IEEE VTS

Connecting the Mobile World

WEBINAR SERIES ON ADVANCED MOBILITY

Acknowledgement

The presenter wishes to acknowledge the IEEE Vehicular Technology Society for their sponsorship of the Webinar Series on Advanced Air Mobility.

AERPAW

https://aerpaw.org/

PAWR Project Office

AERPAW: A Programmable Experimentation Platform as a Service for Advanced Wireless and UAS Researchers

June 6, 2023

Ismail Guvenc, Professor
North Carolina State University
Email: aerpaw-contact@ncsu.edu

NC STATE UNIVERSITY

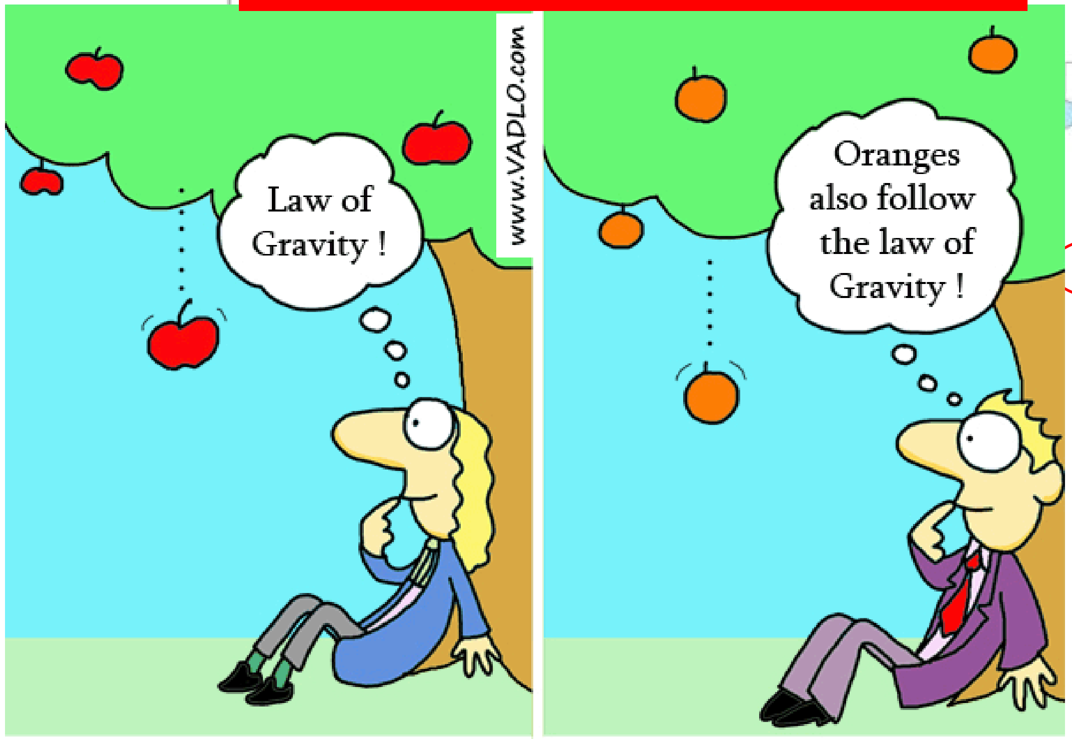
Outline

- **AERPAW Overview and Deployment Areas**
- AERPAW Phase-2 Platform Updates
- Other Recent Platform Updates

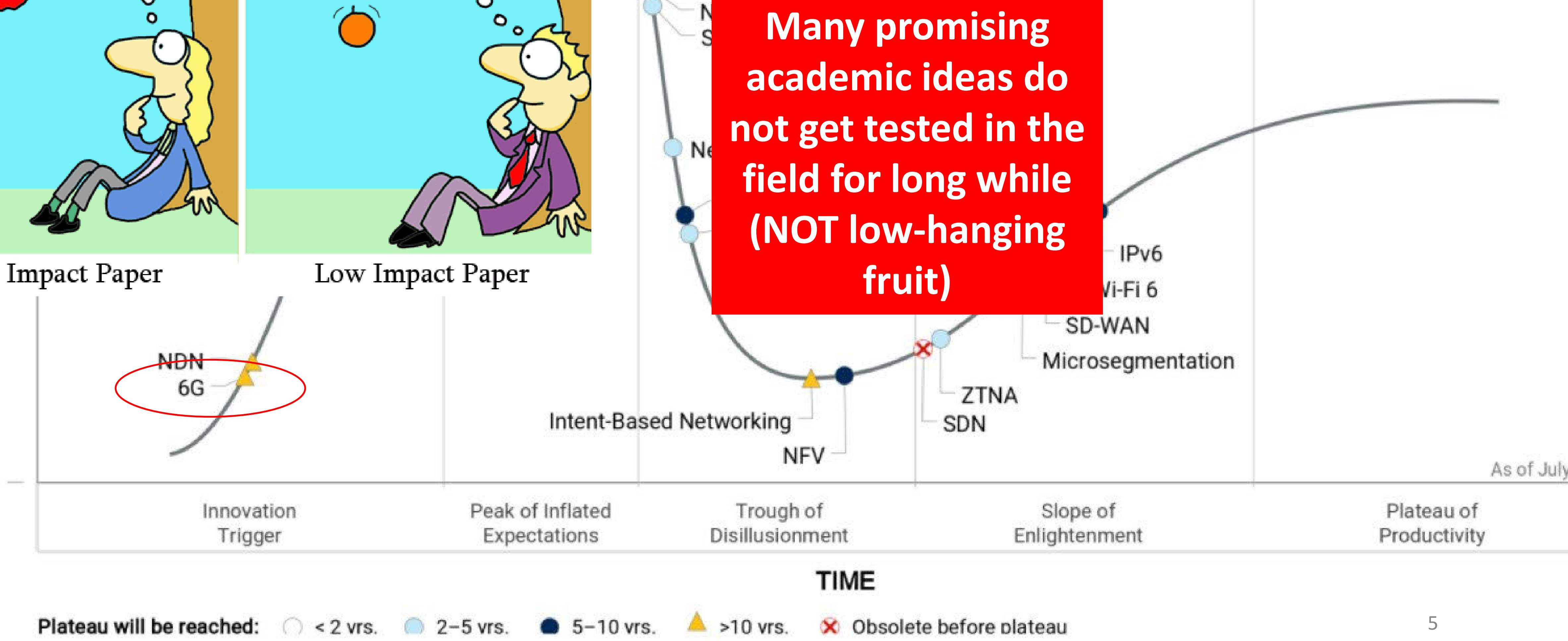
Gartner Hype Cycle: 5G and 6G (2021)

Source:
https://www.theregister.com/2021/07/15/ipv6_istilli_510_years_away/

<= Academia LOVES to work here! =>

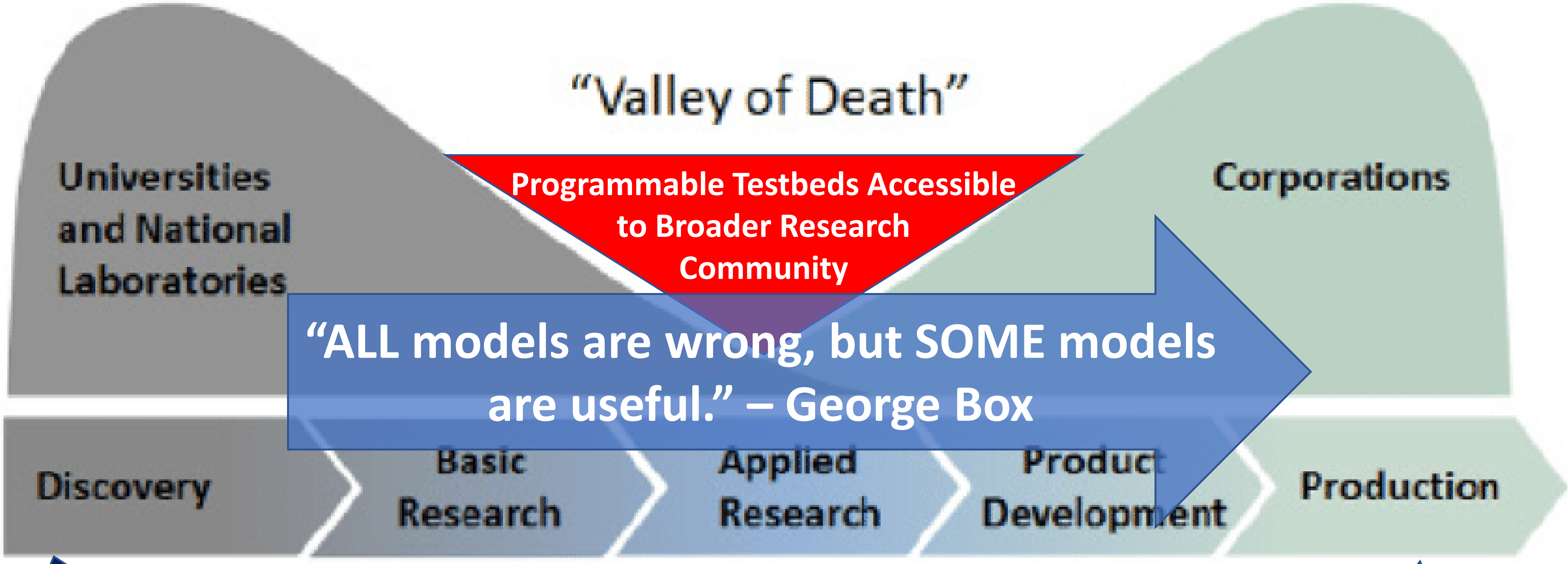


High Impact Paper | Low Impact Paper



Many promising academic ideas do not get tested in the field for long while (NOT low-hanging fruit)

“Valley of Death” for Wireless Research



Driven by publications and citations

Driven by revenue

NSF Platforms for Advanced Wireless Research (PAWR)

Funded Apr. 2018

POWDER

Salt Lake City, UT

Software defined networks and massive MIMO

AVAILABLE TODAY !!

Funded Apr. 2018

COSMOS

West Harlem, NY

Millimeter wave and backhaul research

AVAILABLE TODAY !!

Funded Sept. 2019

Phase-1 Availability: Nov. 2021
Phase-2 Availability (Expected): Aug. 2023

and mobility

AVAILABLE TODAY !!

Funded June 2021

ARA

Ames,IA

Rural broadband wireless

To be Available in 2023

COLOSSEUM

Northeastern University, MA
Large-scale wireless emulation

AVAILABLE TODAY !!

Advanced Wireless Research for Unmanned Aerial Vehicles

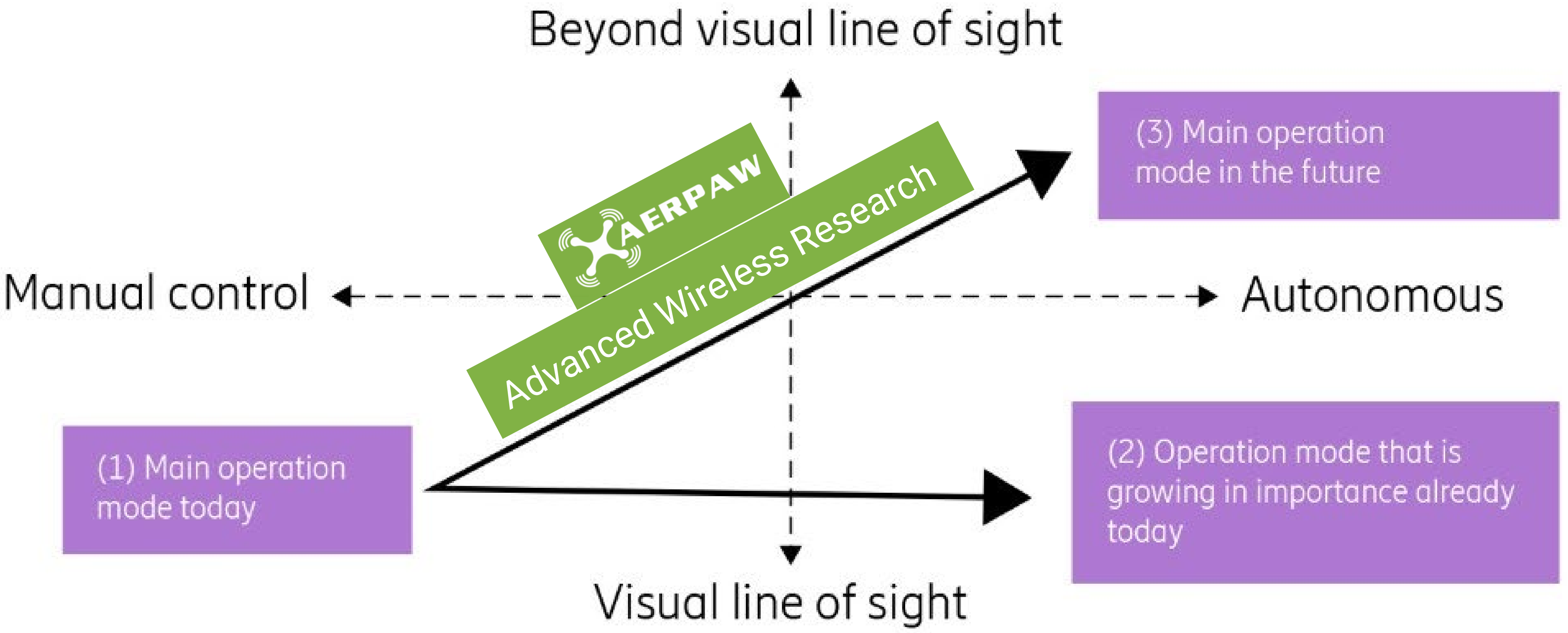


Image source: Ericsson

AERPAW Project Team and Partners

Ismail Guvenc
PI, NC State (SDRs, 4G/5G standards, PHY/MAC)

Rudra Dutta
NC State (SDN, architecture, CentMesh)

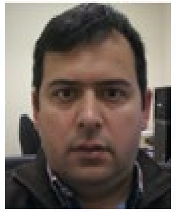
Mihail Sichitiu
NC State (drones, architecture, CentMesh)

Brian Floyd
NC State (mmW circuits, arrays)

Tom Zajkowski
NC State (UAS operations, FAA permitting)

Lavanya Sridharan
NC State (Project Coordinator)

Ed Rogers
NC State (construction permits)



Ozgur Ozdemir NC State (SDRs, Keysight, Facebook TG)

Vuk Marojevic
MSU (security, SDRs, waveforms, CORNET)

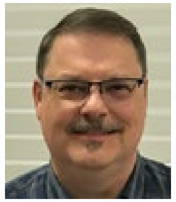
Gerard Hayes
NC State, WRC (wireless and testing)

Yufeng Xin
RENCI, UNC-CH (data models, software architecture control framework)

David W. Matolak
USC (aerial propagation, waveforms)

David Love
Purdue (MIMO, SDRs, agriculture)

Magreth Mushi
NC State (Network Arch. & Platform Ops.)



