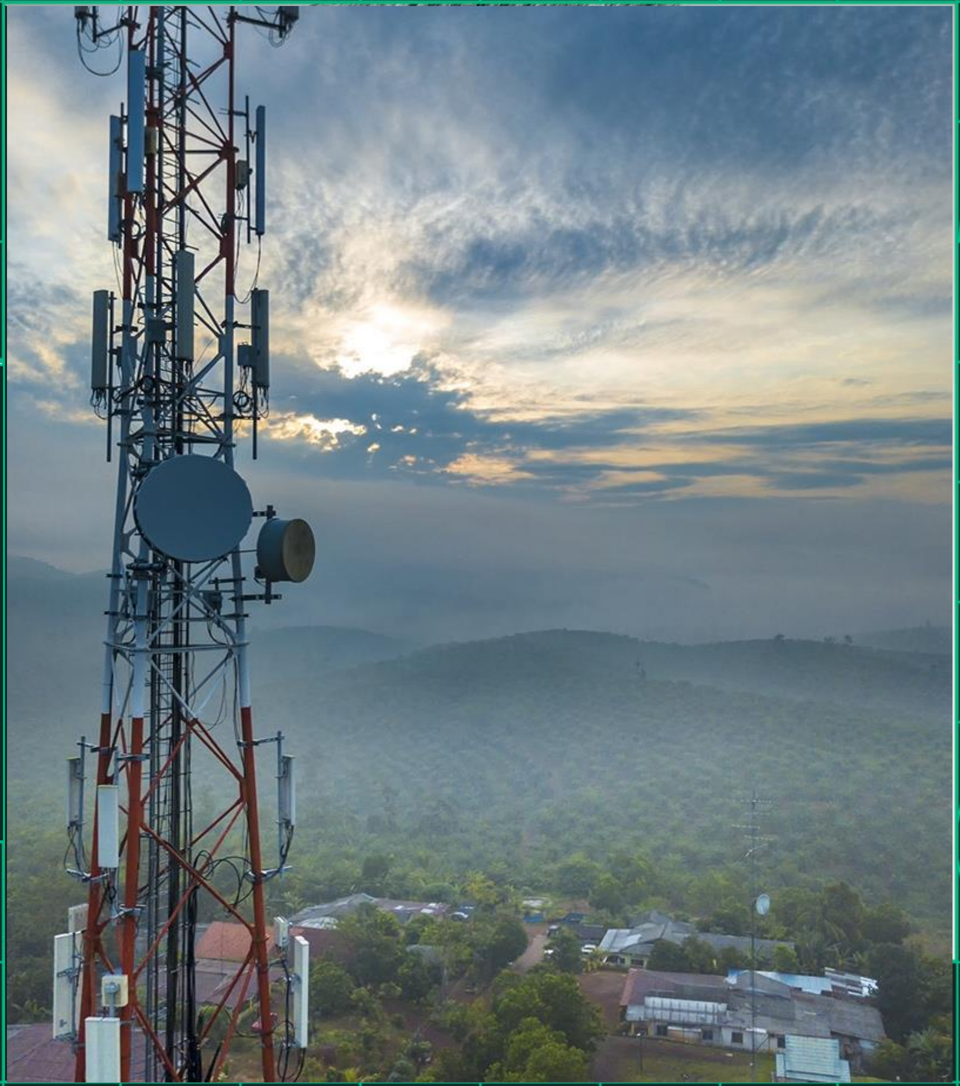
Beyond 5G

How the Shift from 5G to 6G May Impact Testing

Kaushik Chowdhury
NORTHEASTERN UNIVERSITY

Matt Spexarth
NI



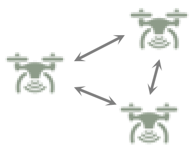
- What Is Beyond 5G? What Can 6G enable?
- 5G+/6G Innovation Areas
- mmWave and sub-THz Frequencies
    - OTA and Near-Field Measurements
- Joint Comms and Sensing
- AI/ML in Future Wireless Standards
    - mMIMO
    - Non-Linear Correction
    - Reconfigurable Intelligent Surfaces
    - RF Fingerprinting
    - ML Training and Testbeds
- Wrap up and Questions

What Could 6G Enable?

The Future of Wireless Communication in Connecting Everyone and Everything

With **5G** continuing to roll out **new capabilities** over the next decade, followed closely by **6G**, we will see a move to much higher frequencies (into the low THz bands), to phased-array antenna solutions, to increasing bandwidths and modulation densities, and to the proliferation of new use cases in massive machine-to-machine communication and in new levels of reliability, security, and network response time.

Applications



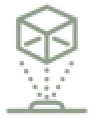
Wireless Cognition

Wireless Sensing

Immersive XR

Device Location

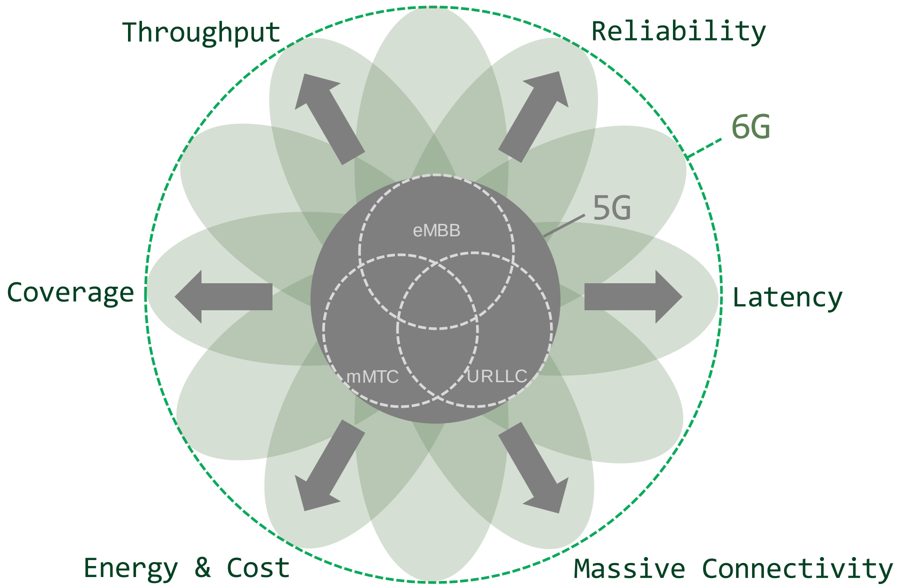
Imaging & Radar



Mobile Hologram

...and more

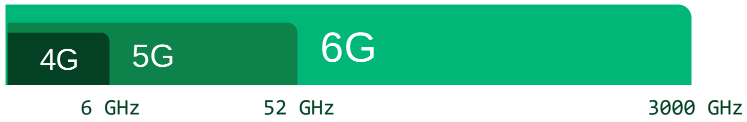
Requirements



6G Sets a new bar for requirements in all dimensions—though not concurrently—as individual applications drive extreme and often narrow use cases

Enabling Technologies

Terahertz Frequencies



Novel Antenna Techniques
(Meta materials, beam tracking, and evolved Massive MIMO)

Evolved Network Topology

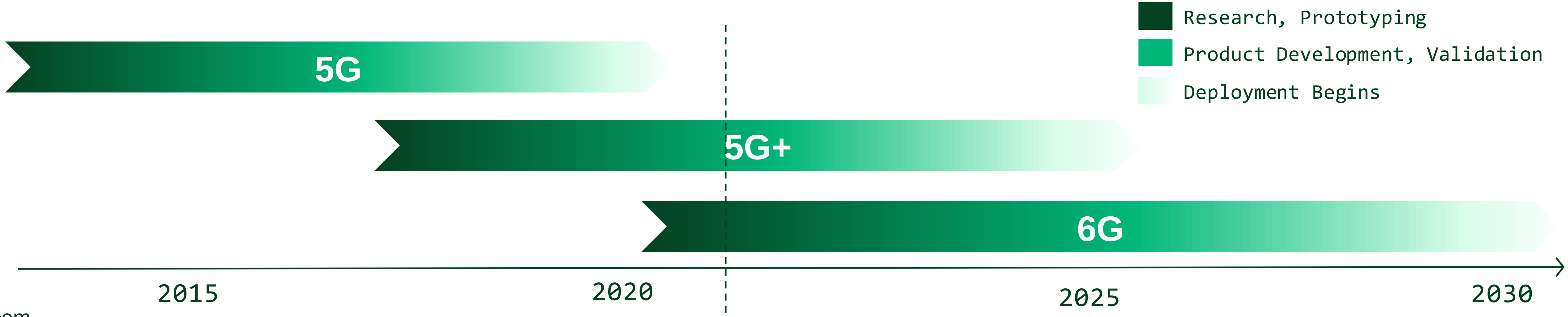
Spectrum Sharing
(including better Wi-Fi coordination)

AI & Machine Learning

Denser and Power-Efficient Modulation
(probabilistic QAM, backscatter, and analog)

Evolution of 5G Toward 6G

Innovation in wireless technology for new and extended use cases

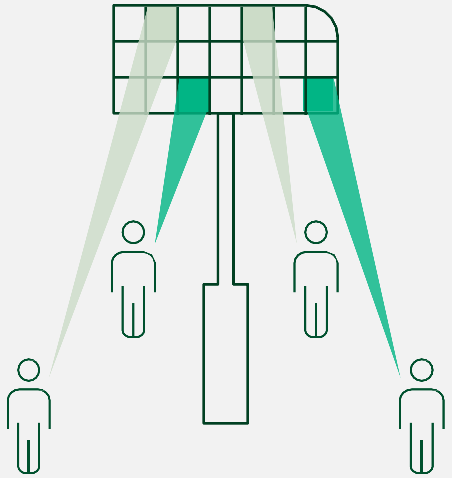


NI wireless research partner program has enabled critical research since 2010

Enabling Technologies that Could Drive 6G

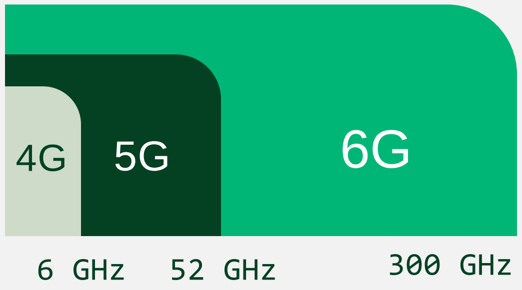
Evolution of MIMO

Build on multi-antenna techniques from 5G with more elements and distributed architecture.



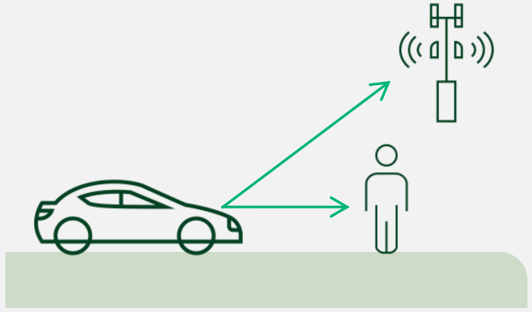
Sub-Terahertz

Utilize extremely wide bandwidths at frequencies once thought impractical for commercial wireless.



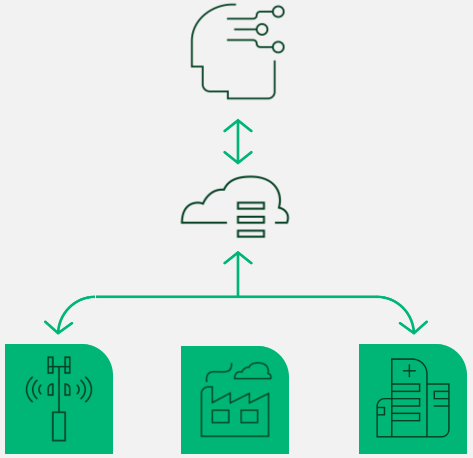
Joint Communications and Sensing

Improve spectral usage by combining sensing and radar functions with communications channels.



Machine Learning and Artificial Intelligence

Leverage new techniques across all 6G — from the signal chain to the network topology.



Extreme MIMO

Building on 5G's legacy

Moving beyond the increased antenna architecture and beamforming enabled by 5G.

NI's Desired Impact: Early testbeds to prove out new techniques key to advancing standards.

