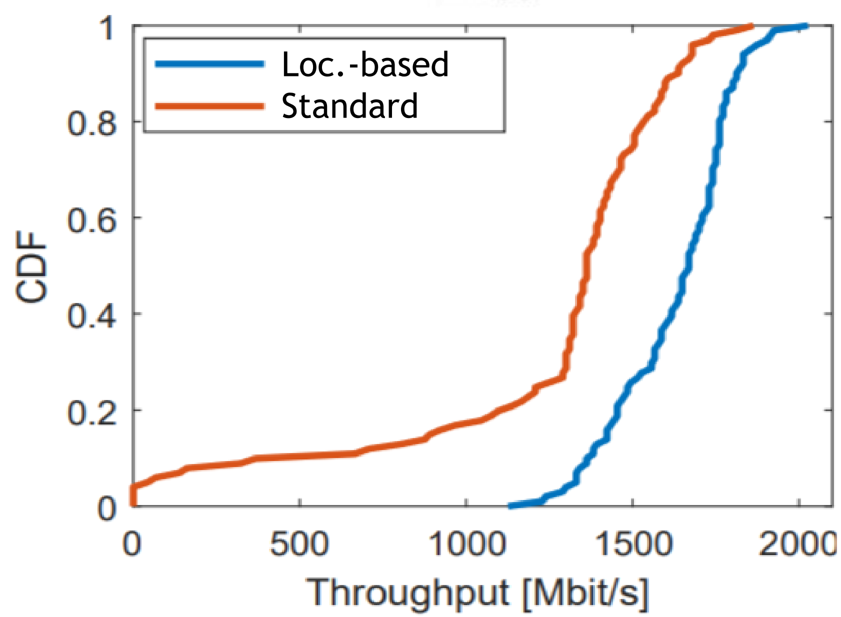
Location-Based Network Control

- In-band location system for beam steering and handover
  - Implementation on commercial hardware
- Evaluated in complex scenario with walls
  - No outages and higher throughput







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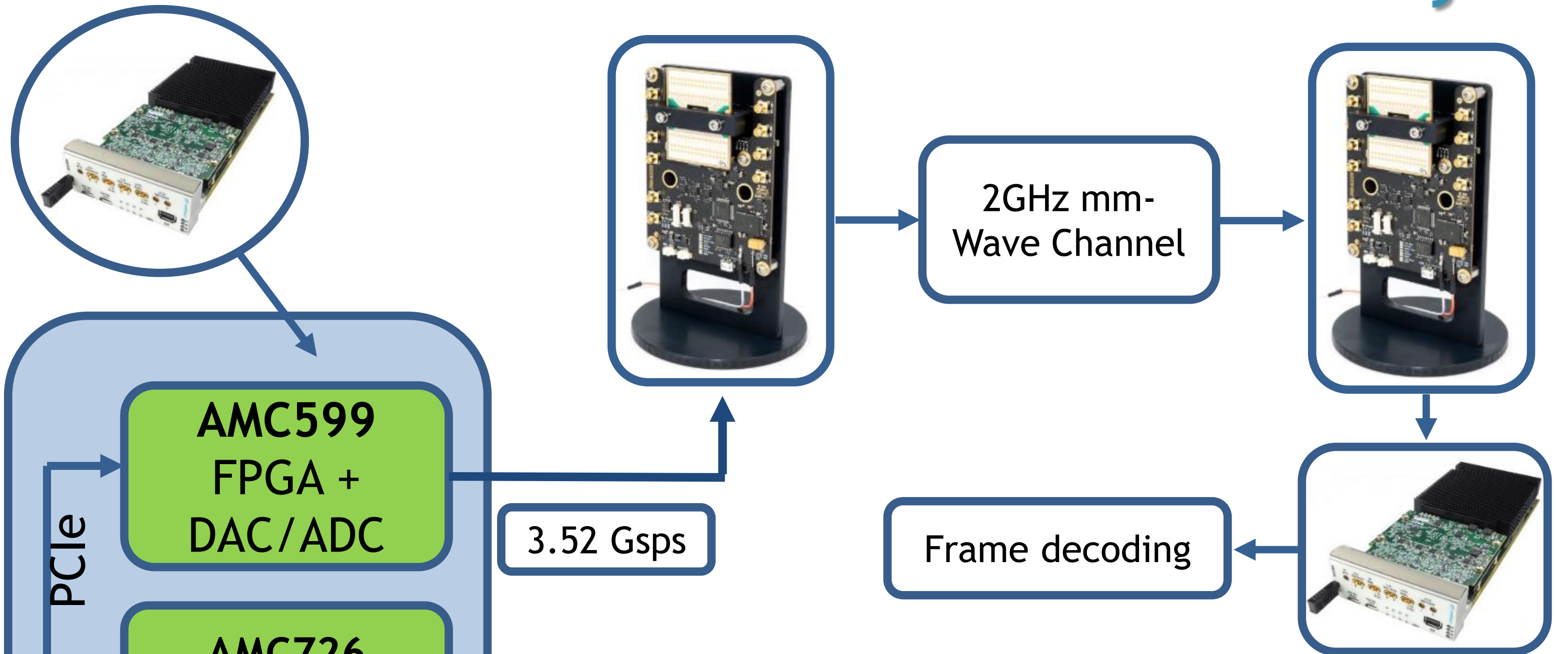
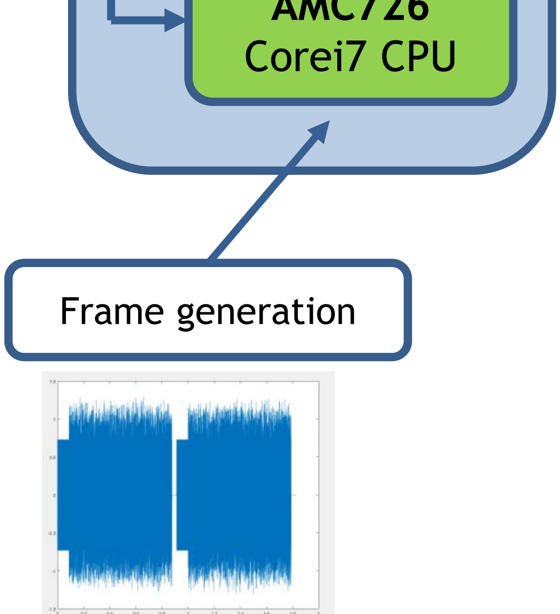
Full-bandwidth mm-Wave SDR System





FPGA platform for mm-wave research

- Large FPGA supporting >2 GHz baseband *and* channel coding
- Tx/Rx of fully 802.11ad compliant frames
- Extension to 5G+ planned
- Sivers up/down converters with phased arrays
- Packet detection, preamble processing on FPGA
- Frame decoding offline (will be moved to FPGA)

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Millimeter-wave SDR-based Open Experimentation Platform (MISO)

- Framework for on site and remote experimentation
- Mixed hardware/software design using GNU Radio + RFNoC
- Flexibly mix function blocks on the FPGA and in software → vastly speeds up prototype development
- Scales to wideband SDRs (costly, very high bandwidth and rate) and standard SDRs such as USRPs (low cost, but limited bandwidth)
- Open-source source project for use in industry and academic research as well as teaching, allows for extensions and upgrades

Narrowband processing system (Remote Lab - ORCA)

Wideband processing system (on site - IMDEA Networks)

Mm-wave Baseband Processing System

A/D and Upcon-verters

mm-Wave Channel

THANK YOU !