Mike Barts
WRC (RF, Towers, Antennas, Front Ends)

Asokan Ram
WRC (4G/5G Ericsson deployment)

Alphan Sahin, USC
mmWave Development

Andrew Balmos, Purdue
LoRa Development

Mark Funderburk, NC State
UAV/UGV Development

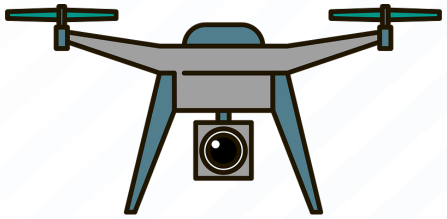
Other Personnel:

- **Postdoctoral Scholars:** Talha F. Rahman, Sung Joon Maeng
- **PhD Students:** Anil Gurses, Keith Powell, Ashwini Ganesh, Mrugen Deshmukh, Moin Chowdhury
- **MS Students:** Vishwas Gowda, Sainath Gorige
- **Other WRC and RENCI Personnel:** Thomas Hoover, Michael Stealey, Erica Fu, Erik Scott
- **ITRE Aviation Personnel/Pilots:** Evan Arnolds, Shawn Deardorff, Michael Picinich
- **Undergrad Students:** John Kessler, Keshav Sridhar, Byron Qi, Joshua Moore

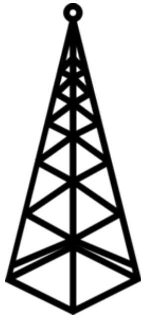
Unique Features of AERPAW

Programmable Radios Deployed at Scale
4G, 5G, LoRa, spectrum sensors, custom waveforms

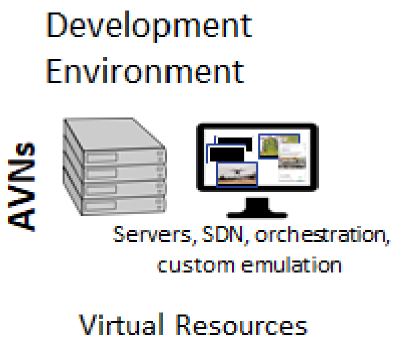
Programmable Vehicles
UAVs, UGVs, controlled and repeatable mobility, autonomous navigation



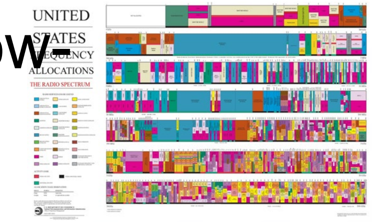
Outdoor Towers and UAS Flight Area
Lake Wheeler and Centennial Campus



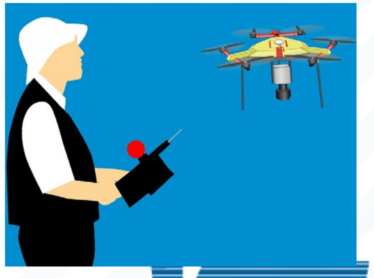
Cloud-based Development Environment for Canonical Experiments
Emulation (digital twin) prior to testbed deployment



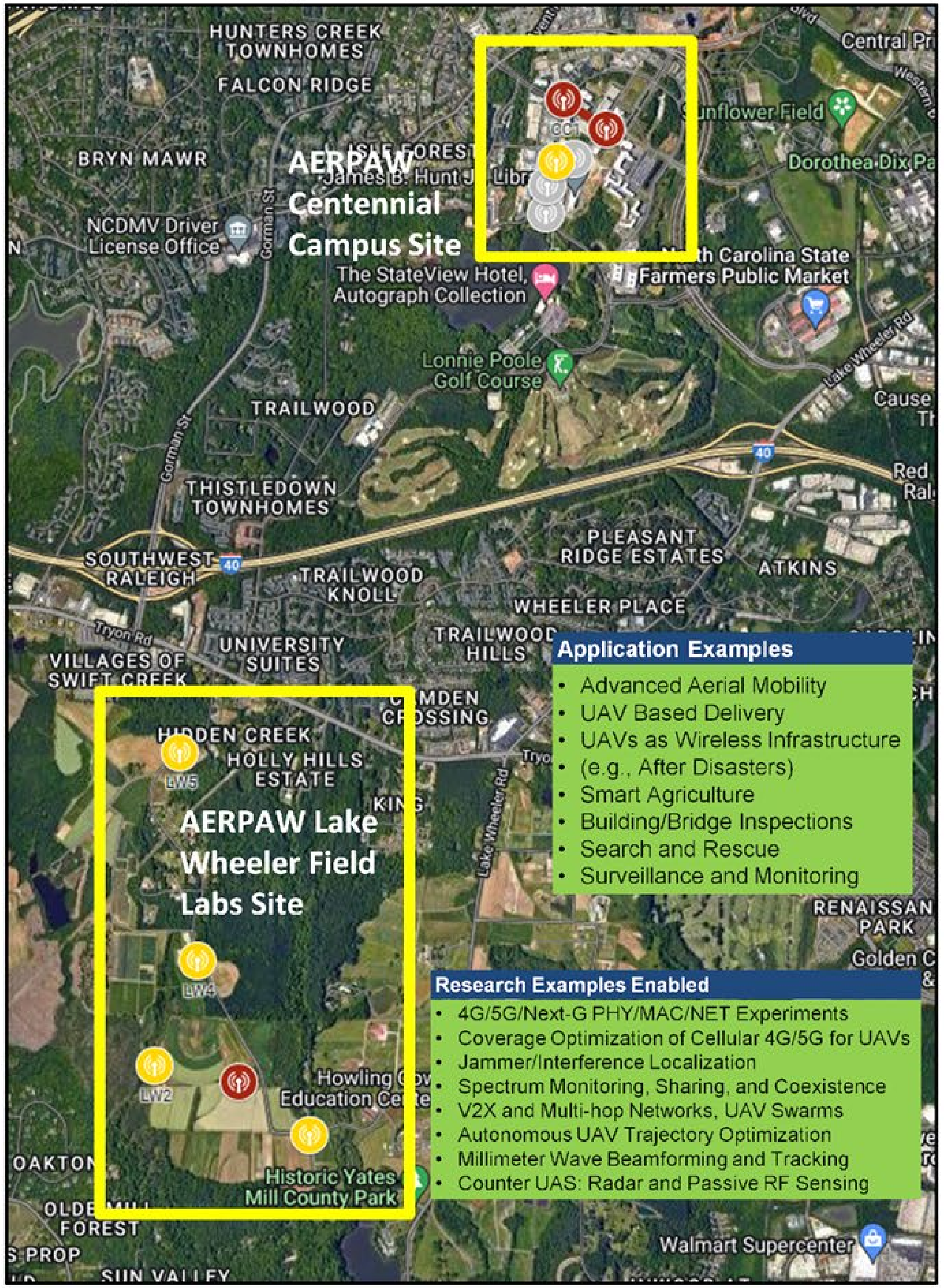
FCC Spectrum Licenses
Low-band and mid-band (soon mmWave)



UAS Expertise, Pilots, and FAA Waivers
Part-107 pilots available for supporting experiments



Deployment Map for AERPAW Fixed Nodes



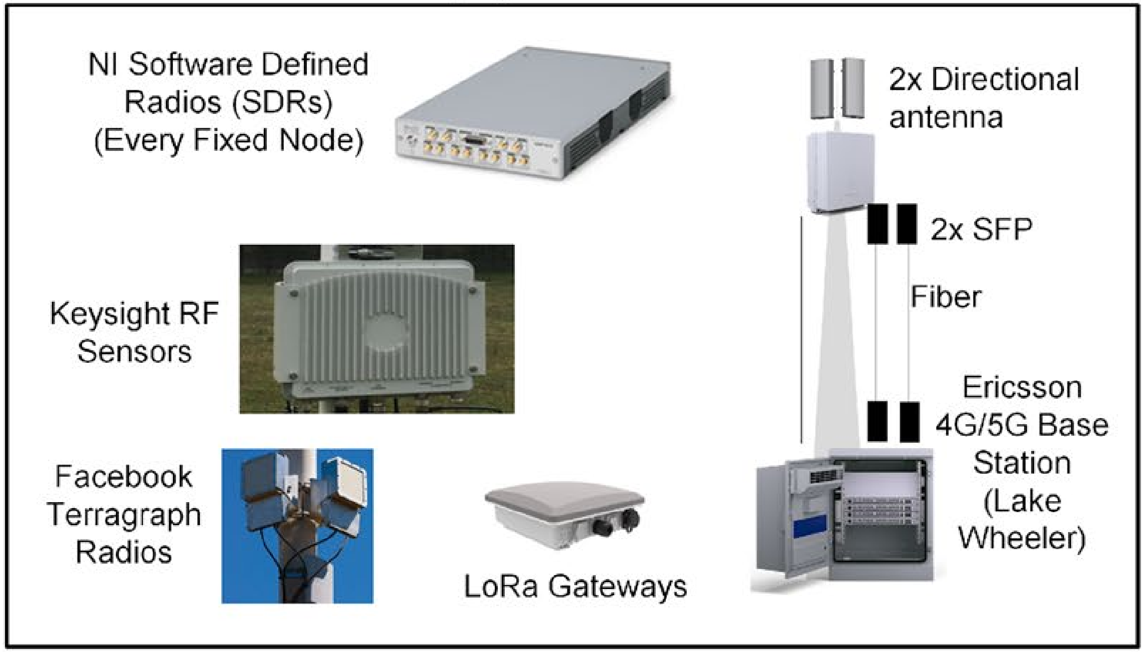
Application Examples

- Advanced Aerial Mobility
- UAV Based Delivery
- UAVs as Wireless Infrastructure
- (e.g., After Disasters)
- Smart Agriculture
- Building/Bridge Inspections
- Search and Rescue
- Surveillance and Monitoring

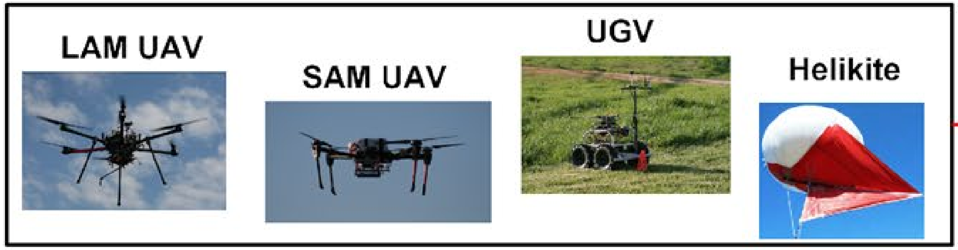
Research Examples Enabled

- 4G/5G/Next-G PHY/MAC/NET Experiments
- Coverage Optimization of Cellular 4G/5G for UAVs
- Jammer/Interference Localization
- Spectrum Monitoring, Sharing, and Coexistence
- V2X and Multi-hop Networks, UAV Swarms
- Autonomous UAV Trajectory Optimization
- Millimeter Wave Beamforming and Tracking
- Counter UAS: Radar and Passive RF Sensing