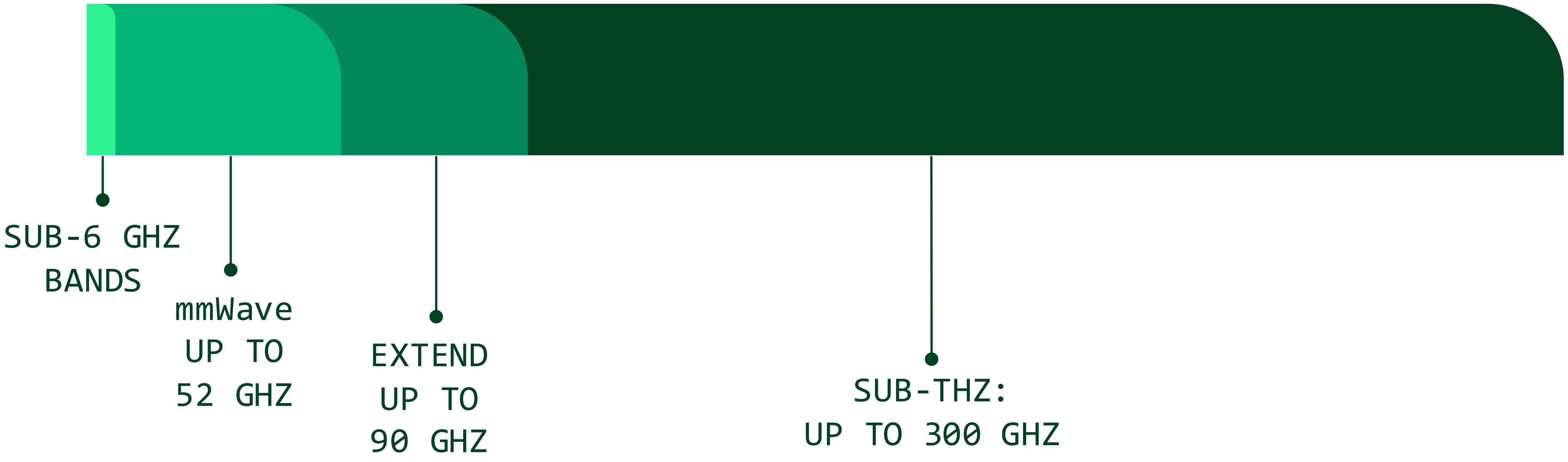
Sub-8-GHz Advancements

- Goal: 10x current spectral efficiency in a given area (Bits/second/Hertz/km^2, increasing cell capacity
- Distributed MIMO
- Advanced beamforming techniques

mmWave and Beyond

- Goal: Overcome propagation path loss challenges and improve cell density coverage
- More elements and gain per area
- Advanced channel sounding/modeling to understand propagation characteristics and effect on beam formation
- Application enabled: Enhanced location services

Exploring New Spectrum



Benefits

Faster data rates and higher capacity for wireless communication

Novel applications with sensing and imaging as well as high precision localization

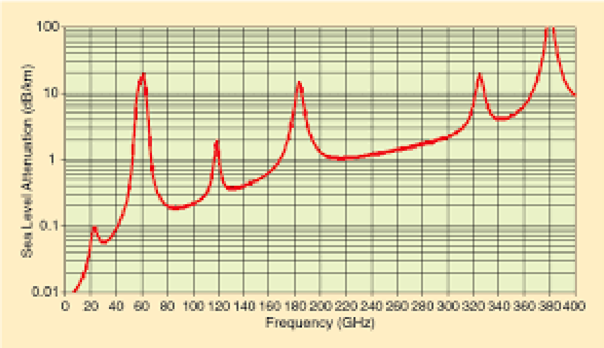
Challenges

Overcoming path loss

Integration of devices

Cost

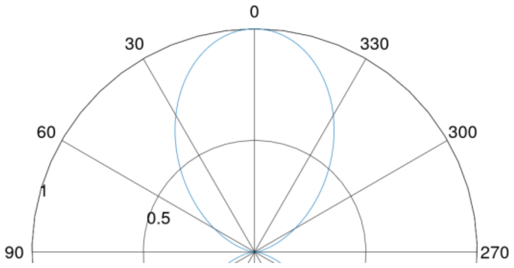
From mmWave to (sub)-THz Frequency



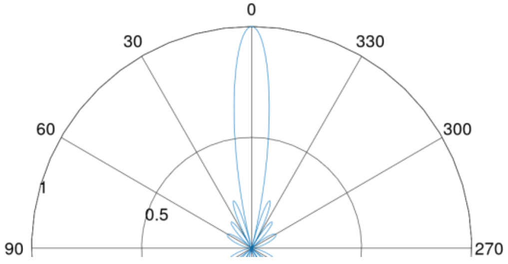
“Faster Than Fiber: The Future of Multi-Gb/s Wireless”, IEEE Microwave Magazine, May 2009

Path loss increases with higher carrier frequencies

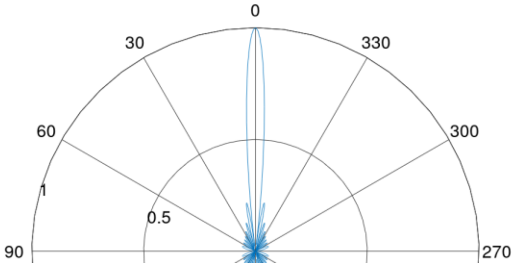
Antenna gain increases when using **large number of antennas** related to wavelength



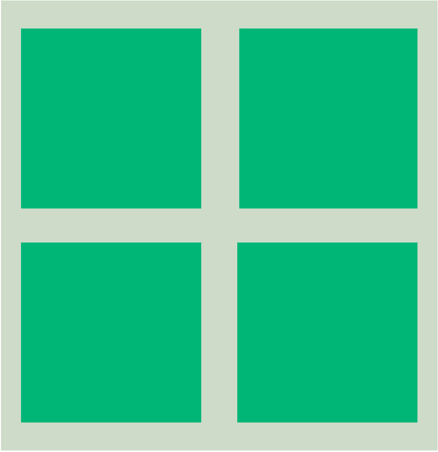
3 GHZ (2X2)



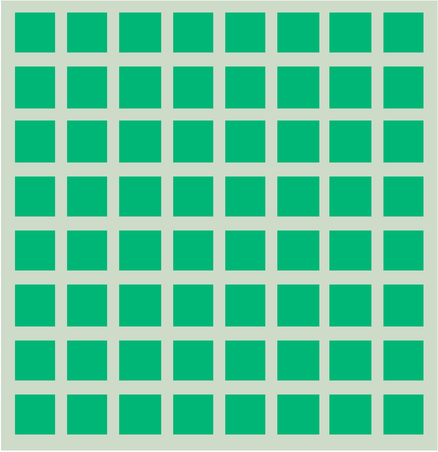
30 GHZ (8X8)



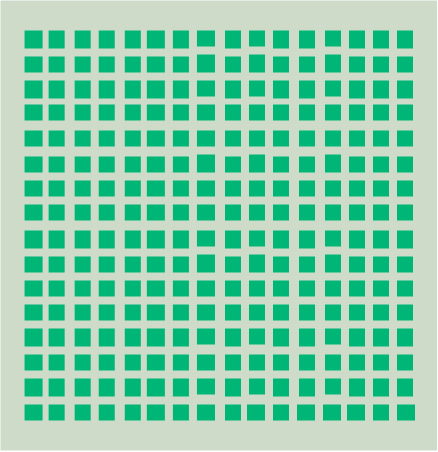
300 GHZ (16X16)



WAVELENGTH / 2: 50 MM



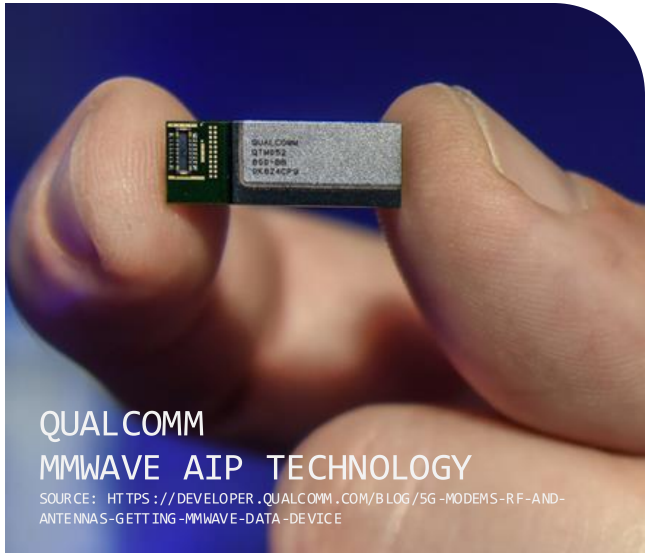
5 MM



0.5 MM

A New Generation of Antennas

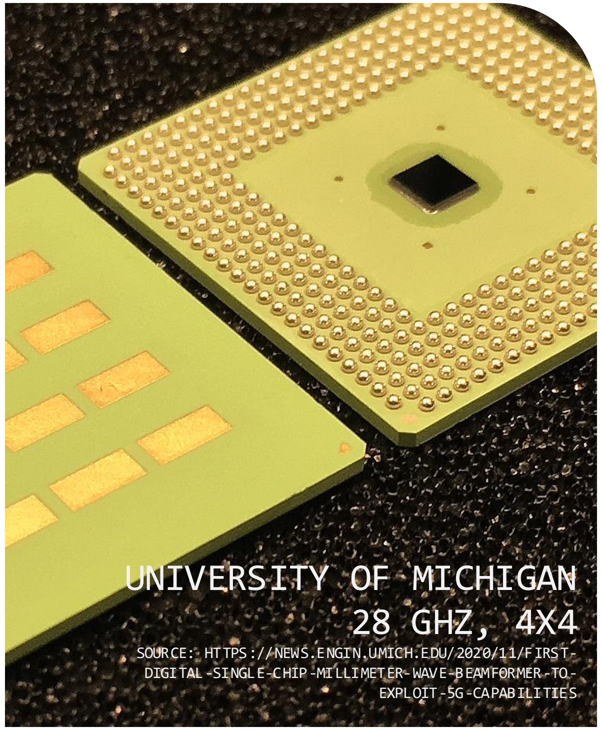
- mmWave active antenna arrays are being deployed already for 5G
- Trend towards highly integrated antenna in package (AiP) designs
- Combined use of analog and digital beamforming



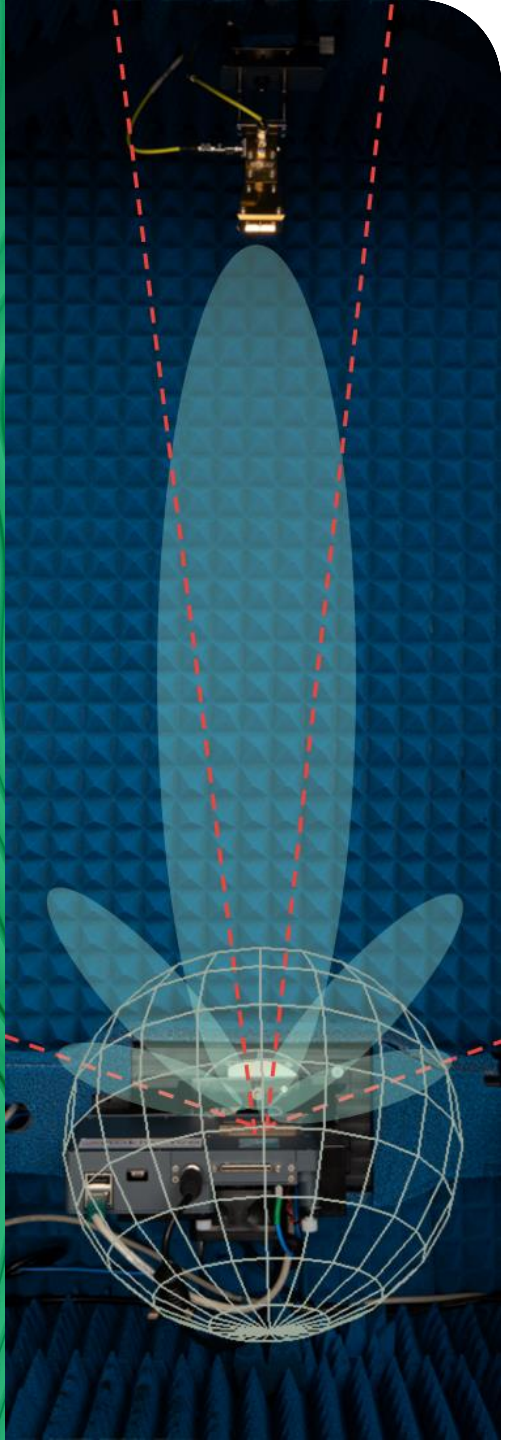
QUALCOMM
MMWAVE AIP TECHNOLOGY
SOURCE: HTTPS://DEVELOPER.QUALCOMM.COM/BLOG/5G-MODEMS-RF-AND-ANTENNAS-GETTING-MMWAVE-DATA-DEVICE

USED
5G mmWave
MODULES IN IPHONE 12
SOURCE: HTTPS://DE.IFIXIT.COM/TEARDOWN/IPHONE+12+UND+12+PRO+TEARDOWN/137669

IBM/ERICSSON 28 GHZ 8X8
SOURCE: HTTPS://WWW.MICROWAVEJOURNAL.COM/ARTICLES/27830-IBM-AND-ERICSSON-ANNOUNCE-5G-MMWAVE-PHASE-ARRAY-ANTENNA-MODULE