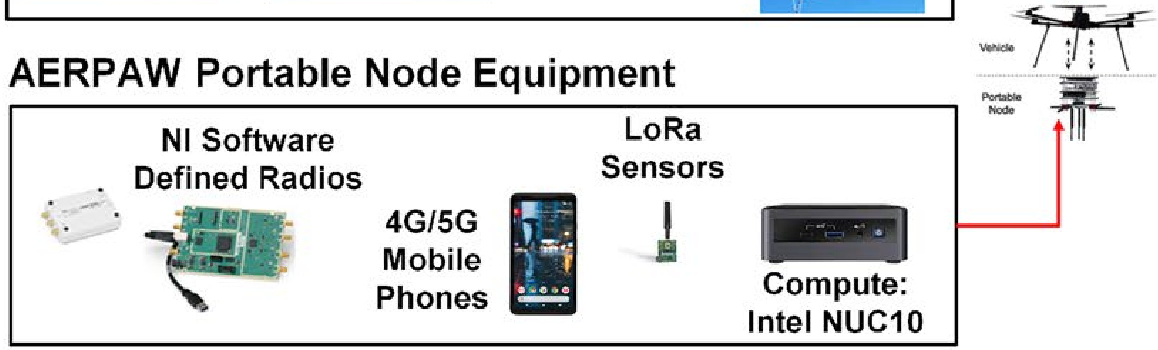
AERPAW Fixed Node Equipment



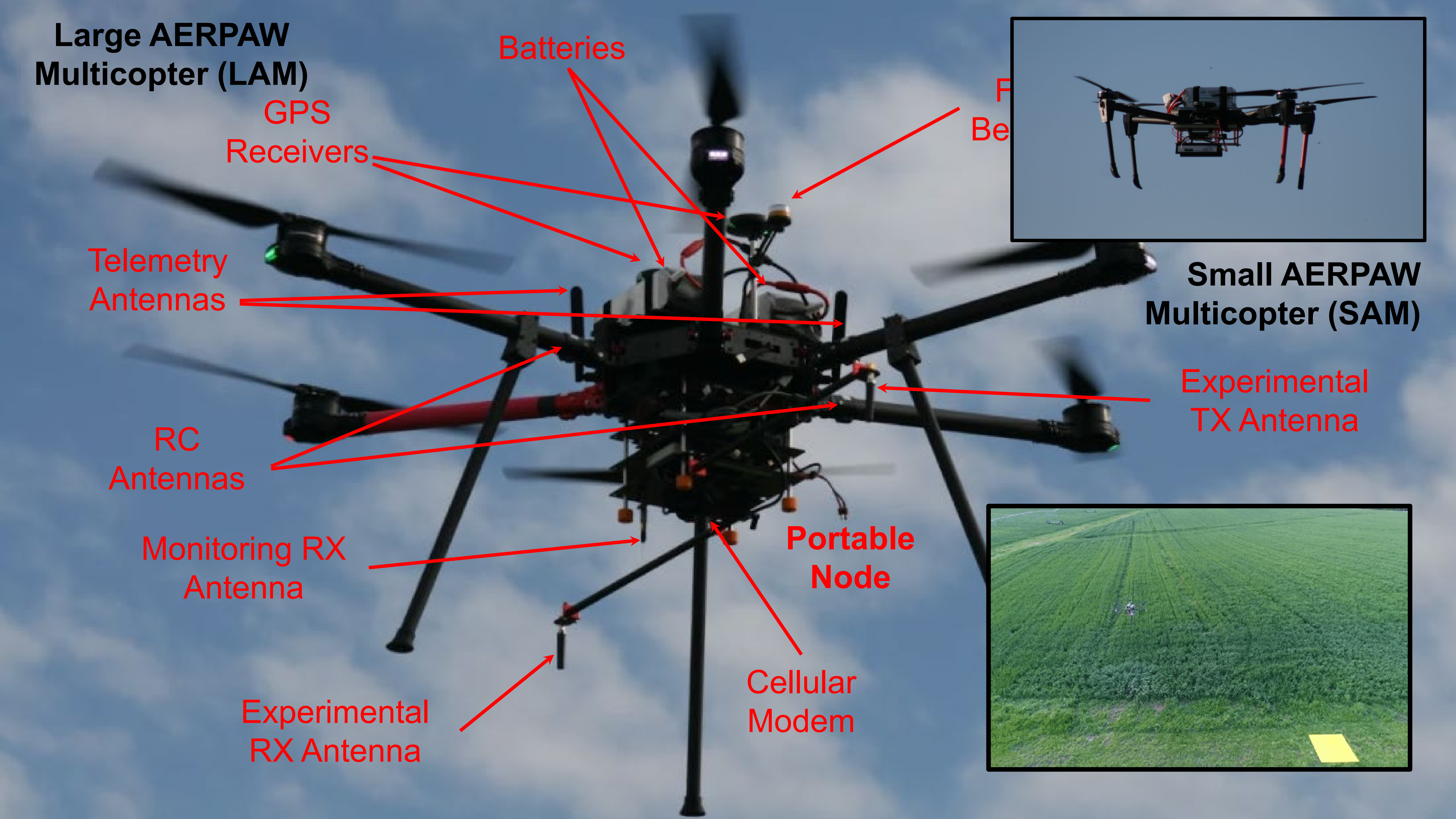
AERPAW Vehicles

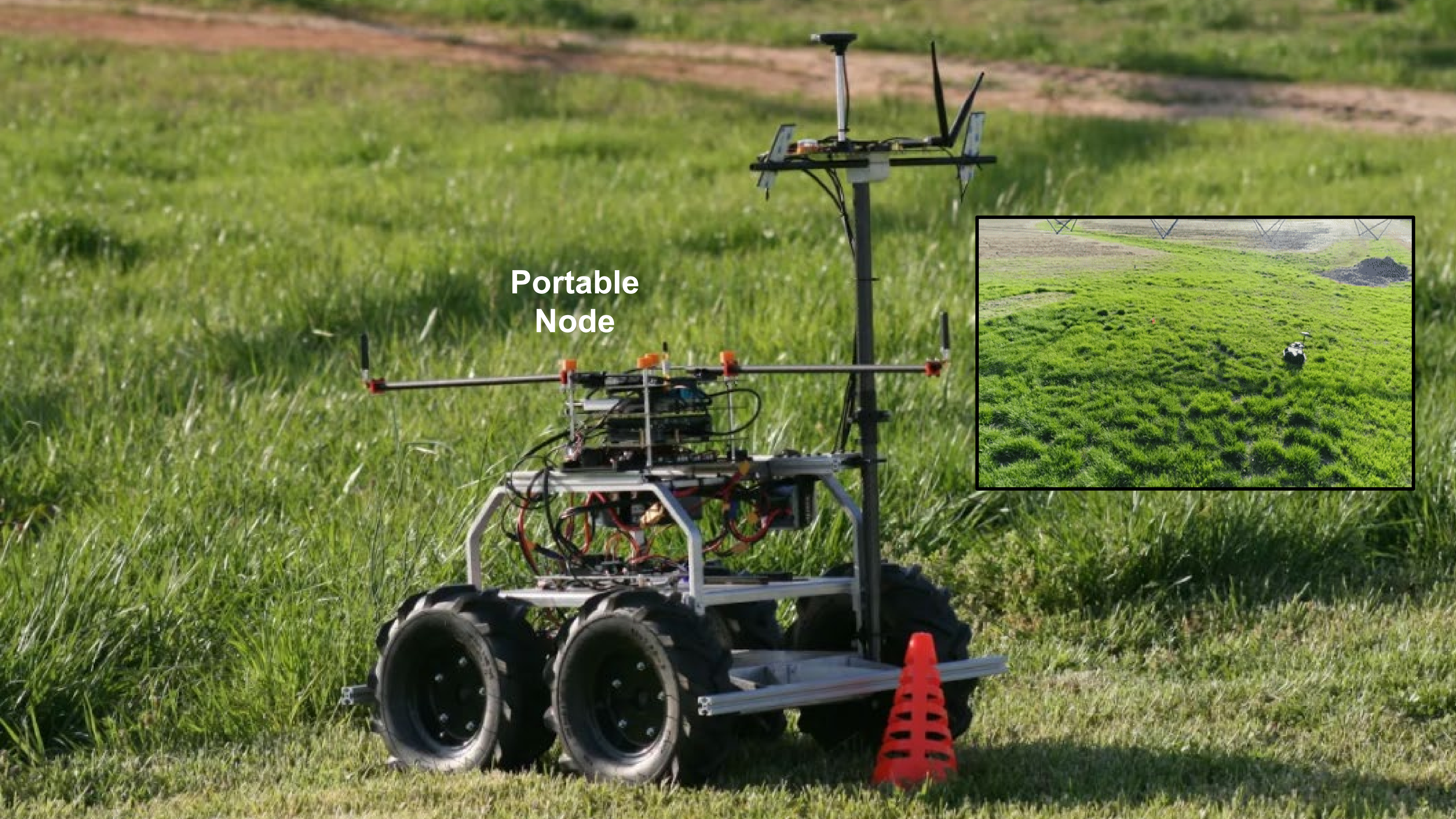


AERPAW Portable Node Equipment

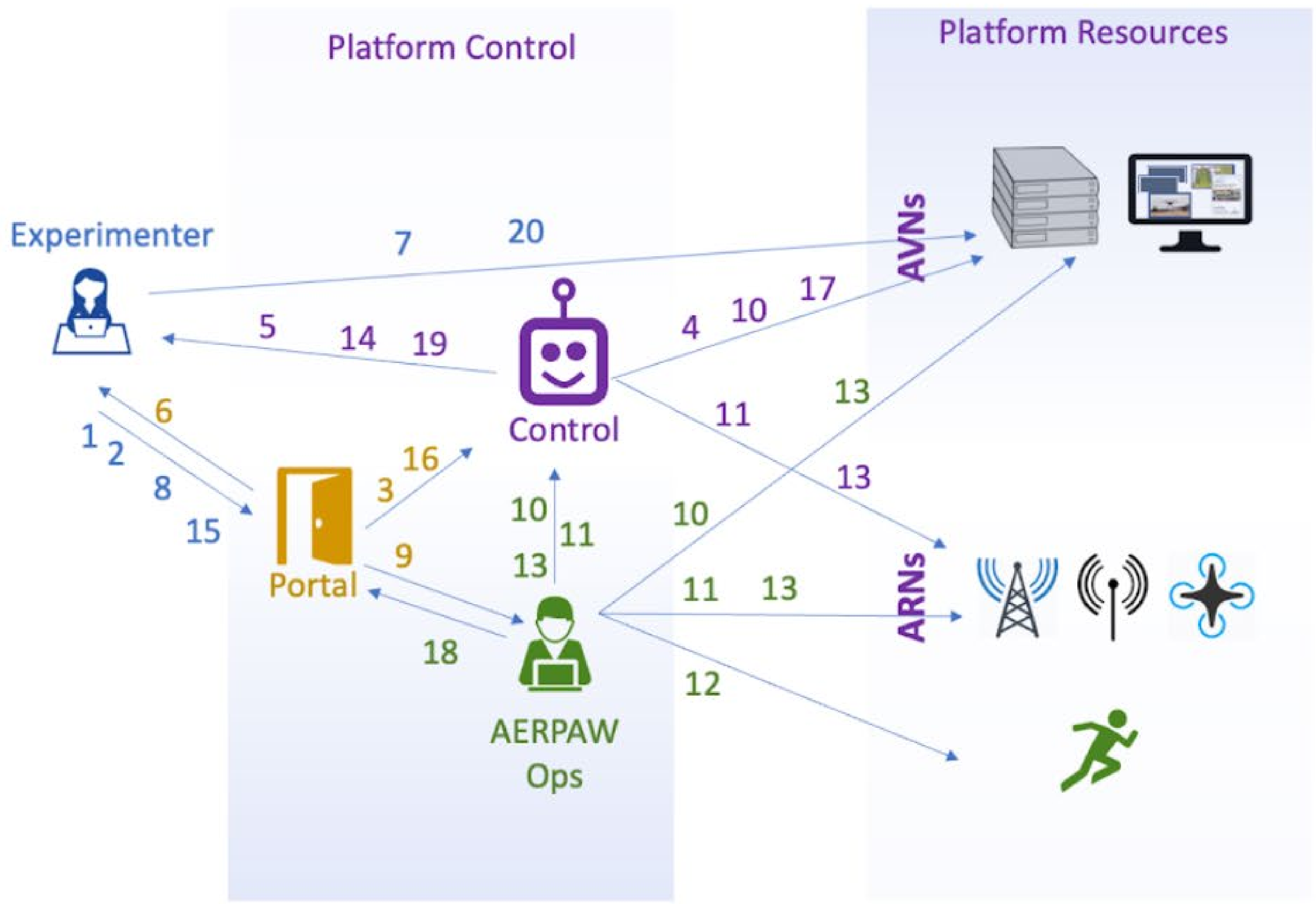


Project Website: https://aerpaw.org/ User Manual: https://sites.google.com/ncsu.edu/aerpaw-wiki


Large AERPAW Multicopter (LAM)
Batteries
GPS Receivers
Telemetry Antennas
RC Antennas
Monitoring RX Antenna
Experimental RX Antenna
Cellular Modem
Portable Node
Experimental TX Antenna
Small AERPAW Multicopter (SAM)


Portable
Node

AERPAW Portal, Development Environment, and Testbed



1 Register, supply credentials
2 Create experiment, request develop
3 Trigger virtual experiment request
4 Instantiate virtual experiment
5 Notify virtual experiment ready
6 Provide virtual experiment access
7 Login to virtual nodes, code, test
8 Save experiment, submit to testbed
9 Trigger testbed experiment request
10 Retrieve experiment from virtual
11 Install experiment on testbed
12 Handover to pilots/operators
13 Retrieve experiment, set complete
14 Notify experimenter of status
15 Request develop returned expmt.
16 Trigger virtual experiment request
17 Re-instantiate virtual experiment
18 Change status
19 Notify virtual experiment ready
20 Login to virtual nodes, view

AERPAW Service Models

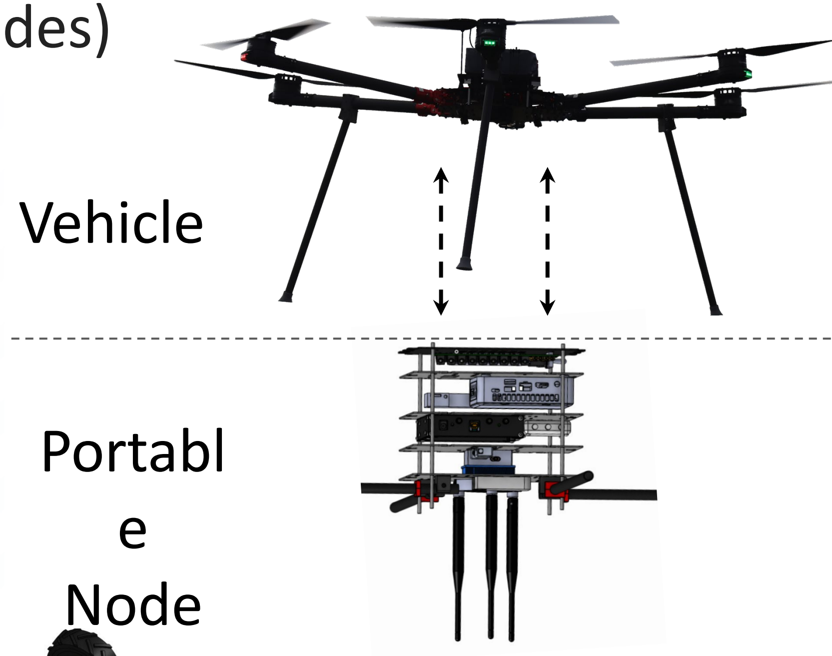
- AERPAW is a batch-mode facility:
  - Experiments are first developed in a virtual environment, then submitted to AERPAW Ops for execution in the physical testbed
  - AERPAW is primarily a physical (v.s. computing) facility
- Program it Yourself (PiY)
  - Experimenters develop their experiments exclusively in the virtual environment
  - Researchers working as part of NSF funded projects has free access
  - Limited live access: Keysight RF sensors (available now) and LoRa (Phase-3)
- AERPAW as a Service
  - For more complicated projects
- Bring Your Own Device
  - You need to contact us at aerpaw-contact@ncsu.edu to explore feasibility
- NSF-funded projects can receive supplements each year as other PAWR platforms
  - https://www.nsf.gov/pubs/2020/nsf20046/nsf20046.jsp

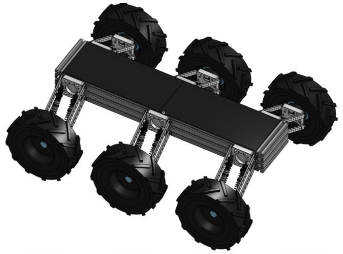
Outline

- AERPAW Overview and Deployment Areas
- **AERPAW Phase-2 Platform Updates**
- Other Recent Platform Updates

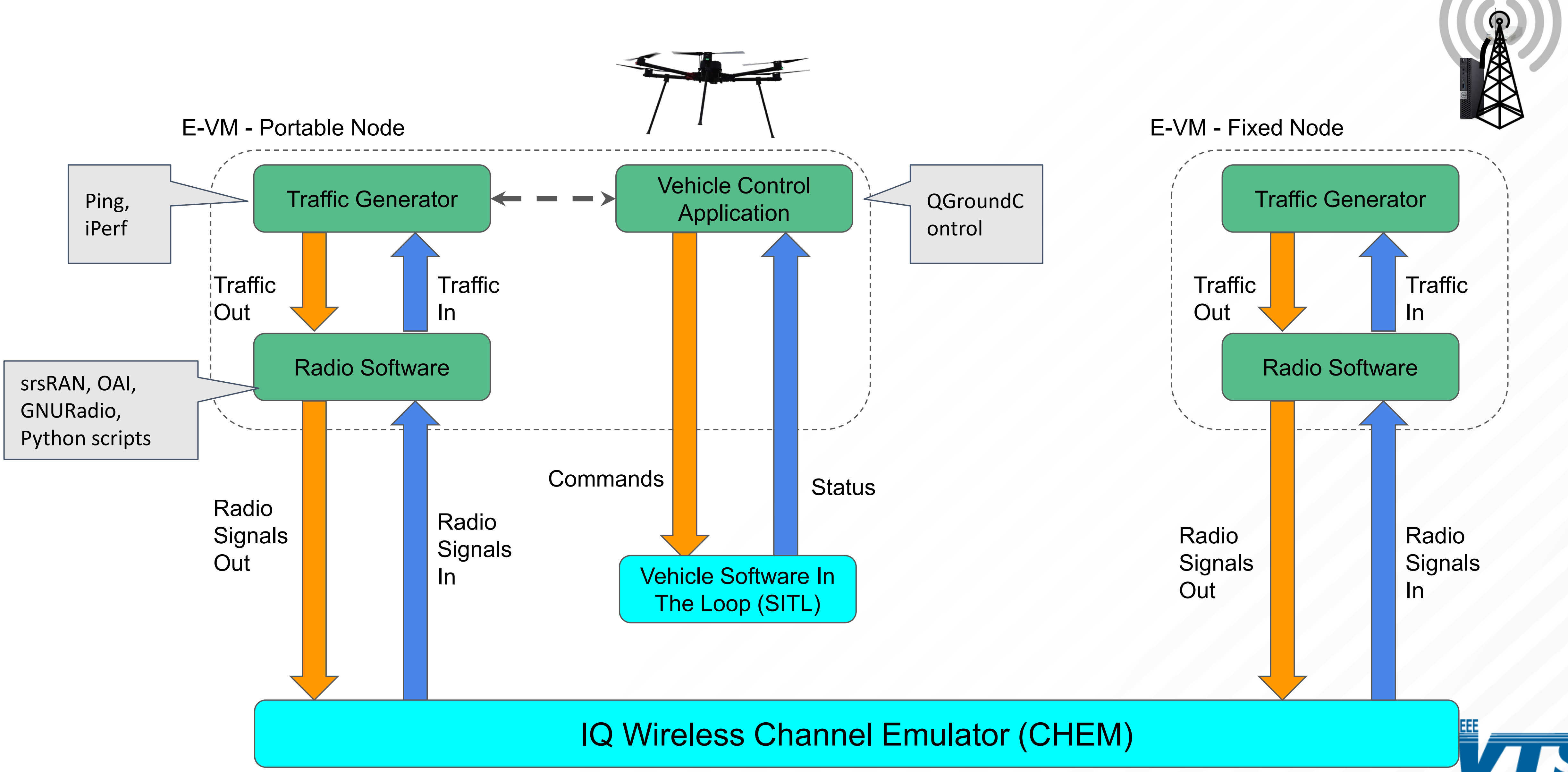
Phase-2 Fixed Nodes, Portable Nodes and Vehicles

- Fixed node footprint finalized (8 fixed nodes + 3 FB TG nodes)
- 3 upgraded LAMs (Large AERPAW Multicopters):
  - new yaw control (GPS based)
  - new battery mounting system
  - cameras (for BVLOS flights)
  - RTK enabled (~1cm precision on trajectory)
- 4 upgraded SAMs (Small AERPAW Multicopters):
  - New battery and portable node mounting systems
  - cameras, RTK enabled
- 2 rovers (1 upgraded with RTK and 1 new - all terrain)
- 6 upgraded Large Portable Nodes (SDR-based, work on all LAMs and rovers)
- 4 Small Portable Nodes (work on all vehicles, support Android Phones, COTS modems, LoRa dongles)





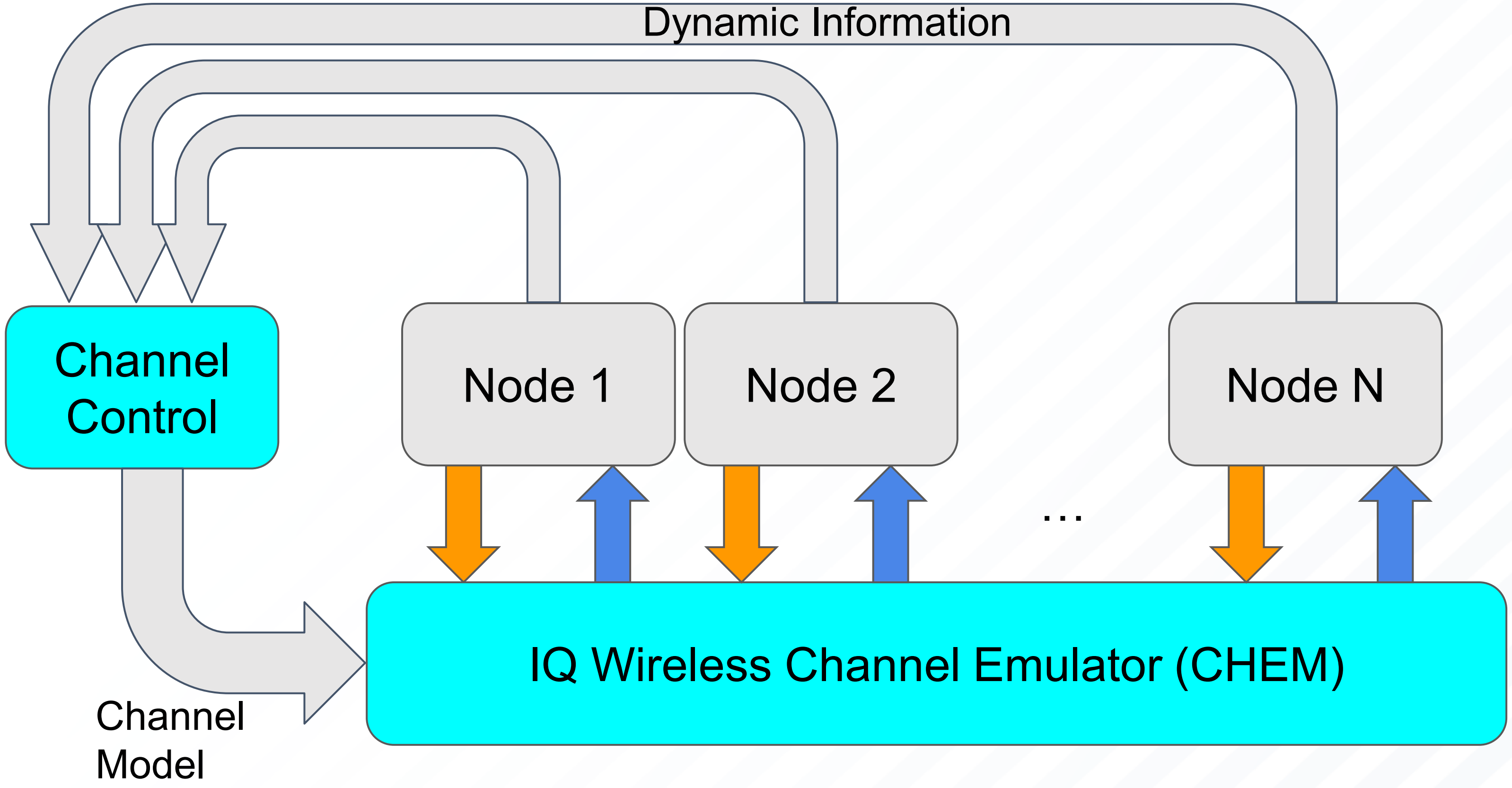
AERPAW Software Emulation Environment (Digital Twin) (1)



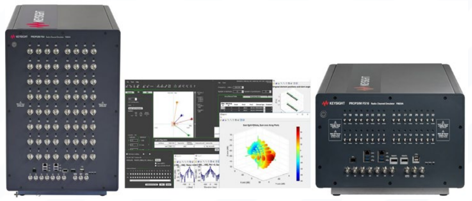
AERPAW Software Emulation Environment (Digital Twin) (2)

Wireless Channel Emulator:

- Forwards IQ samples between radio nodes
- Supports:
  - Free Space and 2Ray Ground propagation models
  - Multiple frequencies
  - Up to 100 MHz instantaneous bandwidth per channel
  - Multi-rate processing
  - Different antenna patterns
  - Support for srsRAN, GNU Radio, I/Q sample collection
  - Support for different background noise levels
- Can support large number of experimenters and nodes simultaneously



Future Plans: AERPAW Sandbox with Keysight Propsim (32 ports)



Example Experiments Availability for Phase-2 through AERPAW's Development Environment

4.1) Radio Software

- 4.1.1) srsRAN Experiments
  - SE1: Multi-Node LTE SISO
  - SE2: LTE Cell Scan
  - SE3: Two-Node LTE MIMO
  - SE4: Multi-Node IoT
  - SE5: LTE Handover
  - SE6: Single-Node 5G SA
- 4.1.2) OAI Experiments
  - OE1: Two-Node LTE SISO
- 4.1.3) GNU Radio Experiments
  - GE1: OFDM TX-RX
  - GE2: Channel Sounder
  - GE3: LoRa PHY TX-RX
- 4.1.4) UHD Python-API Experiments
  - UHD1: Spectrum Monitoring
  - UHD2: IQ Collection
- 4.1.5) Keysight RF Sensor Experiments
  - KRSE1: Spectrum Monitoring
  - KRSE2: Signal Classification
- 4.1.6) Ericsson Experiments
  - EE1 5G Modem RF logging in Idle mode
  - EE2: 5G Modem RF Logging in Connected Mode

Limited Live Access

4.2) Vehicle Control Software

- 4.2.1) Preplanned Trajectory
- 4.2.2) GPS Logger
- 4.2.3) Multiple Vehicle Coordination
- 4.2.4) Autonomous Vehicle Control

4.3) Traffic Generation Software

- 4.3.1) Ping
- 4.3.2) iPerf

Phase-2 General Availability is Expected by August 2023

https://sites.google.com/ncsu.edu/aerpaw-wiki/aerpaw-user-manual/4-sample-experiments-repository