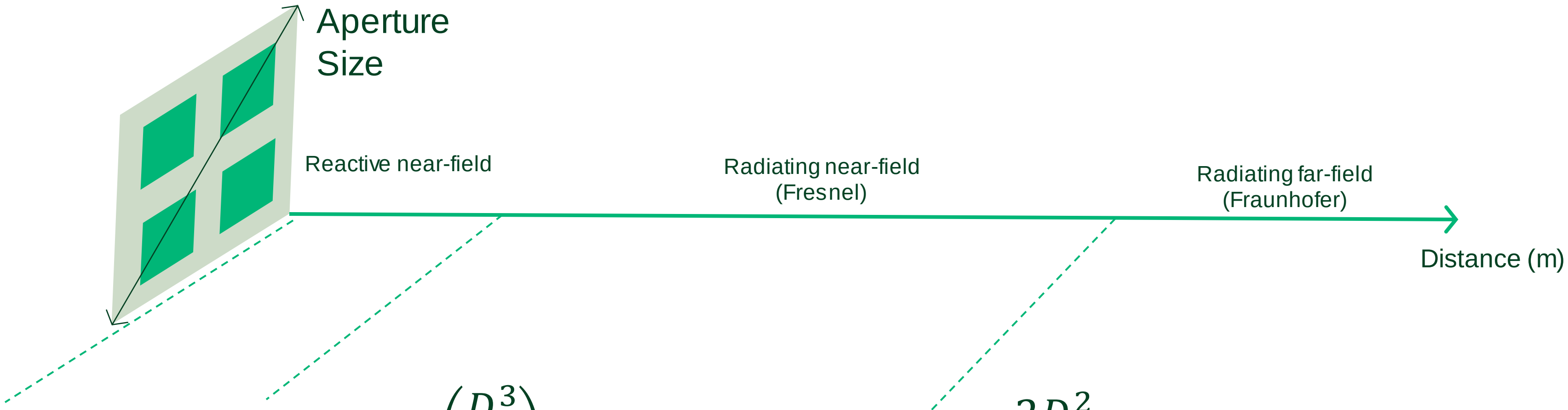


UNIVERSITY OF MICHIGAN
28 GHZ, 4X4
SOURCE: HTTPS://NEWS.ENGIN.UMICH.EDU/2020/11/FIRST-DIGITAL-SINGLE-CHIP-MILLIMETER-WAVE-BEAMFORMER-TO-EXPLOIT-5G-CAPABILITIES



The Challenge with Over-The-Air Measurement Distances

OTA Measurement Distance Increases with Frequency



$$r_{NF} = 0.62\left(\frac{D^3}{\lambda}\right)$$

$$r_{FF} = \frac{2D^2}{\lambda}$$

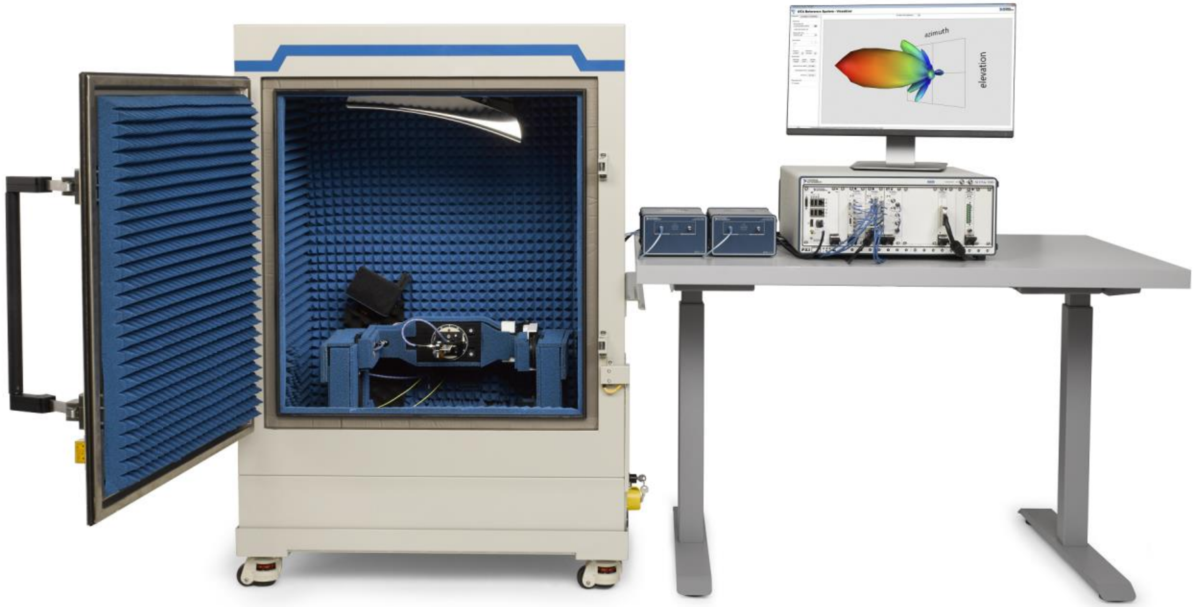
Frequency	Near-Field r_{NF}	Far-Field r_{FF}
3 GHz	2.2 cm	5 cm
30 GHz	6.9 cm	50 cm
300 GHz	22 cm	500 cm

Aperture size: D = 5 cm

OTA Measurement Approaches and Tradeoffs

Direct Far-Field	Indirect Far-Field	Near-Field Scanning
3D scan with movable probe or DUT at far-field distance	Use precise reflector antennas to create planar waves and emulate far-field	Scan surface in the radiating near-field and apply NF-FF transformation

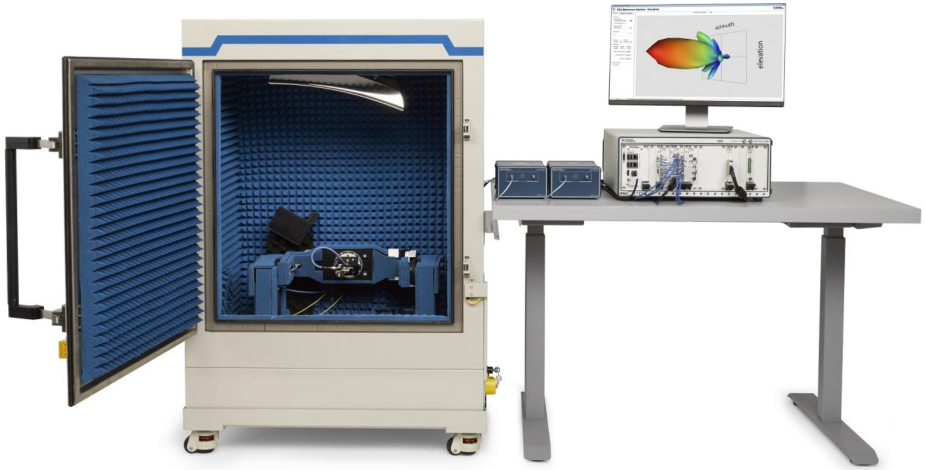
Direct or Indirect Far Field (CATR) configurations in the same chamber for testing larger DUTs



mmWave Vector Signal Transceiver for CW and 5G NR waveform generation and analysis

NI mmWave OTA Validation Reference Architecture

Opportunity for OTA Research and Innovation



SMALL CHAMBER BASED MMWAVE OTA
VALIDATION SYSTEM

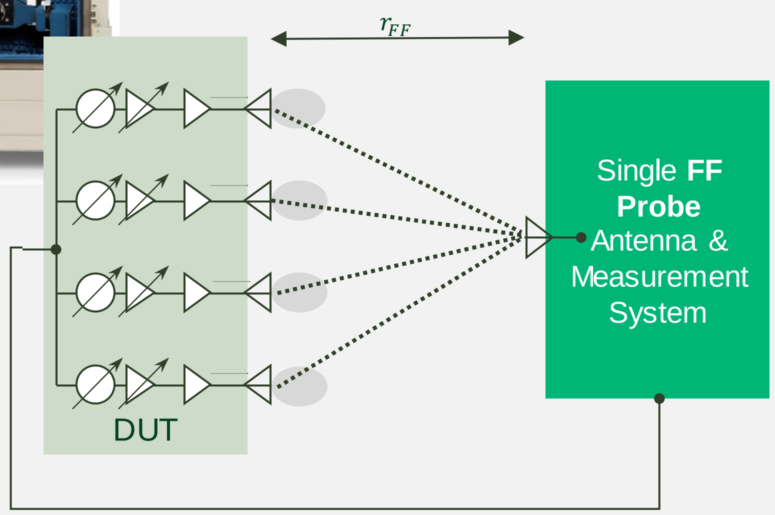
TRADITIONAL CONDUCTED
TEST SYSTEM

Goal: OTA measurement approaches similar like conducted
test in terms of measurement accuracy, size, speed, and costs

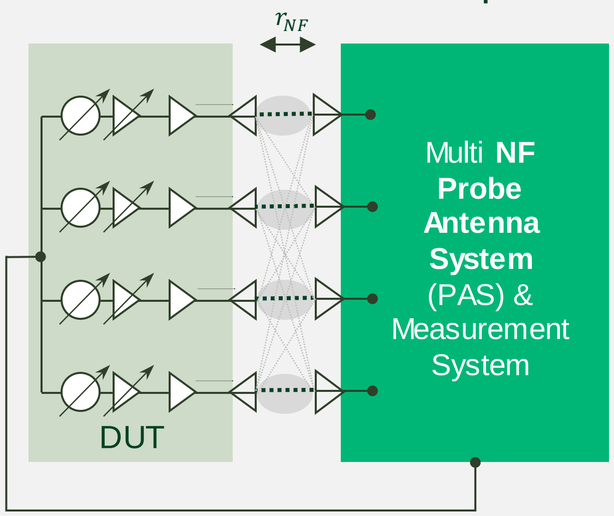
A New Approach: Near-Field Probe Antenna System (PAS)

Reduced footprint enables cost-effective OTA production test

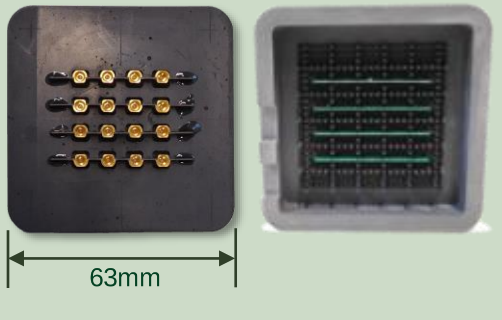
Classical Direct Far-Field Measurement Setup