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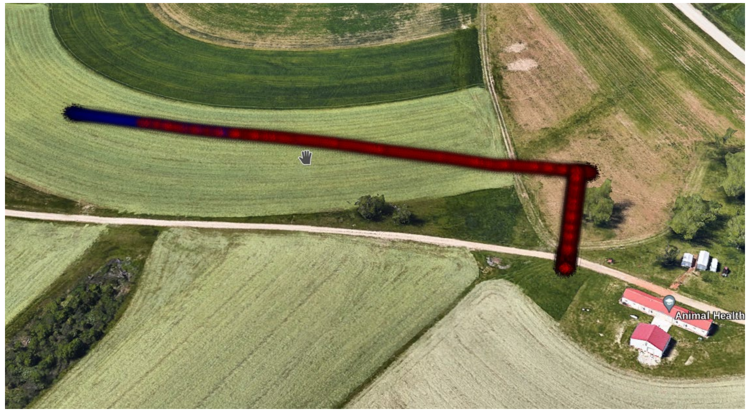
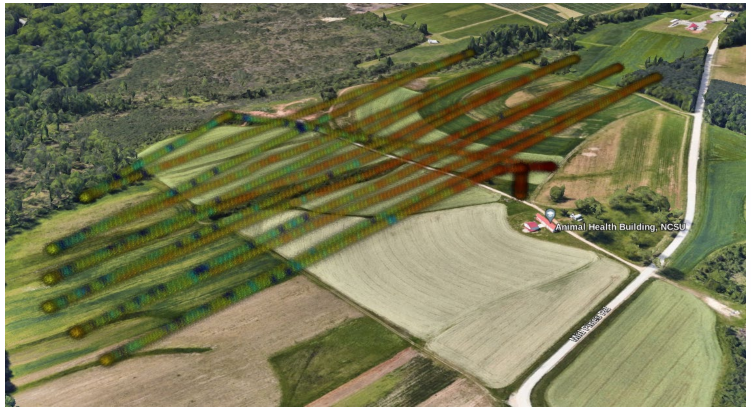
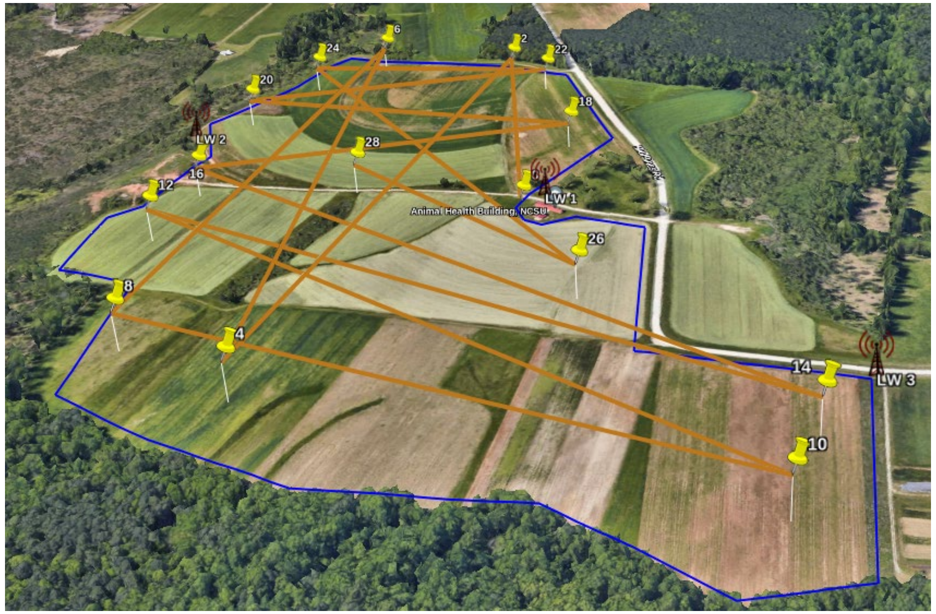
AERPAW Sample Plan Files for Phase-1 Fixed Node Footprint





AERPAW New Plan Files with LW1-LW5 for Phase-2 Fixed Node Footprint

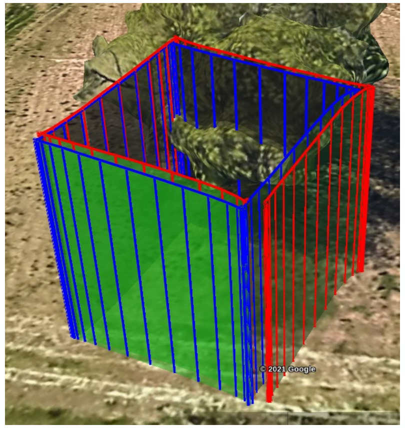


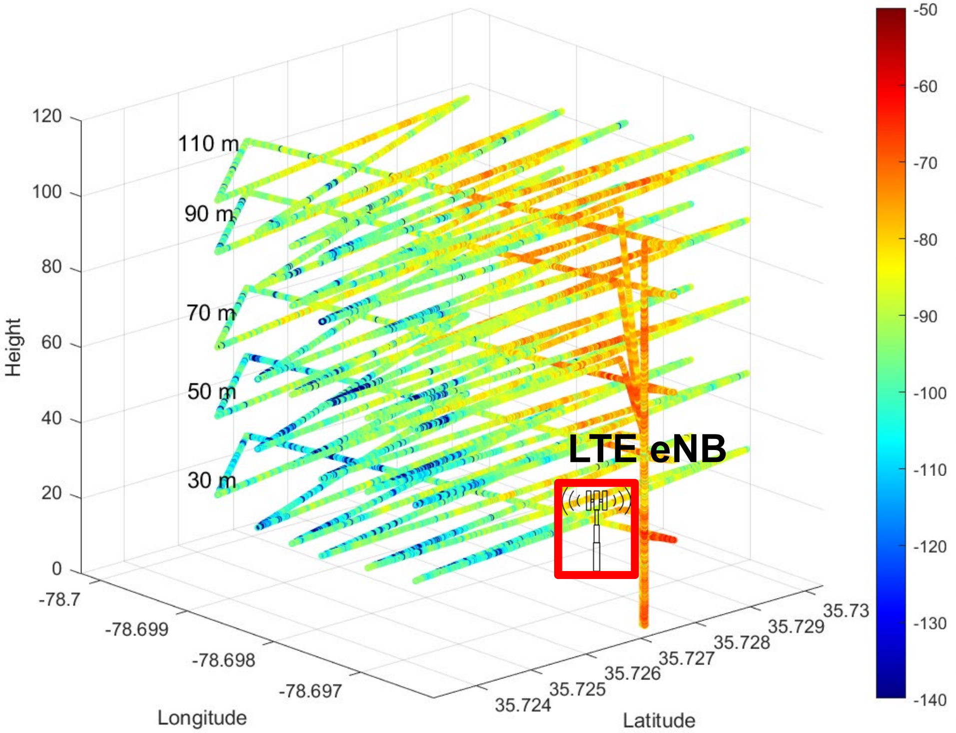
AERPAW Existing Vehicle Plan Files: https://sites.google.com/ncsu.edu/aerpaw-wiki/aerpaw-user-manual/3-experiment-structure-overview/3-1-vehicles-and-vehicle-software/creating-and-editing-mission-plan-files/existing-plan-files

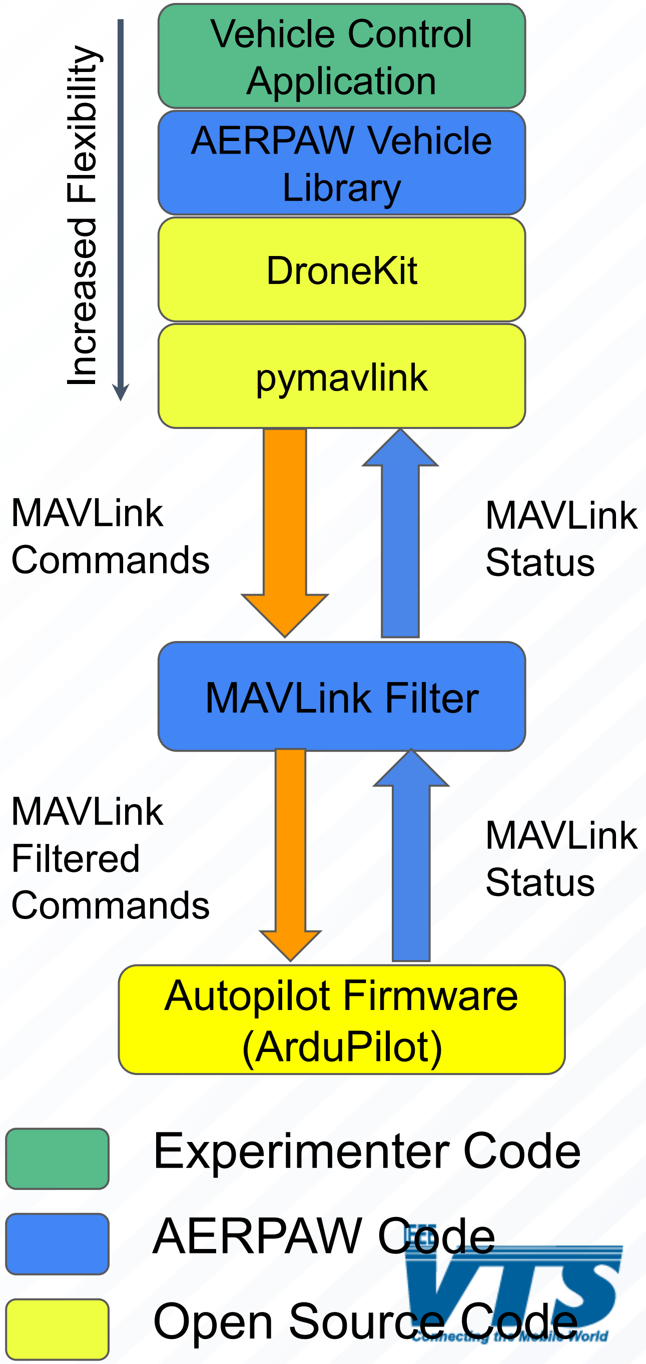
Repeatable and Controlled Mobility in Emulation Real-World Experiments in Testbed

- Users develop the vehicle and radio code jointly
- Same TX/RX locations and trajectories each time: protocol/waveform testing always for same scenario
- Can compare emulation (fully repeatable) and real-world performance

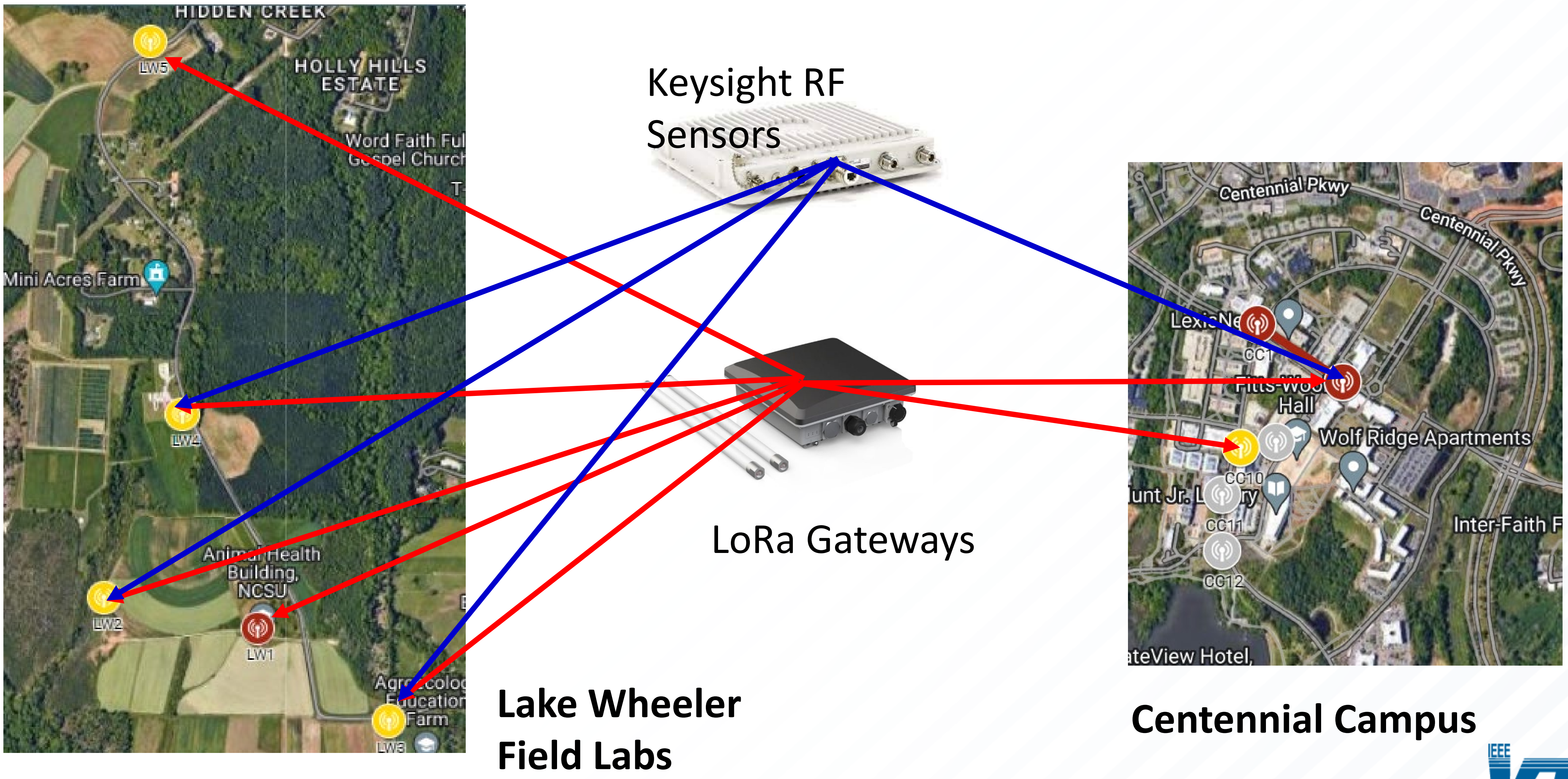
UAV pilot is only a “safety” pilot: user developed code does all the vehicle control



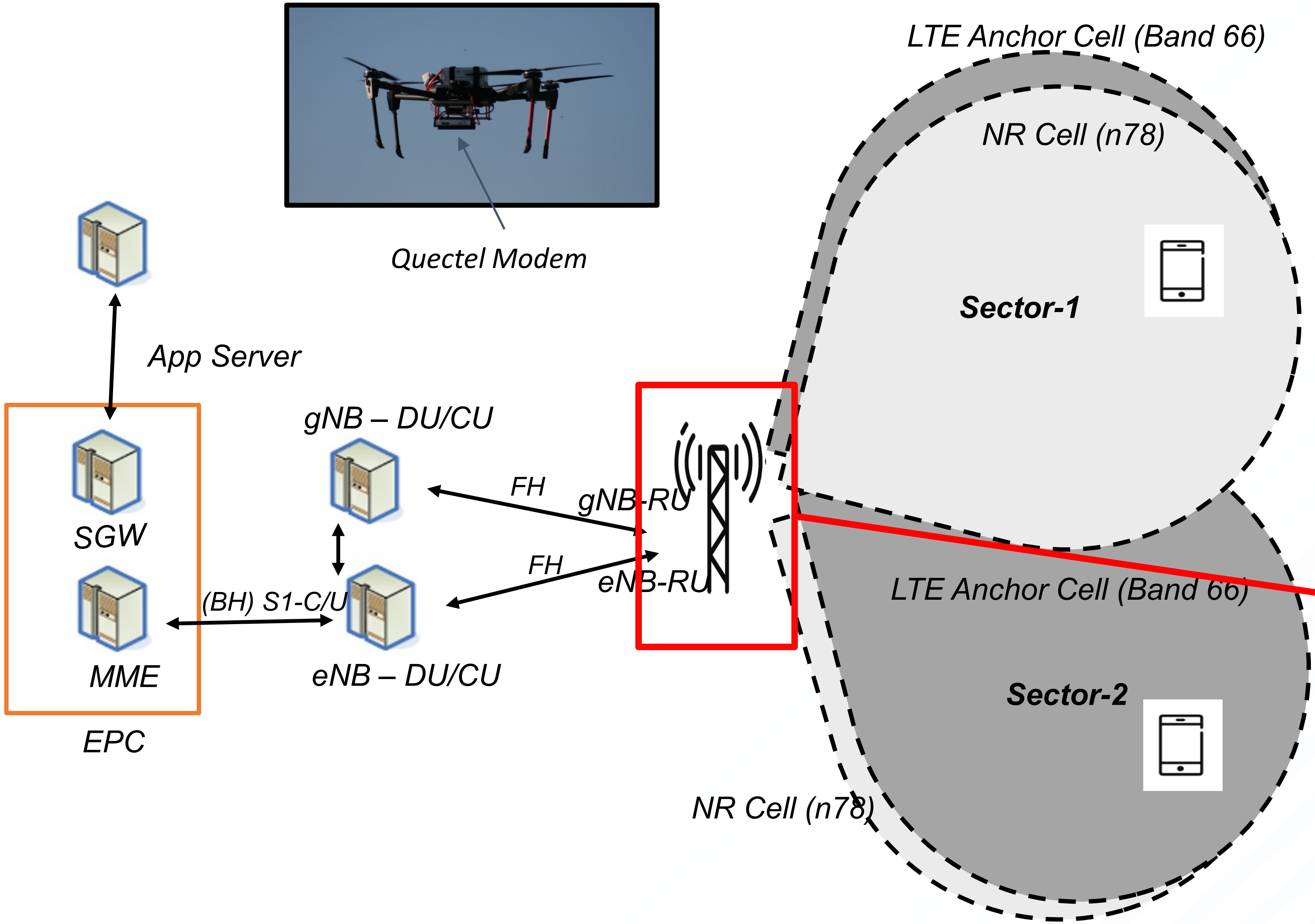




LoRa and Keysight RF Sensor Phase-2 Deployments

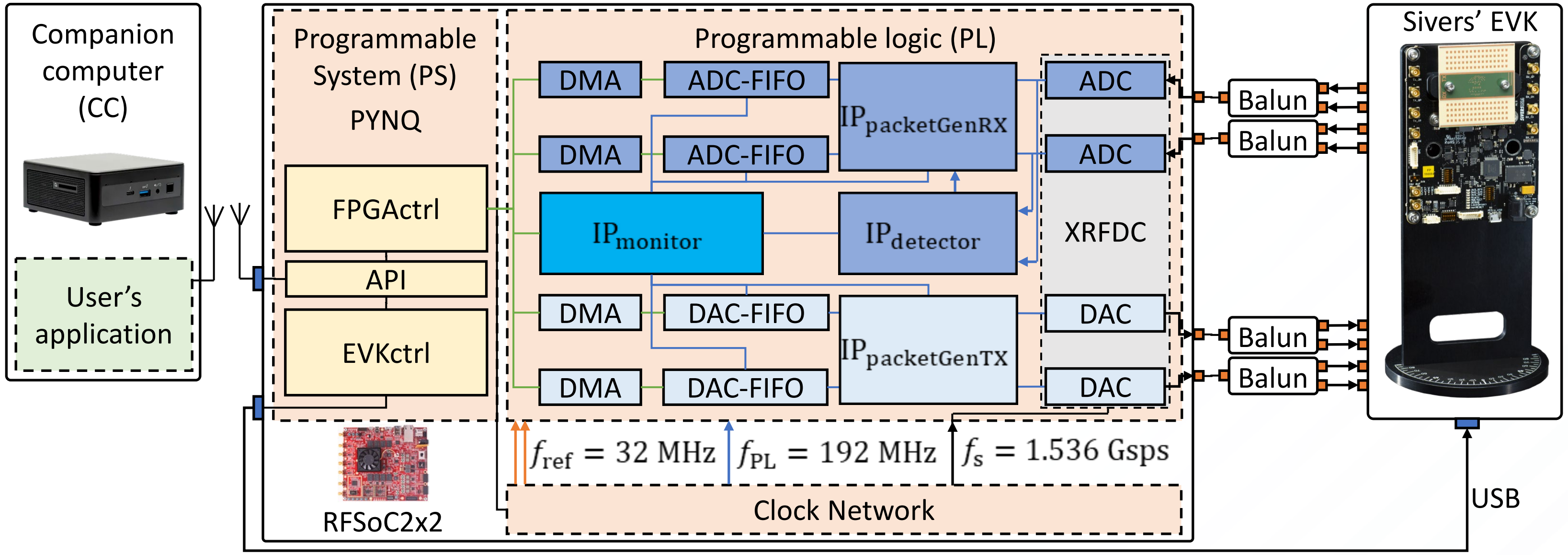


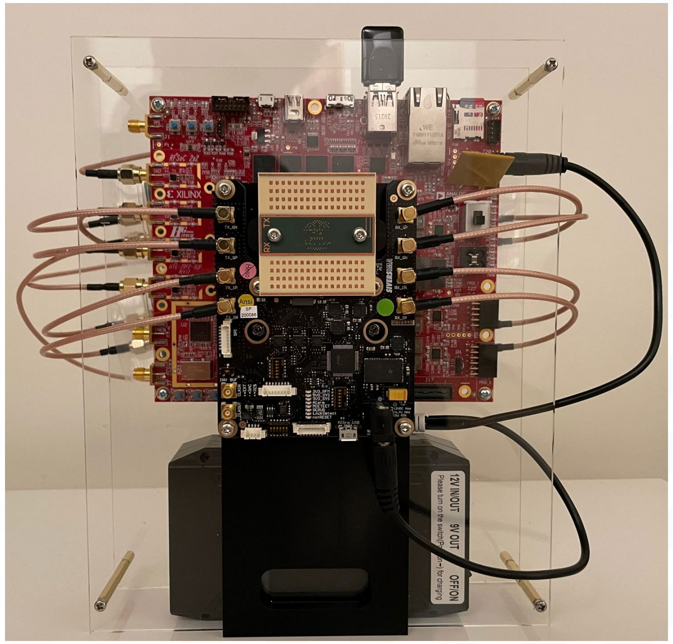
4G/5G NSA Ericsson Network at AERPAW



Lake Wheeler Field Labs

mmWave SDR Experiments (to be available in late Phase-3)





- A. Sahin, M. Sichitiu, I. Guvenc, "A Millimeter-Wave Software-Defined Radio for Wireless Experimentation," IEEE INFOCOM Workshops - Computer and Networking Experimental Research using Testbeds, May 2023

AERPAW's FCC Innovation Zone and Experimental Licenses

Frequency Band	Type of operation	Allocation	Fixed Station Maximum EIRP (dBm)	Mobile Station Maximum EIRP (dBm)
617-634.5 MHz (DL)	Fixed	Non-federal	65	-
663-698 MHz (UL)	Mobile	Non-federal	-	20
907.5-912.5 MHz	Fixed & Mobile	Shared	65	20
1755-1760 MHz (UL)	Mobile	Shared	-	20
2155-2160 MHz (DL)	Fixed	Non-federal	65	-
2390-2483.5 MHz	Fixed & Mobile	Shared	65	20
2500-2690 MHz[1,2]	Fixed & Mobile	Non-federal	65	20
3550-3700 MHz[1,2,3]	Fixed & Mobile	Shared	65	20
3700-3980 MHz[1,2]	Mobile	Non-federal	-	20
5850-5925 MHz	Fixed & Mobile	Shared	65	20
5925-7125 MHz[2]	Fixed & Mobile	Non-Federal	65	20
27.5-28.35 GHz	Fixed & Mobile	Non-federal	65	20
38.6-40.0 GHz	Fixed & Mobile	Non-federal	65	20

1 Commission rules do not permit airborne use on all or portions of these bands.

2 Any experimental use must be coordinated with authorized users and registered receive-only fixed satellite earth stations.

3 Operations must be coordinated with a spectrum access system administrator

Phase-1 GA Frequencies

SDR Experiments

- 3.3-3.55 GHz
- 902-928 MHz

New Phase-2 GA Frequencies

SDR Experiments

- 3.1-3.45 GHz (in process)

Ericsson Radio

- LTE: 1.7/2.1 GHz
- 5G NR (NSA): 3.4 GHz

LoRa

- 902-928 MHz

Keysight RF Sensors (Receive Only)

- 100 MHz – 6 GHz

New Phase-3 GA Frequencies

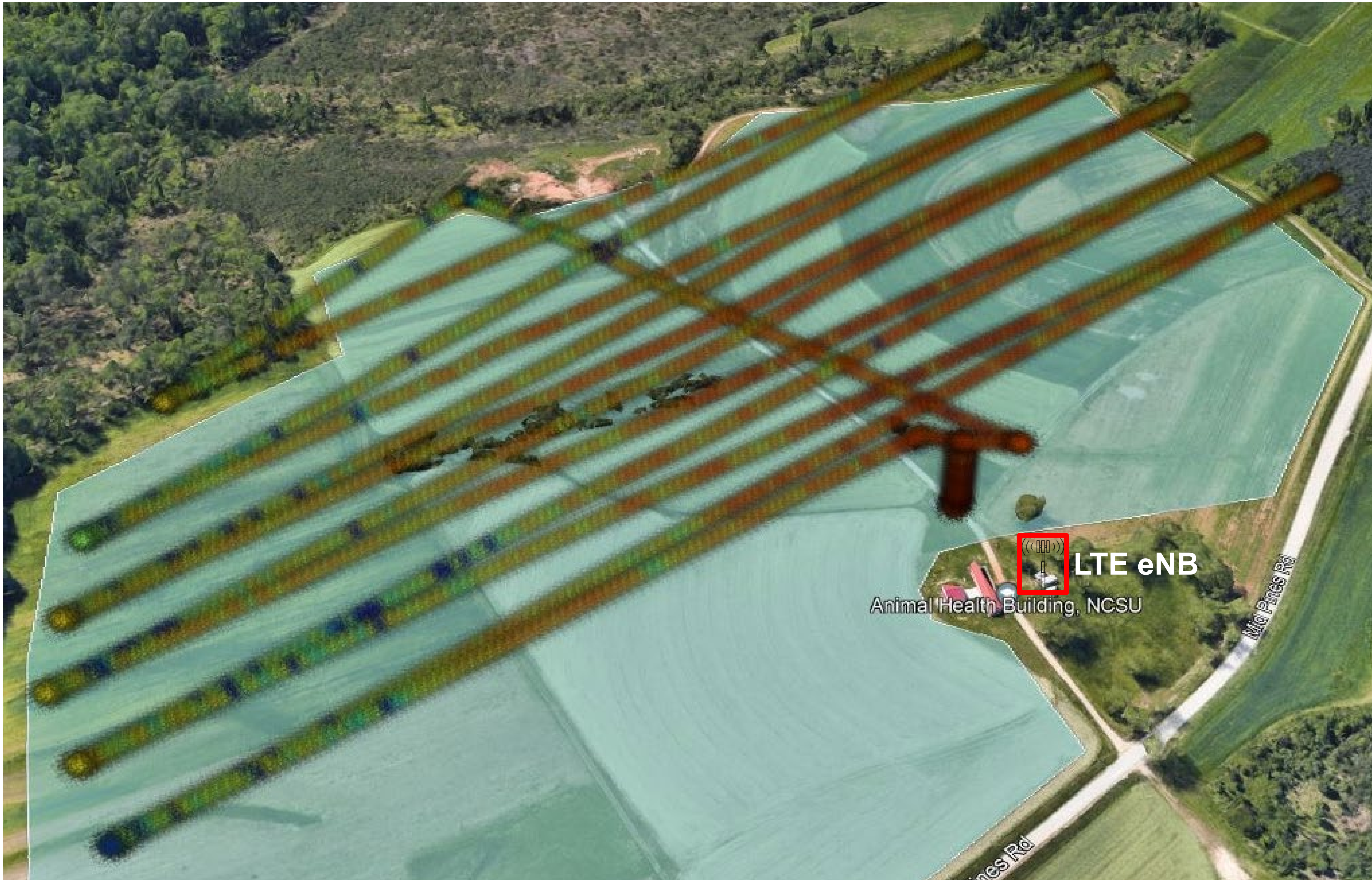
- 28 GHz (Sivers experiments)
- 5031-5090 MHz (planned)

AERPAW's FCC Call Sign: WK2XQH (searchable at: https://apps.fcc.gov/oetcf/els/reports/CallsignSearch.cfm)