New Near-Field Measurement Setup



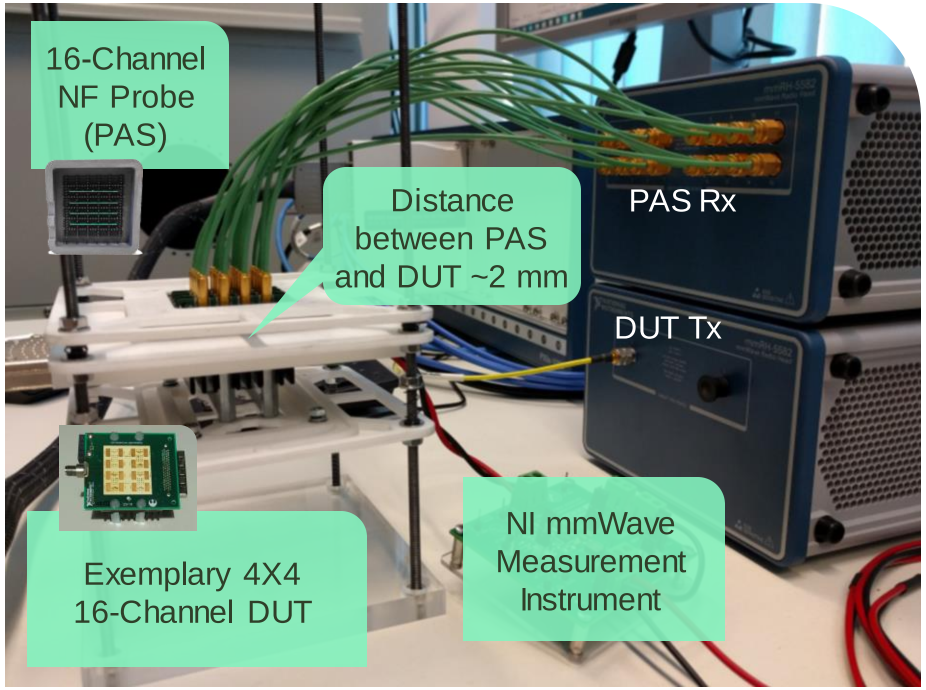
16-Channel PAS Prototype

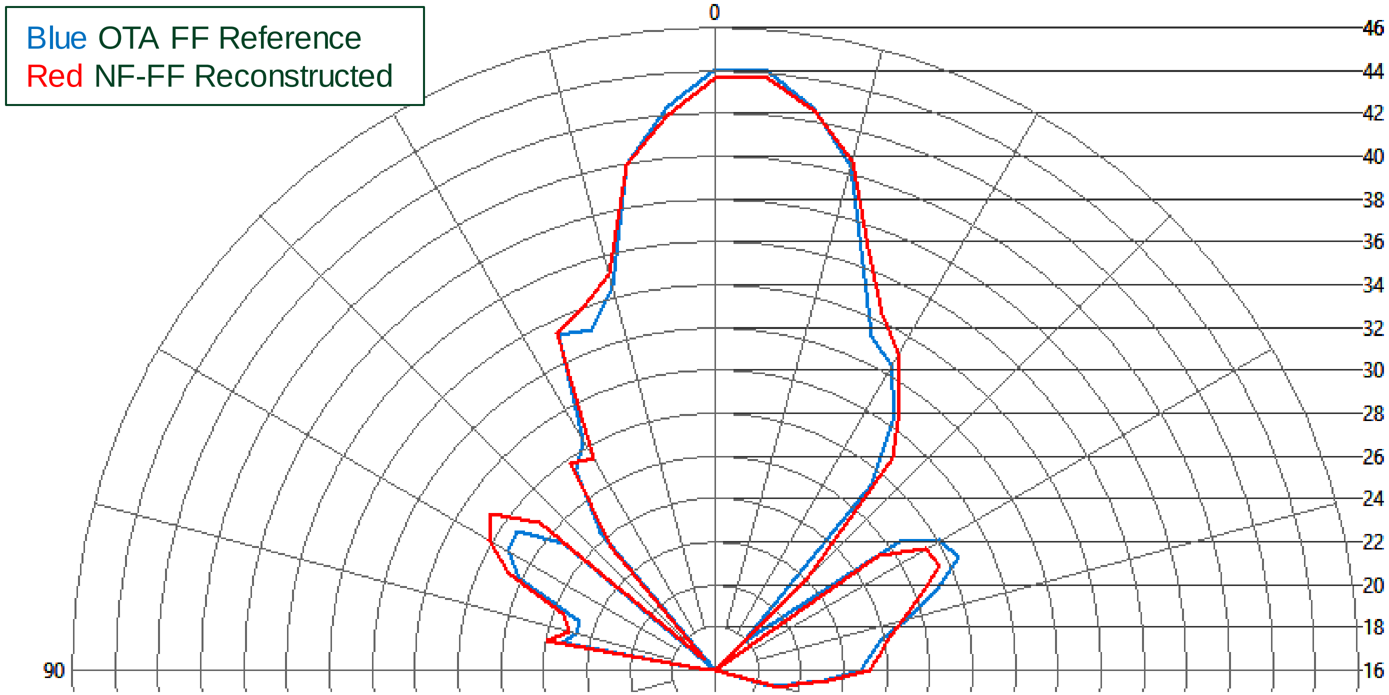


Paper submitted to EuMW 2021

Promising Performance versus Traditional Methods

Initial Validation Results of PAS Prototype





- Designed PAS Prototype for exemplary 28 GHz 4X4 Active Antenna Array
- PAS and DUT connected with NI mmWave VST Platform (usually used for conductive beamformer tests)
- Reconstructed gain patterns show very good overlap with reference results measured in OTA FF chamber

Paper submitted to EuMW 2021

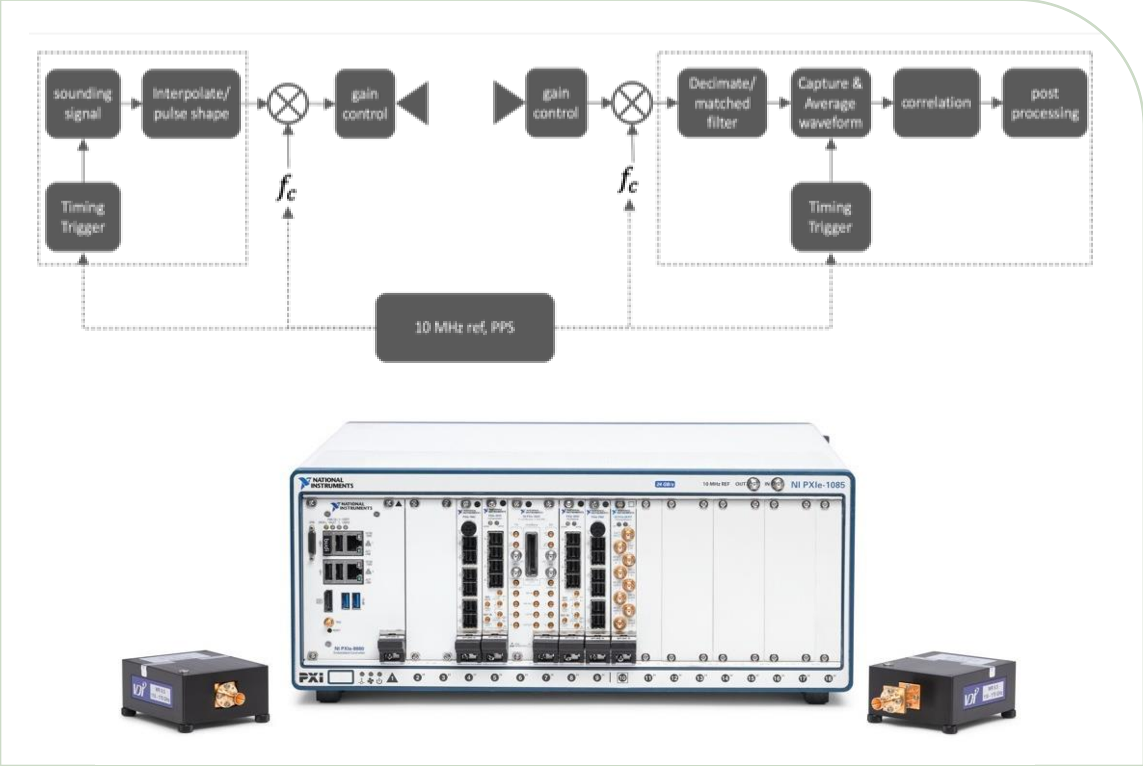
Sub-THz

Terahertz Communications

Overview

Utilize potential of extremely wide bandwidths at frequency ranges once thought impractical for commercial wireless.

NI's Focus: Develop new standards for testing and validate devices at THz frequencies.



New technologies, new testing

- New packaging technologies will be required — forcing new testing standards
- Shift towards module-level BIST
- New connector and antenna technology needed to be explored for test

Application focus

- Channel sounding — accurate channel information is required
- AR/VR
- Indoor wireless
- Succeeding where 5G mmWave has struggled

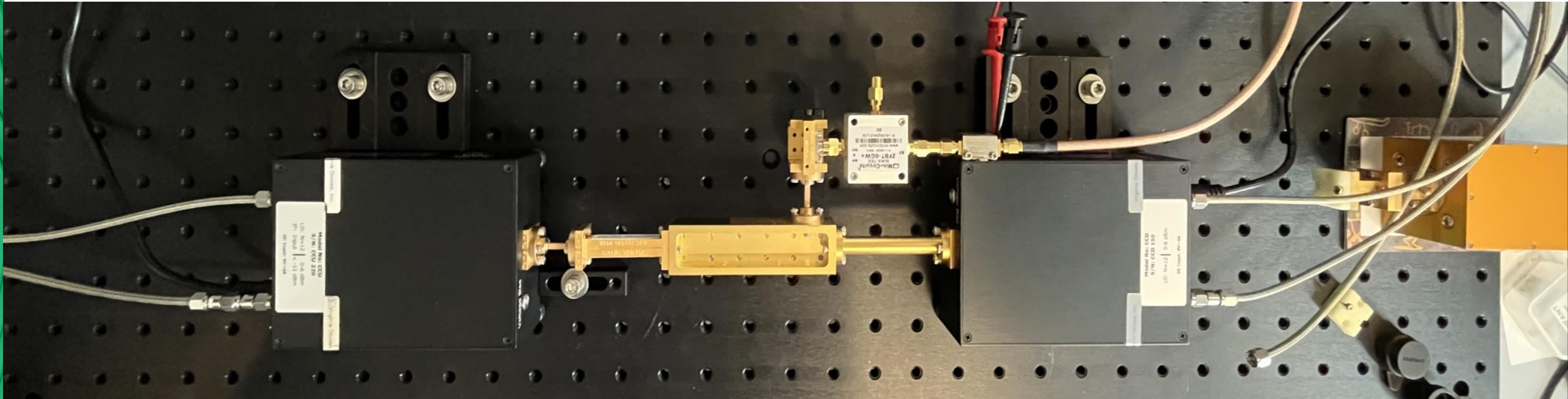
Metrology above 100 GHz

Overview: Understand the uncertainty and accuracy of RF signaling in the sub-THz frequency domain

NI's Focus: Enable measurements at mmWave and sub-THz with the same confidence and ease of sub-6GHz

New technologies, new testing

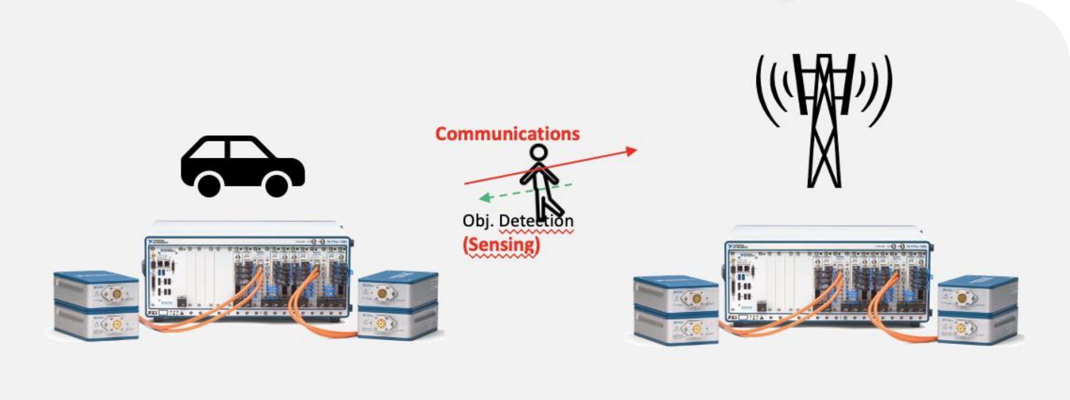
- Traceable standards and transfer mechanisms
- Conducted and OTA measurement interfaces
- New connector and antenna technology needed to be explored for test



Joint Comms & Sensing

Overview

Improve spectral usage and **enable new use cases** by combining sensing and radar functions with communications channels.



NI's Focus: Early testbeds to prove out new techniques key to advancing standards and regulatory constraints.

Use cases

- Fundamentally new cellular technology that will pull 6G to new business models and markets
- Autonomous transportation
- Advanced beam management
- Increased spectrum usage
- AR/VR: integrating sensor data to the device

Early demonstrations

- Waveform based explorations
- Partnership with Barkhausen Institute to demonstrate potential waveform design for an automotive sensing application

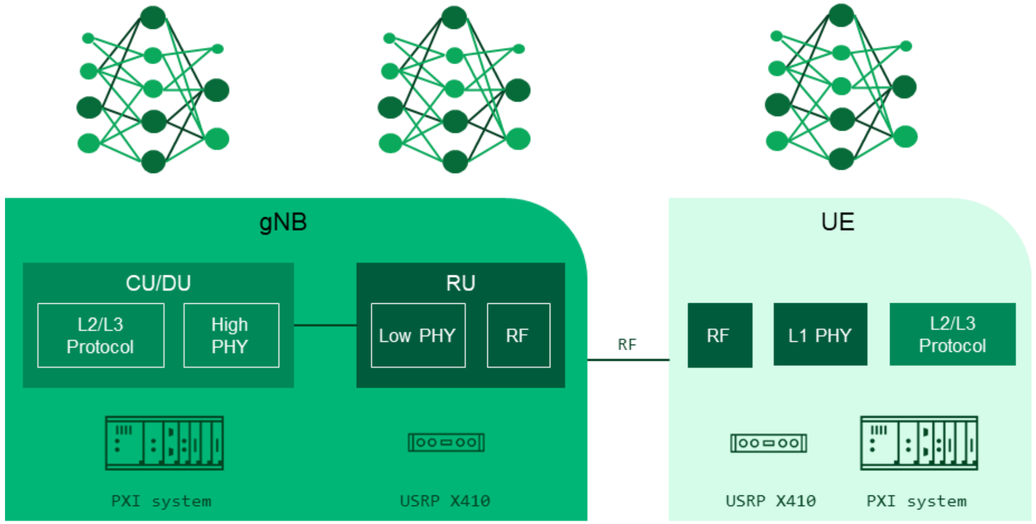
AI & ML in RF and Network Design

AI/ML in Wireless Comms

Overview

Optimization of an increasingly complex wireless communications systems to meet new KPIs through advanced signal processing techniques.