Outline

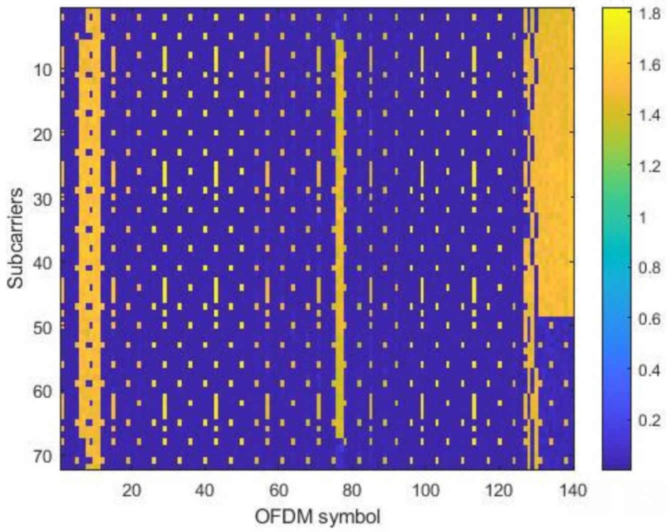
- AERPAW Overview and Deployment Areas
- AERPAW Phase-2 Platform Updates
- **Other Recent Platform Updates**

Sample Recent Results

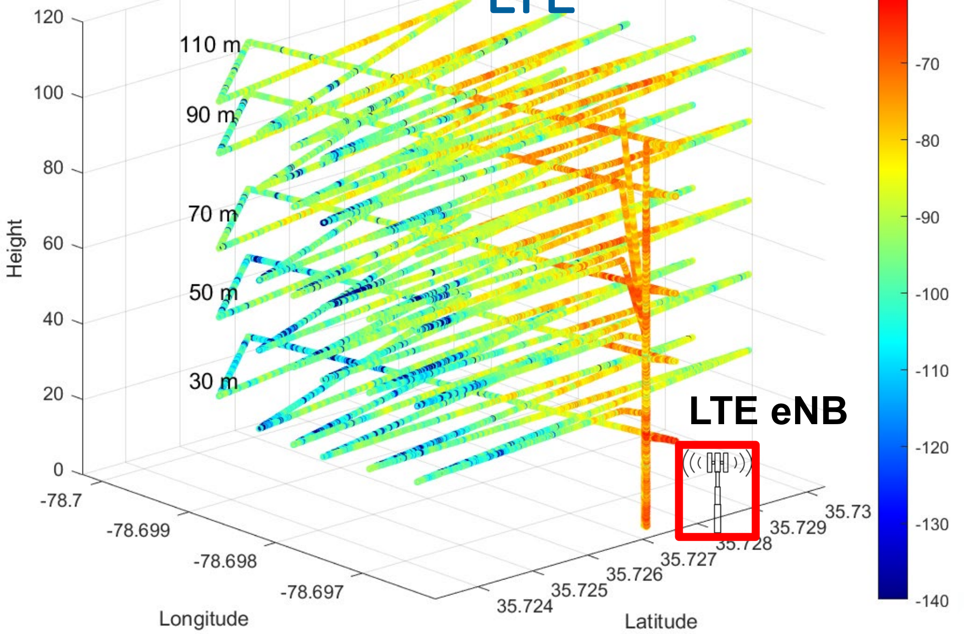


NRDZ UAV Testbed Experiments with 4G LTE

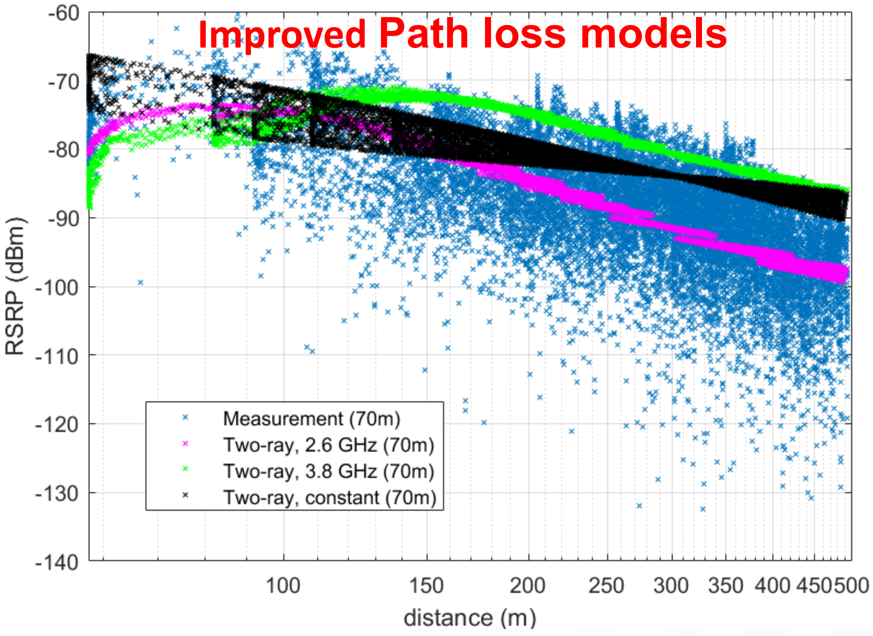
20 ms (2 LTE frames, high SNR)



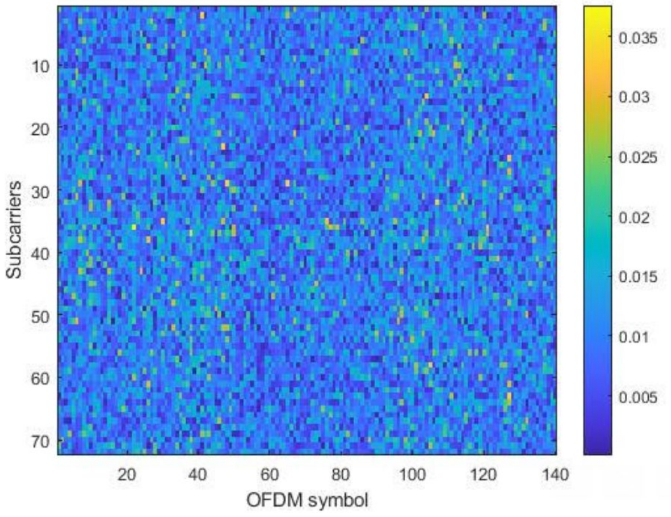
RSRP at different UAV altitudes

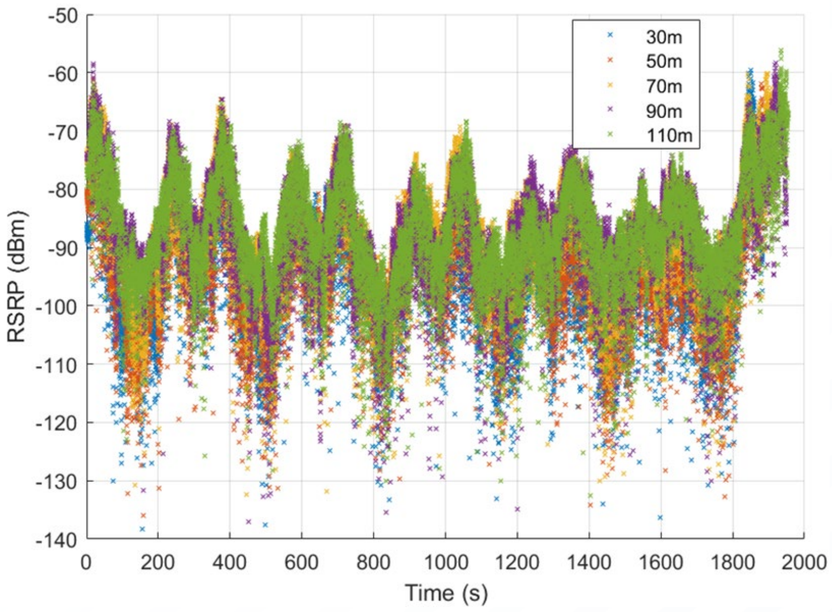


Improved Path loss models

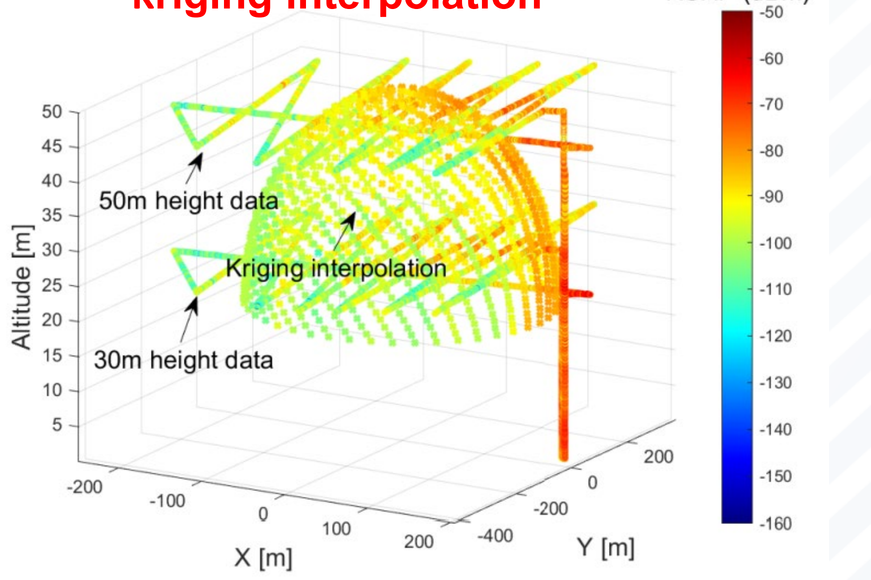


20 ms (2 LTE frames, low SNR)