NI's Focus: Validation and test of AI/ML based systems to ensure safety and reliability.



Application Areas of AI/ML in Wireless

RF: Fingerprinting, Digital pre-distortion, RF impairment compensation

PHY: Synchronization, (MIMO) Channel estimation and equalization, symbol detection, channel en/decoding

MAC: Time/Frequency/Spatial resource scheduling and link adaptation, beam acquisition/selection and tracking

NI's Research Focus

- Workflow and methodologies for prototyping, validation and test of AI/ML based data driven RF wireless transceiver components
- Data set generation and management for AI/ML wireless communication research
- Partnership with Northeastern University

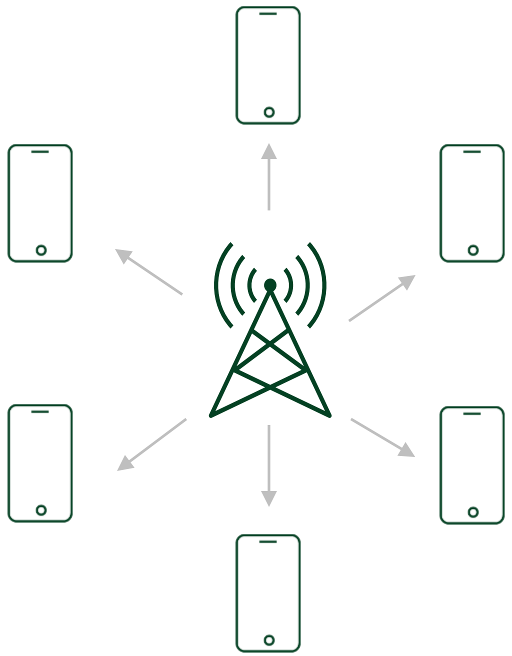
AI-ML for Massive MIMO

Channel Estimation Using Deep Learning

Channel Estimation in mMIMO

Overview

- Massive MIMO (mMIMO) is one of the main enablers to achieve higher Spectral Efficiency in 5G and Beyond-5G
  - Spatial diversity – signal gain obtained by exploiting constructive interference over multiple paths
  - Spatial multiplexing – improved spectral efficiency by injecting multiple data streams in independent paths



Beamforming relies on channel estimation

- CSI = Channel State Information
- CSI metric captures channel-introduced distortion

Estimating CSI is time-intensive

- For mmWave, CSI estimation needs to be Fast (reduced coherence time) and Accurate (higher path loss and lower SNR)

NEU's Research Focus

- Using deep learning to speed up CSI
- Support scaling as antennas increase to hundreds – thousands in number

Proposed ML Approach

Channel model agnostic

Data-driven, if sufficient channel realizations are observed

Demodulation step not required

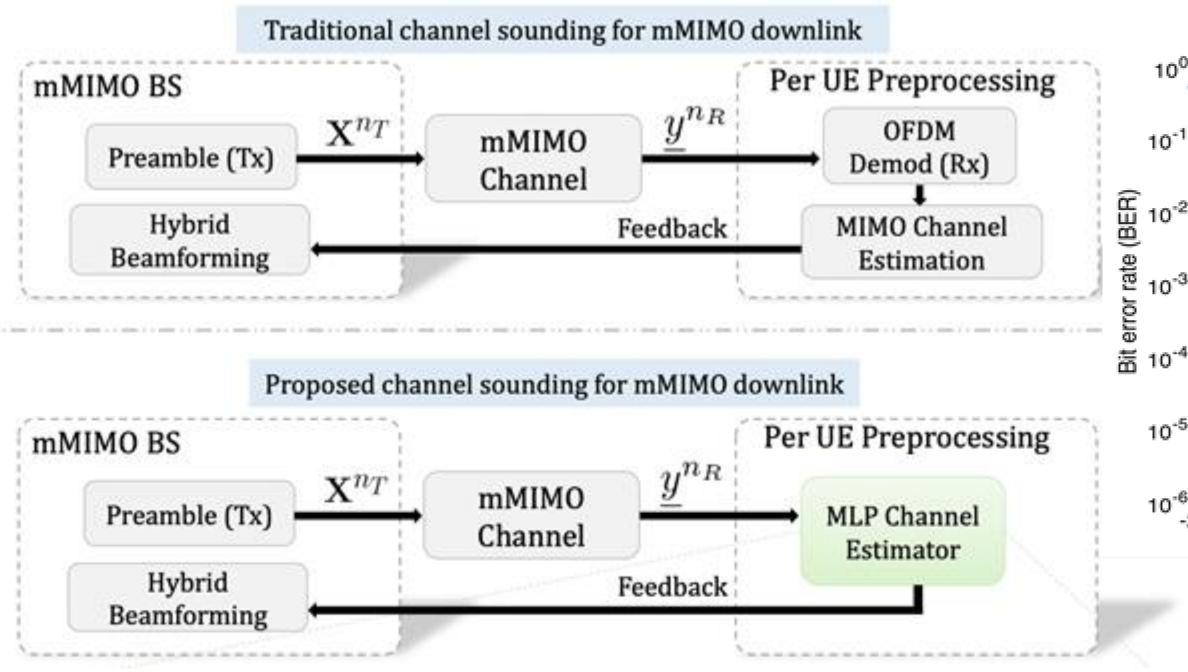
Generalizable to any standard modulation scheme

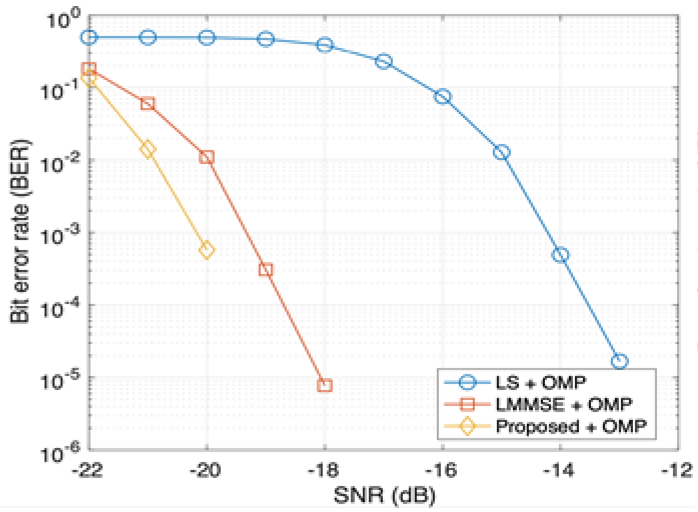
Fast Computation

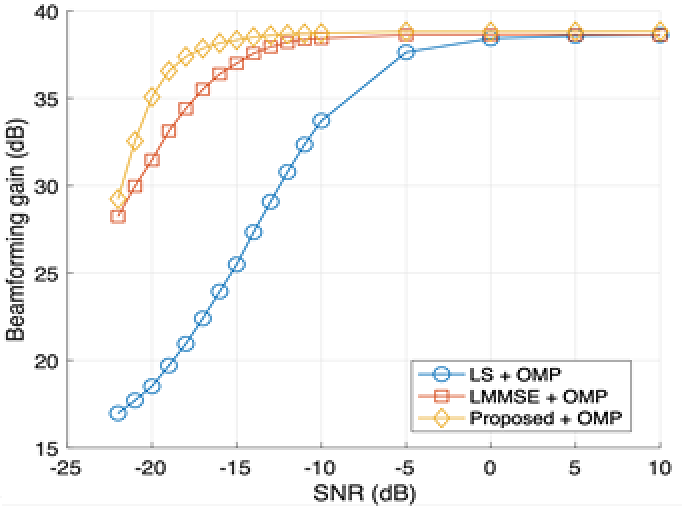
Nt x Nr channels in the frequency domain (for 256 sub-carriers) estimated concurrently using a single forward pass of proposed model

Denoising approach

Obtains accurate estimation in very low SNR conditions





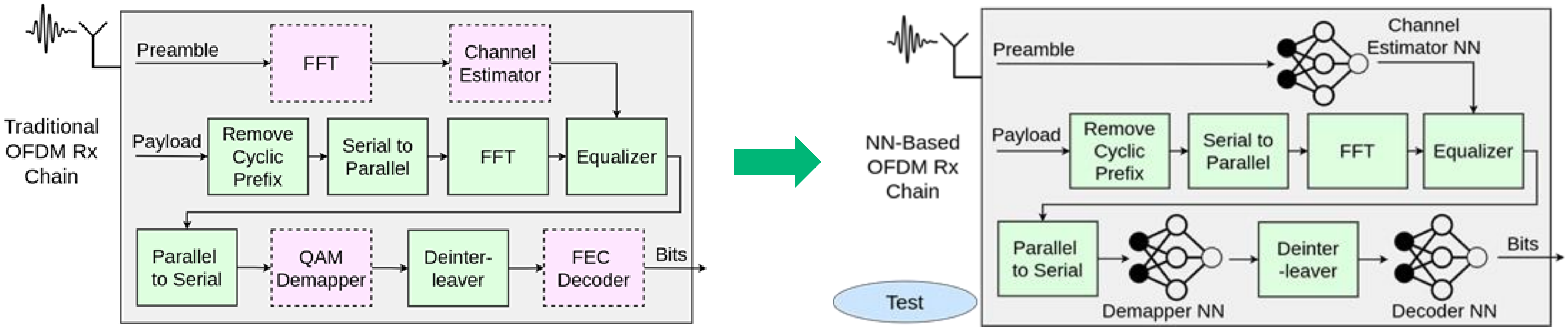


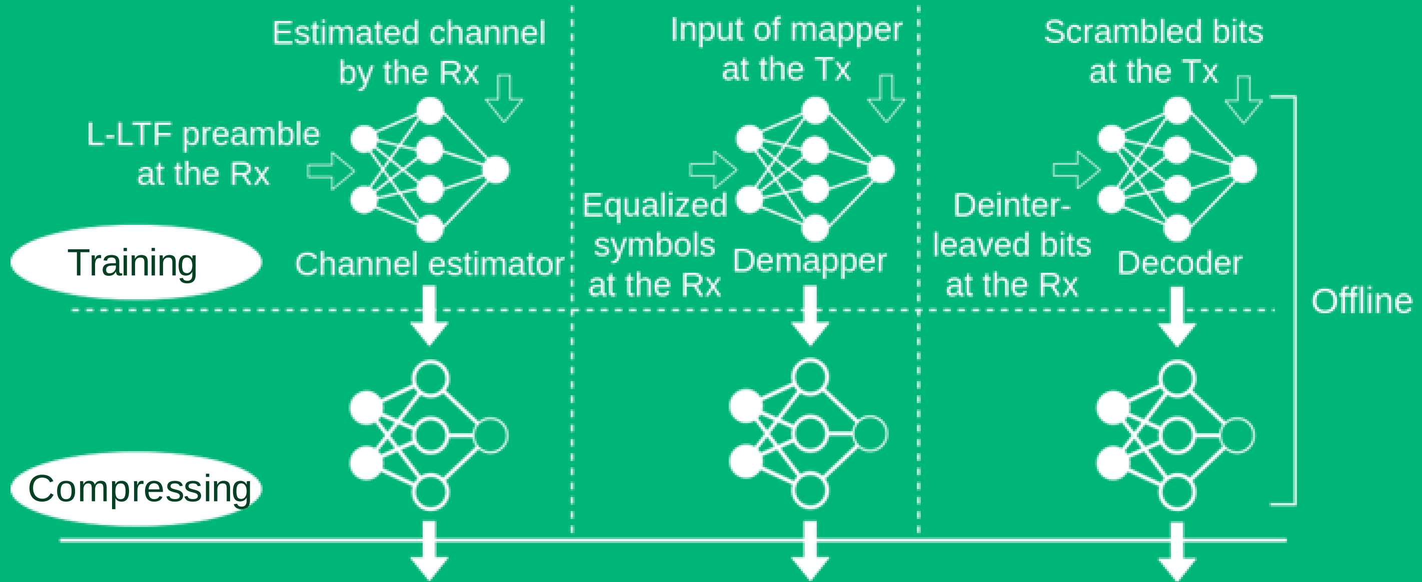
Neural Network based Receiver

Substituting Neural Networks for Receiver Processing Blocks

Channel Estimation in mMIMO

Training NNs to replace classical processing in the receiver chain

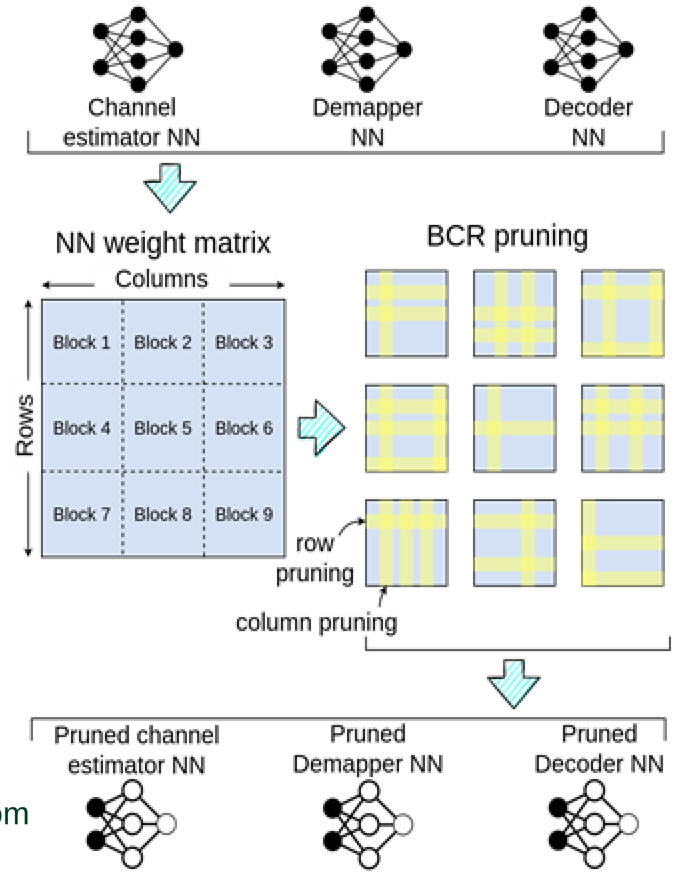




Neural Network Based OFDM Receiver

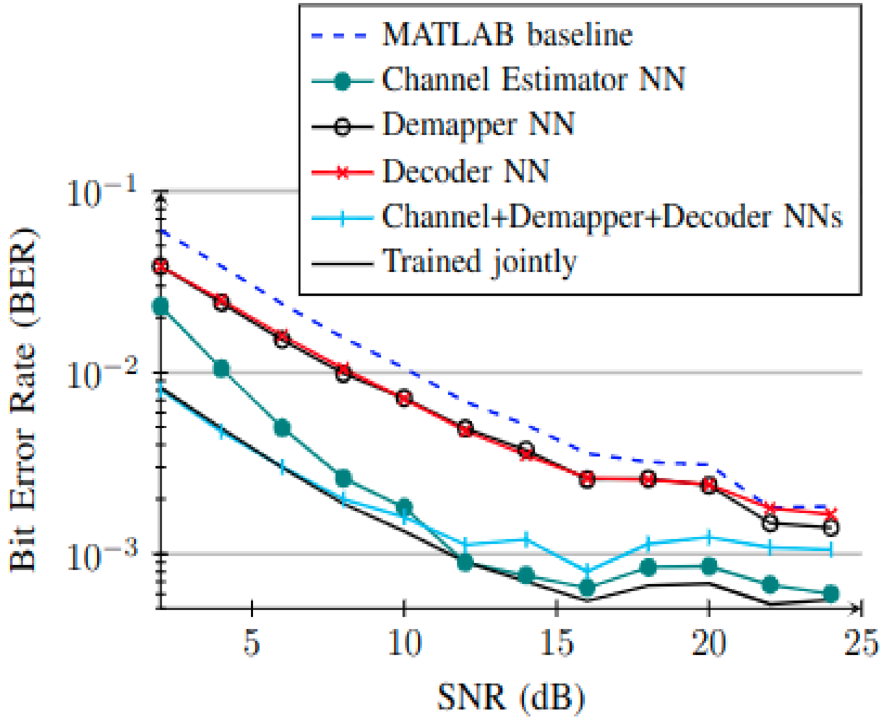
Compression in FPGA

block column row (BCR) Pruning Method



Avg. BER improvement over baseline:

- Channel estimator NN 86%
- Demapper NN 36%
- Decoder NN 36%
- Overall 77%



Latency improvement

After Compression (pruning and quantization) over non-compressed NNs:

- Channel estimator NN: 80%
- Demapper NN: 82%
- Decoder NN: 81%

Reconfigurable Intelligent Surfaces (RIS)

Shaping The Wireless Environment Via RIS

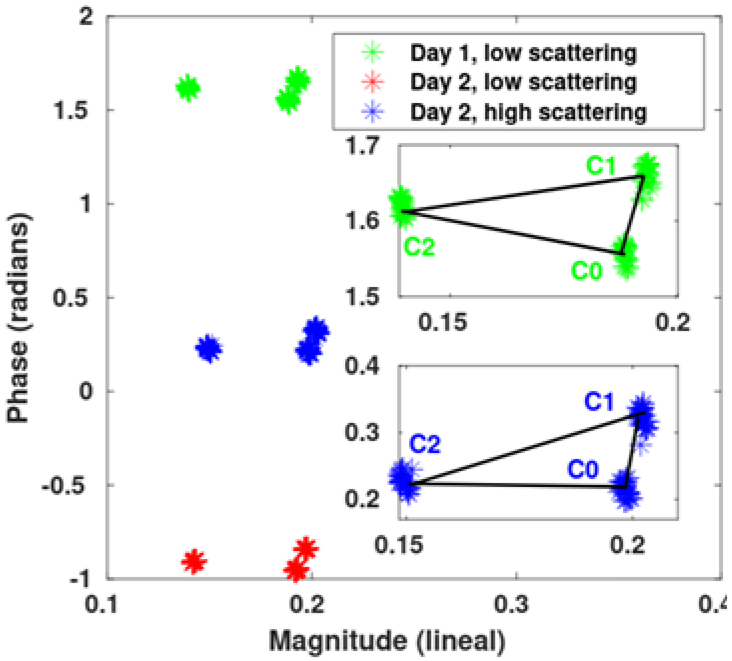
Why RIS?

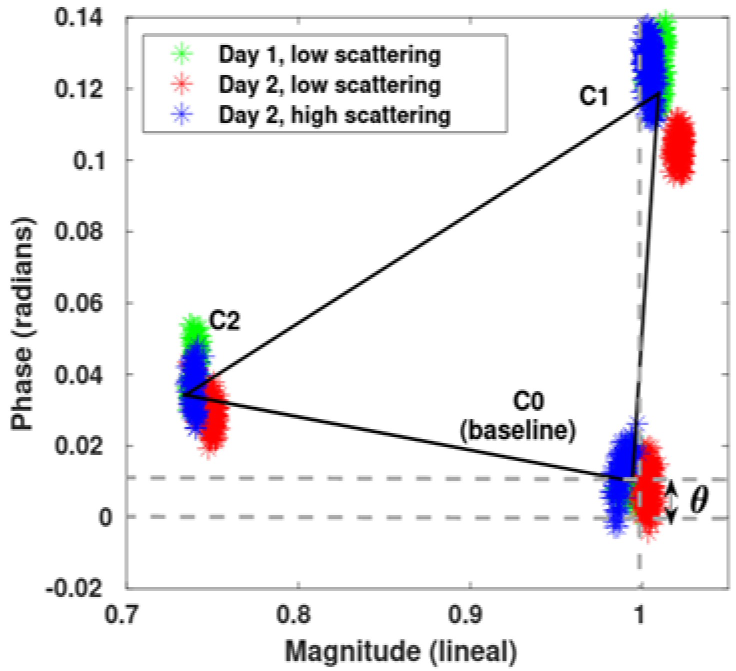
Helps improve beamforming:

Maximize SNR by focusing transmitted energy towards the receiver.

Scenarios of interest:

Low Signal-to-Noise-plus Interference Ratio (SNIR) conditions





Use Cases

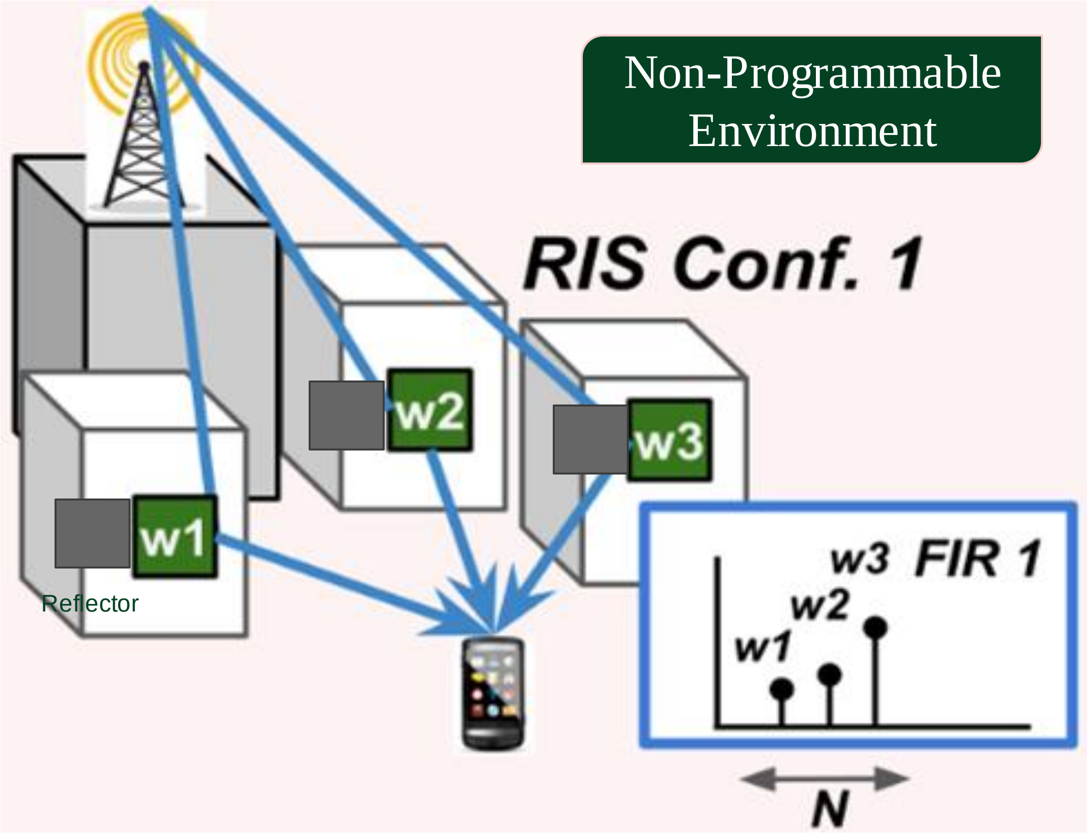
- Overcoming blockage at high frequencies used in 5G (mmWave / THz bands).
- Overcoming deep fading in vehicular networks
- Supporting interference limited systems, e.g. CDMA, unlicensed bands
- Long distance communications (satellite)
- Power constrained communications (in-flight WiFi, medical environments)

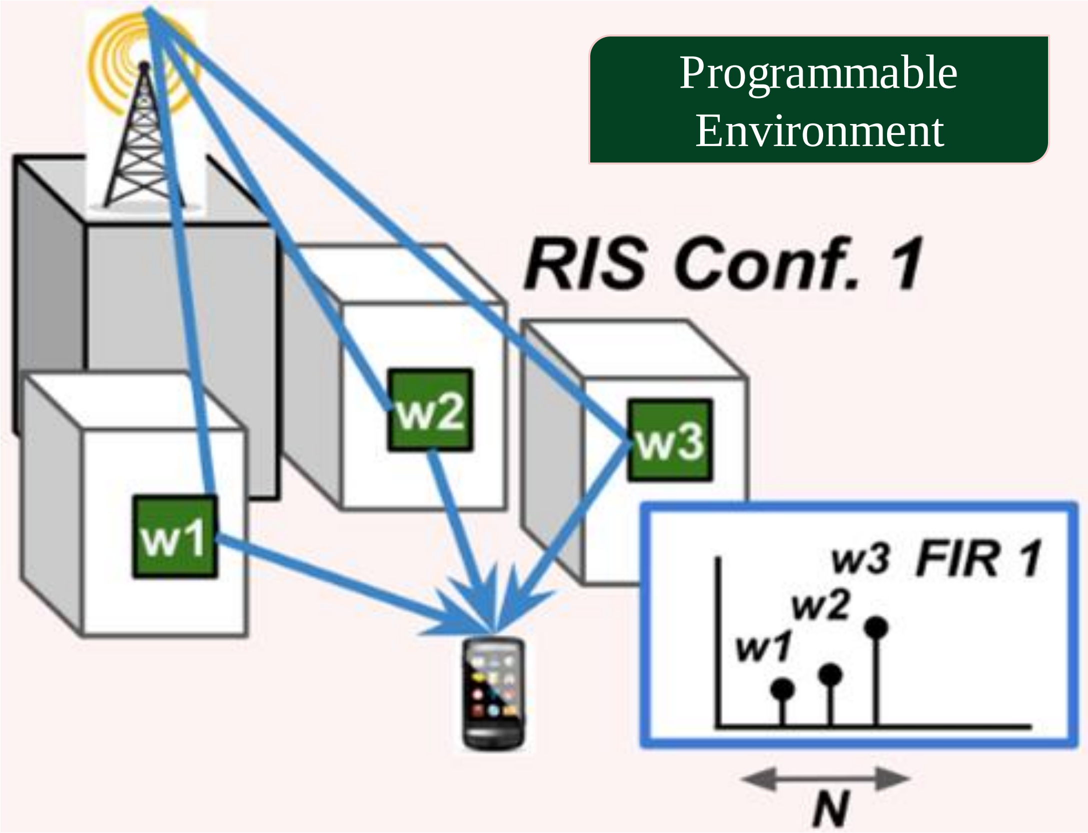
Impact on Channel Impulse Response (CIR)

- The transmitter-to-RIS and RIS-to-receiver channels
- Though signal processing, we equalize the effect of RIS and use RIS to engineer repeated values of the CIR.

Using RIS to "Engineer" The Wireless Environment

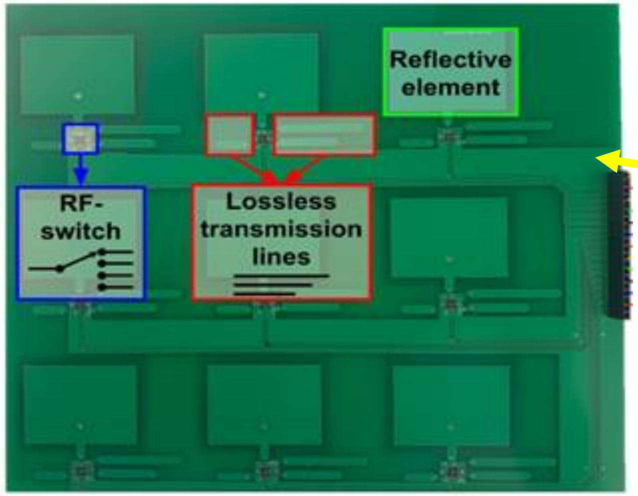
Creating custom-designed reflections and multipath



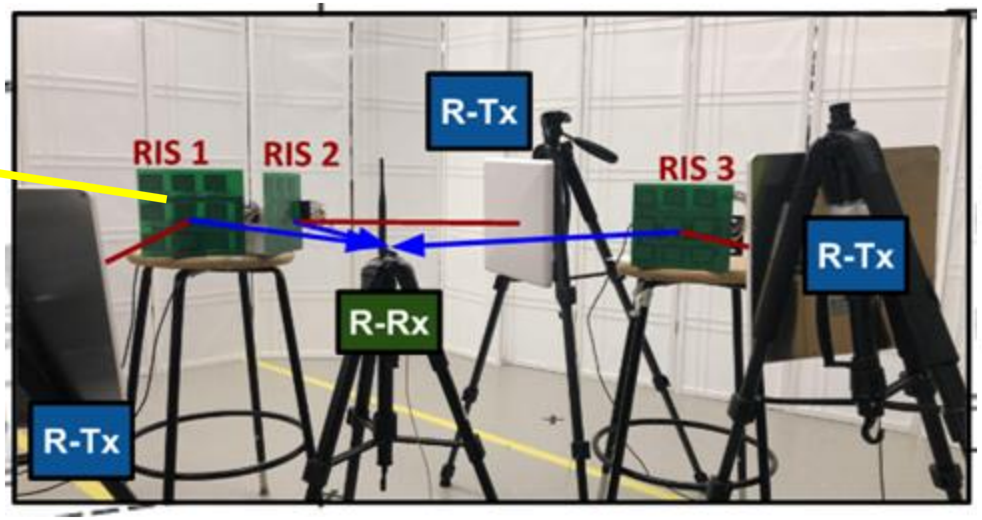


Using RIS to "Compute" in The Environment

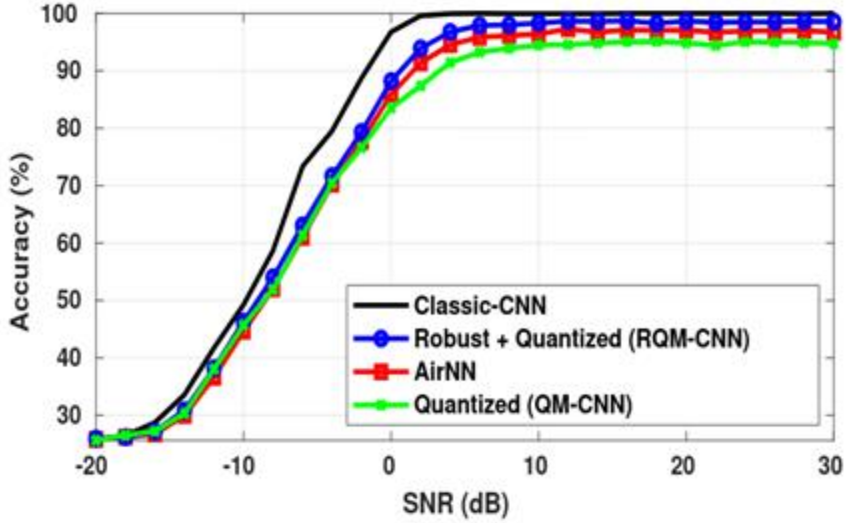
An *Experimental* Demonstration of Over-The-Air (OTA) Convolutions



Custom-designed RIS



SDR Testbed



Using RIS to Create Convolutions – Emulating a CNN Over-the-air

- Implemented OTA convolutions of a CNN for modulation recognition task
- The accuracy closely follows its all-digital CNN counterpart
- Overall drop of only 3.2% for the SNR range of [6, 30] dB.

RF Fingerprinting

Detect Unchanging, Hardware-Centric Imperfections Give Rise to Transmitter Signatures Using Received Signal

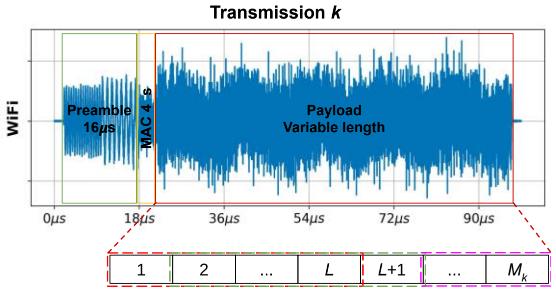
Why RF Fingerprinting?

Number of connected sensing devices worldwide will increase to >200 billion by 2025

Home IOT

Super Bowl

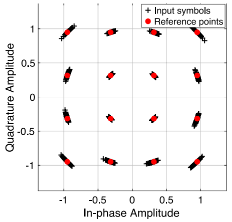
Subway Station



I/Q samples

Device A

Rx



Discriminative signal distortions

Device A

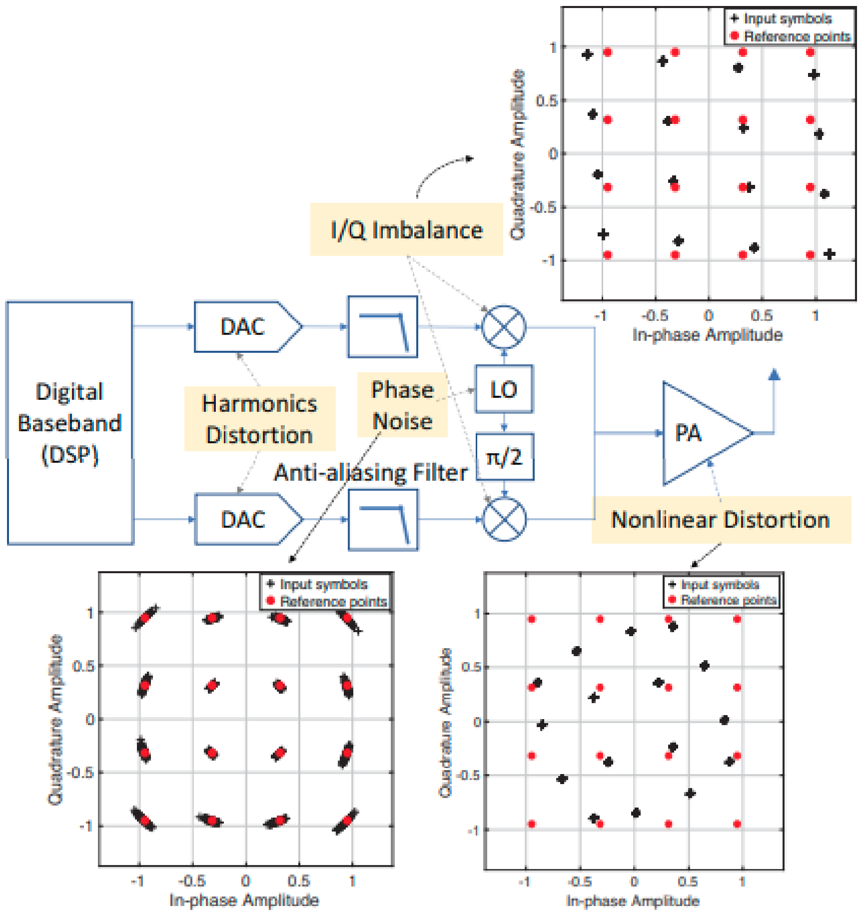
Device B

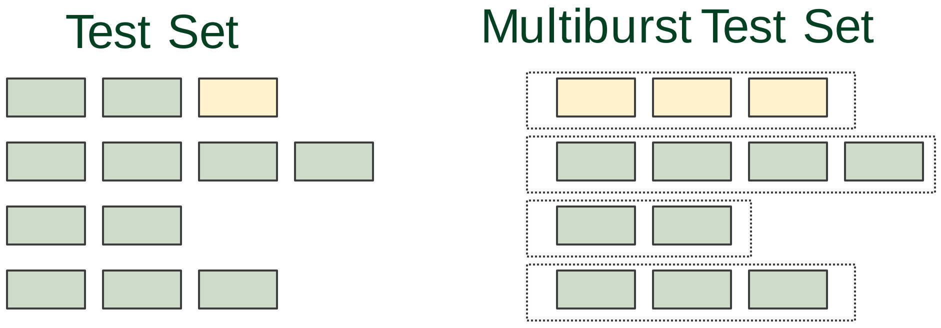
OR

Device identification using only PHY signals; no spoofing of MAC IDs

Challenge: Weak and Subtle Variations That Must Not “learn” MAC ID

Approach: Deep Learning Via Convolutional Neural Networks





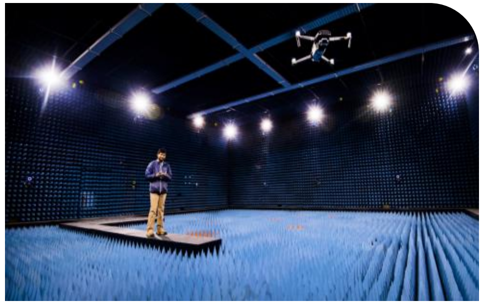
Test Name	WiFi	ADS-B
Multiburst		
Population Hi (1K)	**0.8976** (resnet1d+raw samples)	**0.9508** (resnet1d+raw samples)
Population Mid (500)	**0.9458** (baseline+equalized)	**0.9714** (baseline+raw samples)
Population Low (100)	**0.9904** (resnet1d+equalized)	**0.9916** (baseline+raw samples)

RF Fingerprinting

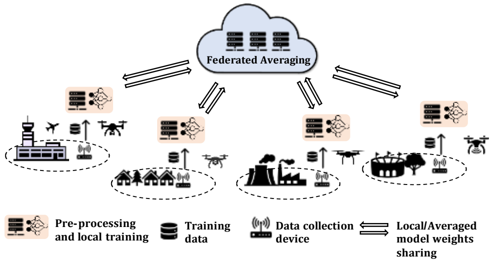
Theory to Real World — Practical Use Cases

POWDER PAWR platform. ID BSs transmitting 5G/LTE/WiFi waveforms

Using receiver feedback to enhance fingerprints



Using ensemble of classifiers with data collected in RF anechoic chamber



UAV type detection with FL (simpler problem that same device type)

Additional Relevant Information

Research Directions	Outcomes
Architectures ReNet, VGG, Siamese	From images to RF IEEE INFOCOM'19, IEEE IOTMag'20,
Pre-processing Partial eq, data augment, using feedback loops	How much data? Beating the channel using Receiver f/b IEEE TCCN'19, IEEE INFOCOM'20, IEEE ComMag'20
New class detection Lifelong learning, open world discovery	Outlier detection Learning unseen classes ICDM-1'20, ICDM-II'20, IEEE DySPAN'19
Pruning/quantization FPGA dev, compression	95% compression without accuracy loss IEEE TMC'21
Use-cases 5G, UAVs, rapid AP Association	Support virtualization ID infrastructure IEEE TVT'20, IEEE TVT'21, IEEE ICNP'20

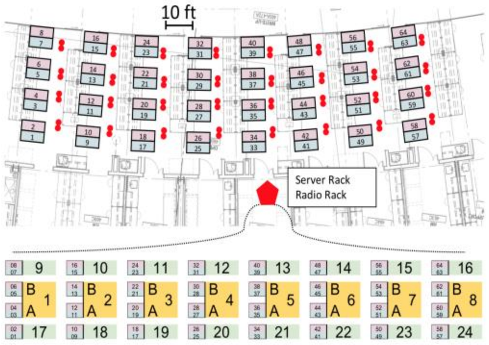
From Testbeds to Datasets to APIs

Colosseum (RF Emulation @NU) | **ARENA (Indoor over-the-air @NU)** | **PAWR (Community-scale exps)**

Test at-a-scale on emulated scenarios →

COLOSSEUM at Northeastern University

Validate in real wireless environment →



Test large-scale capabilities →

Platforms for Advanced Wireless Research

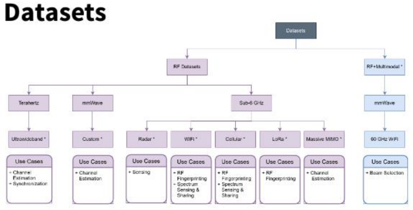
COSMOS

RFDataFactory*

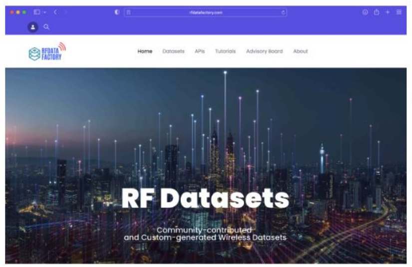
- Platform for accessing and sharing:
  - RF-centric datasets
  - software APIs
  - tutorials for collecting and processing data

*RFDataFactory is supported by the US National Science Foundation CISE Community Infrastructure (CCRI) Award #2120447

Datasets

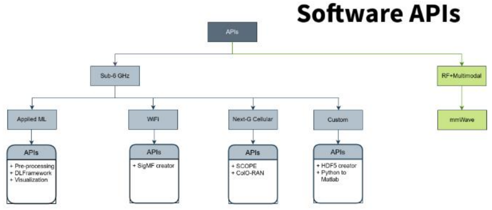


One-stop Resource for Datasets for the Wireless Community

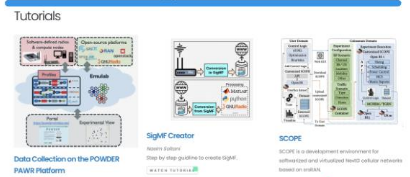


https://www.rfdatafactory.com

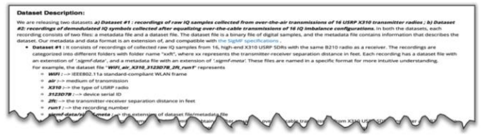
Software APIs



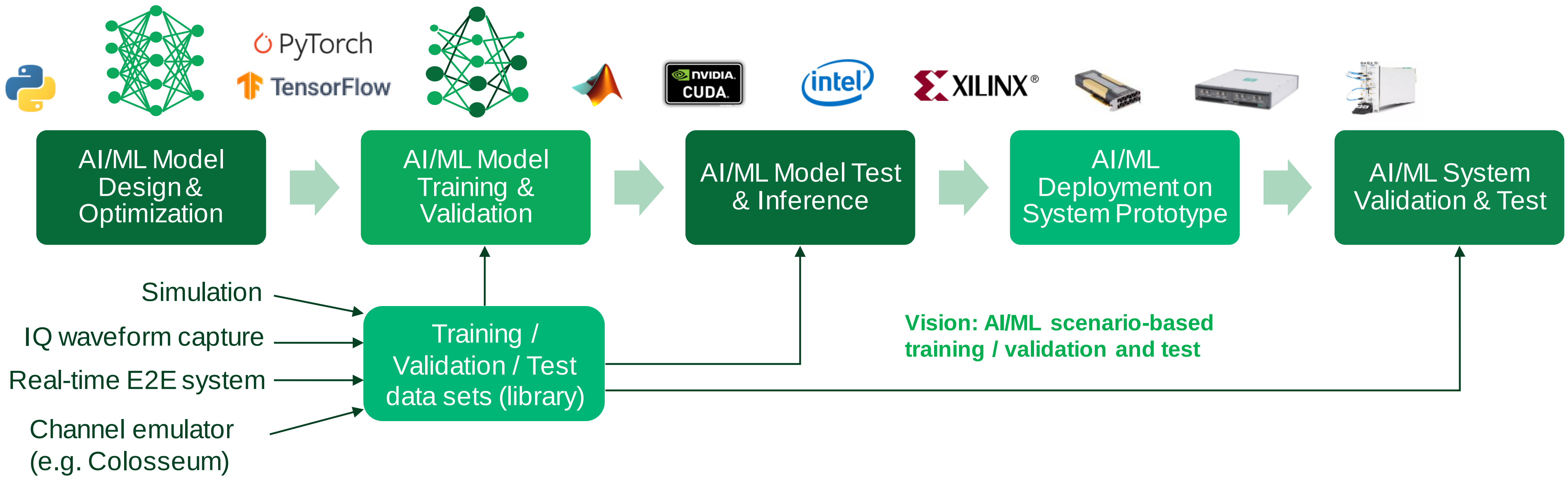
Tutorials



SigMF Metadata

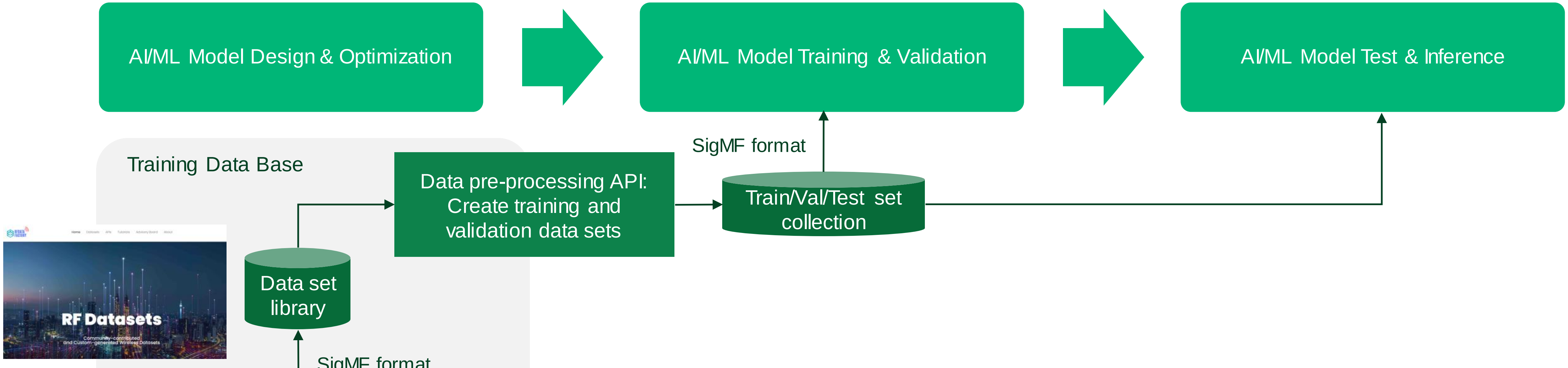


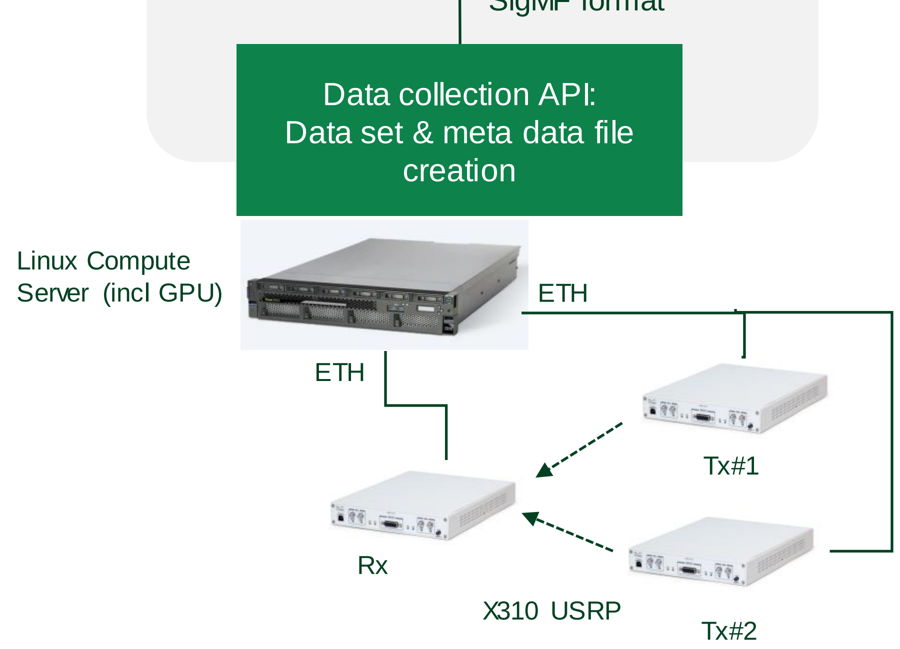
AI/ML in RF Wireless – Objectives



- Create **data set recording reference architecture** including data collection & pre-processing APIs and explore use of existing NI software for data set management
- Understand domain/application-specific AI/ML model **training & validation workflow** for RF / wireless using channel estimation and RF fingerprinting examples
- Partnership with our lead-user **Northeastern University** to inform our AI/ML work and follow closely **3GPP AI/ML standardization** efforts

AI/ML Data Set Recording Reference Architecture





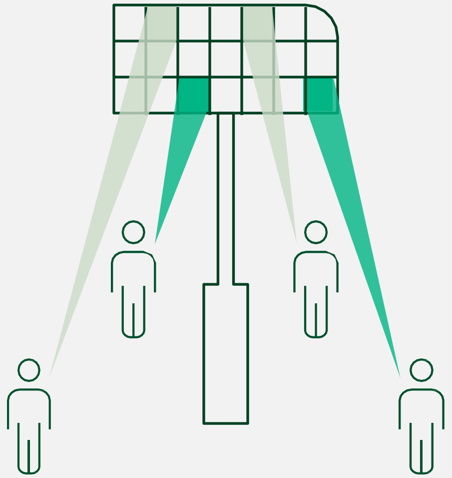
Current Achievements:

- ✓ Initial implementation of data collection API with automatic Tx waveform playback and Rx IQ data capturing using USRP / UHD including instant conversion to SigMF data set format – **API code handed over to NEU**
- ✓ Initial implementation of data pre-processing API to read SigMF based data sets and create training/validation/test data sets as well as labels (targets) - **Successfully applied to an RF fingerprinting AI/ML model to ID 2x USRPs based on Rx IQ data**
- ✓ **CBRS – radar among LTE data transmission**

Questions and Discussion

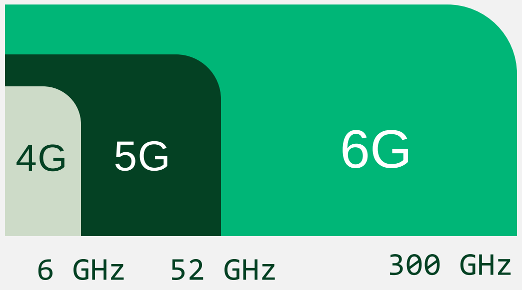
Evolution of MIMO

Build on multi-antenna techniques from 5G with more elements and distributed architecture.



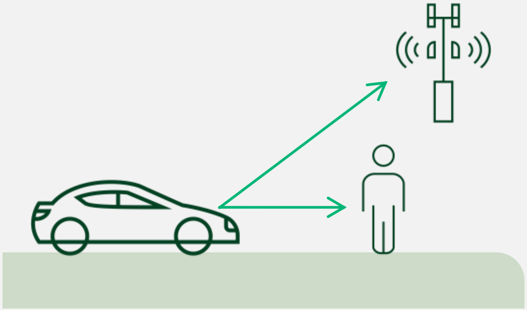
Sub-Terahertz

Utilize extremely wide bandwidths at frequencies once thought impractical for commercial wireless.



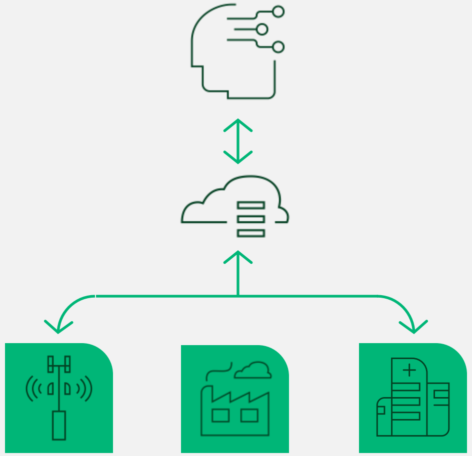
Joint Communications and Sensing

Improve spectral usage by combining sensing and radar functions with communications channels.



Machine Learning and Artificial Intelligence

Leverage new techniques across all 6G — from the signal chain to the network topology.



ni.com

National Instruments
is now NI.

Contact a Technical Expert