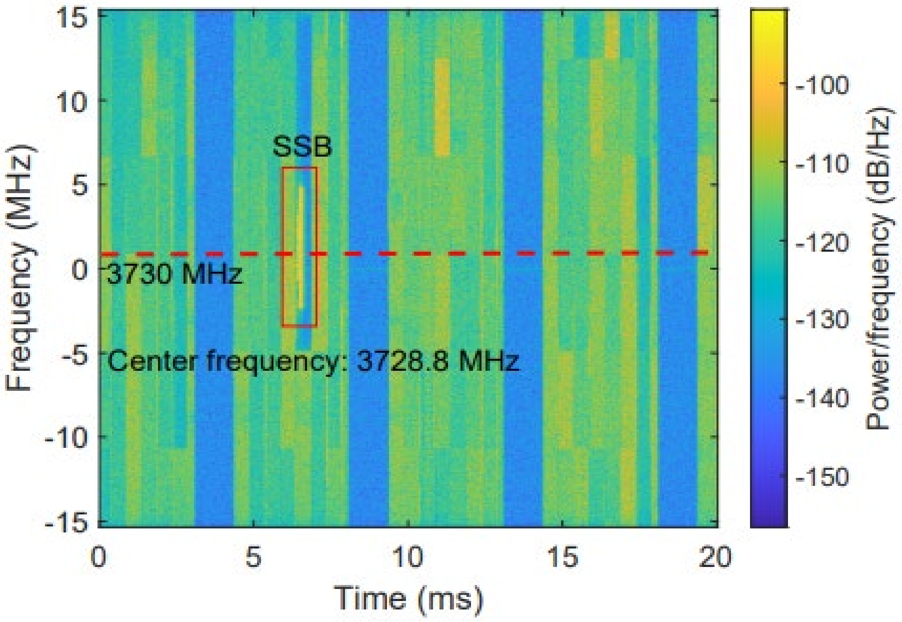


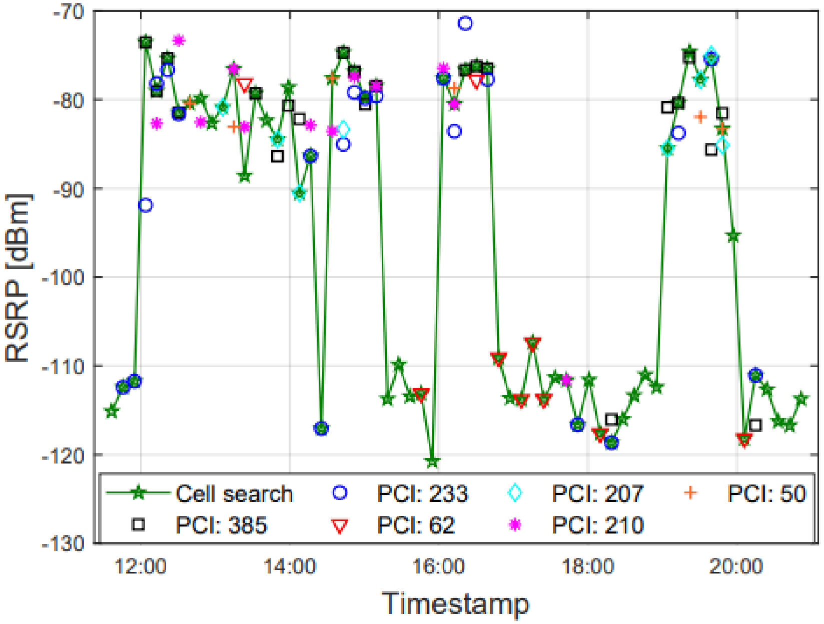


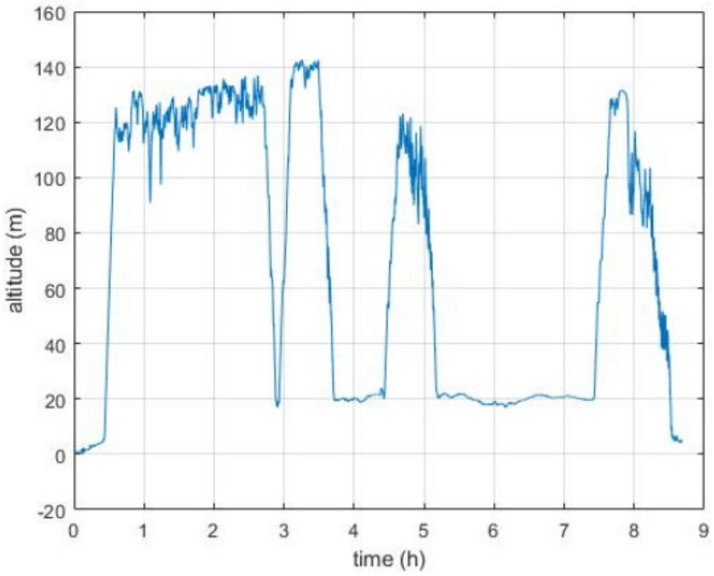
Kriging interpolation

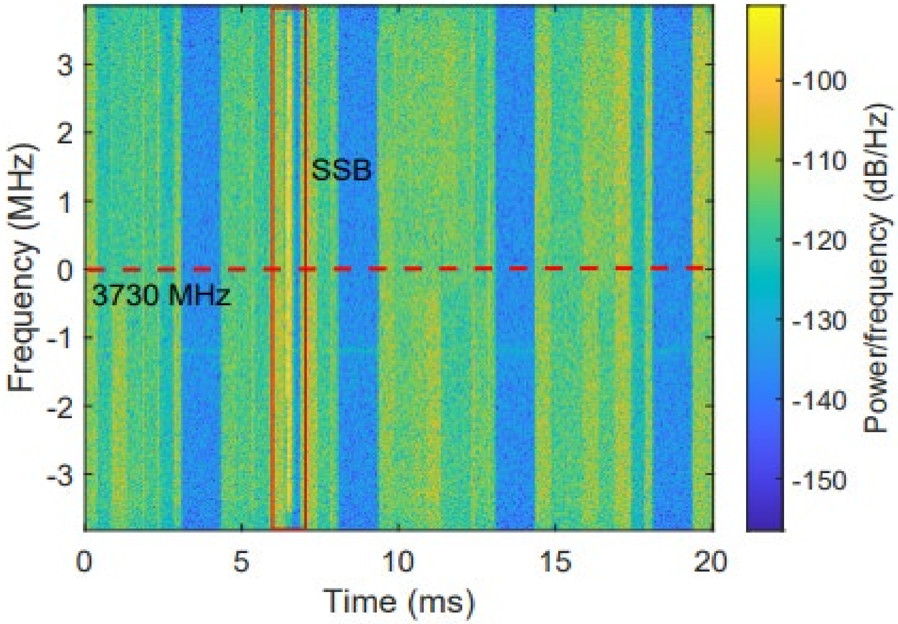


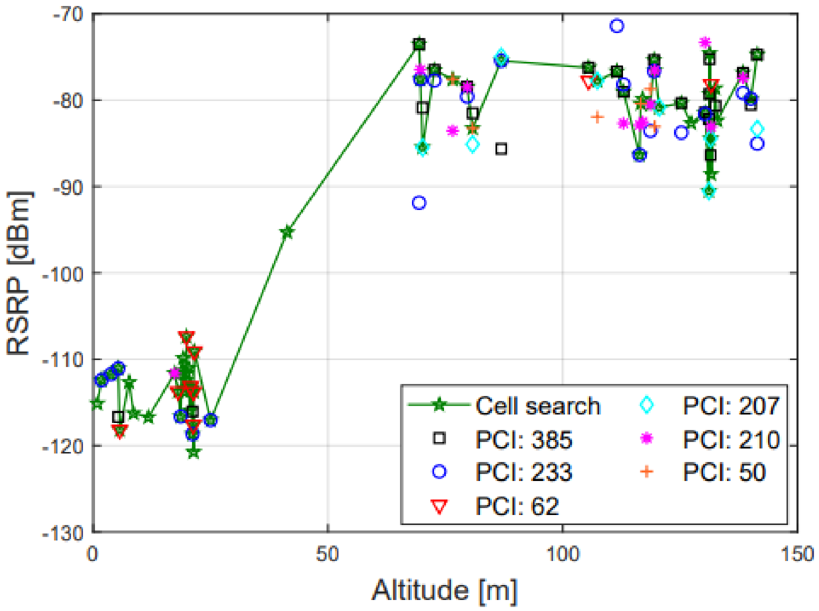
NRDZ UAV Testbed Experiments with 5G NR



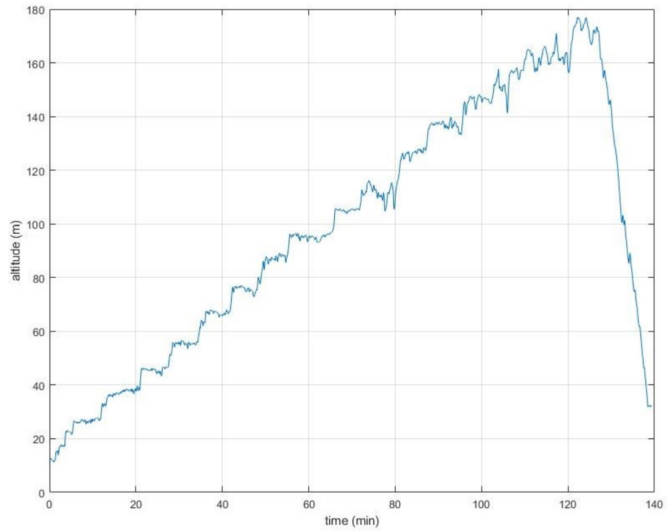


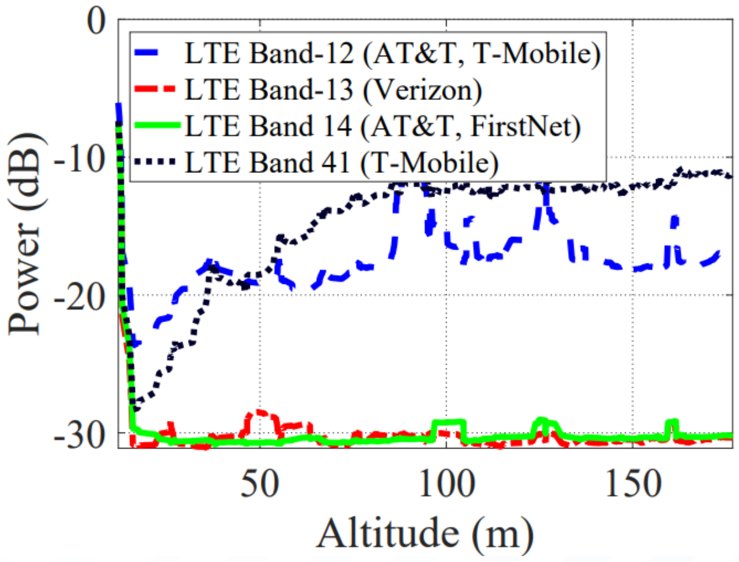


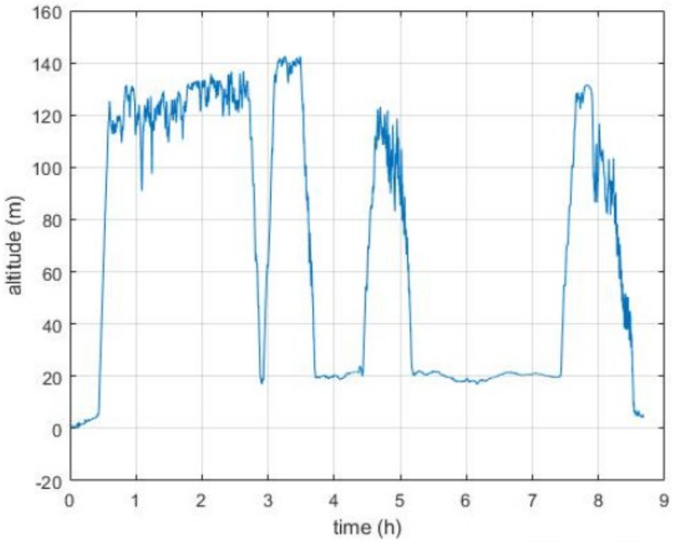


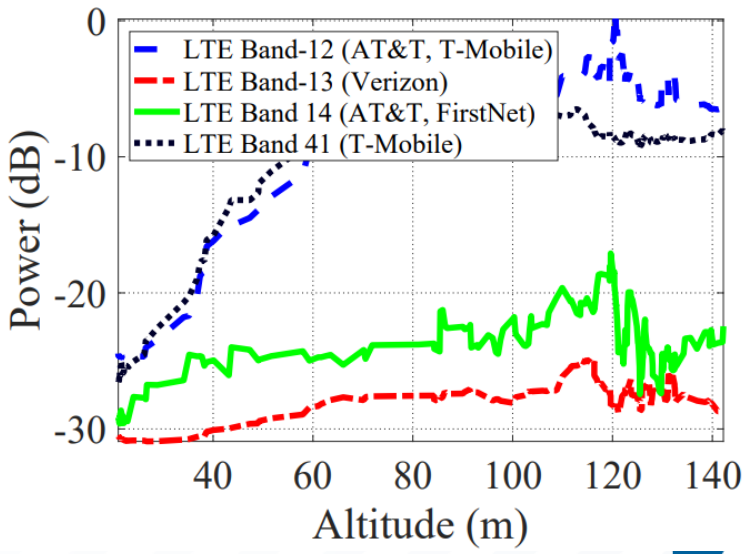


Spectrum Occupancy Measurements and Modeling in Rural & Urban Areas (1)



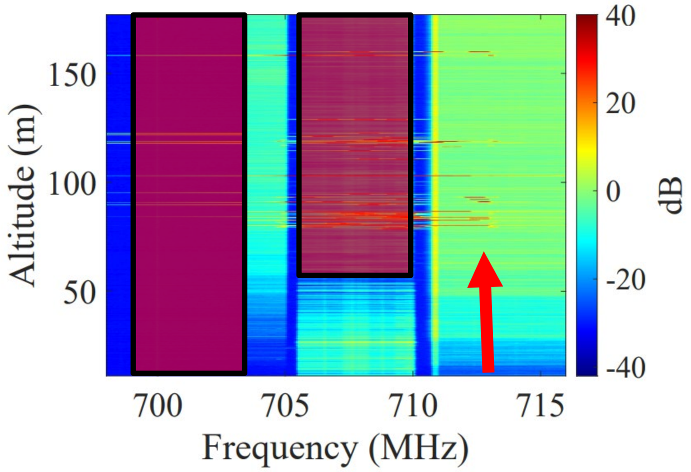




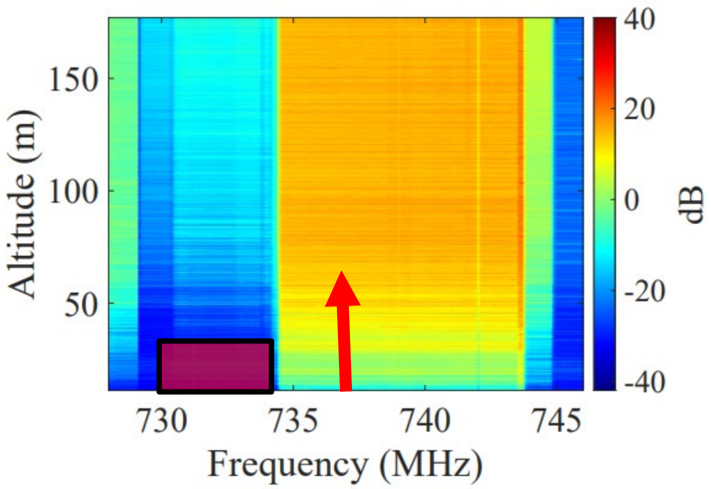


Connecting the Mobile World

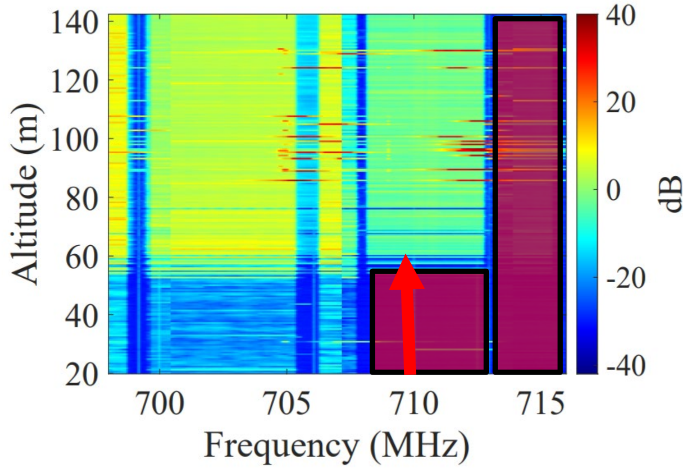
Spectrum Occupancy Measurements and Modeling in Rural & Urban Areas (2)



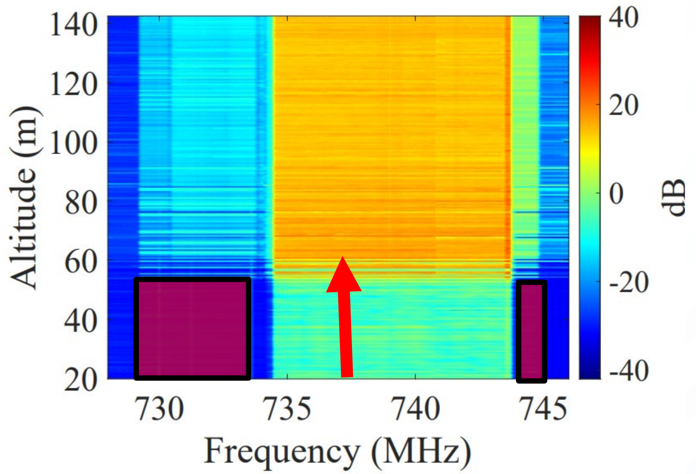
LTE band 12 (UL, Rural)



LTE band 12 (DL, Rural)



LTE band 12 (UL, Urban)

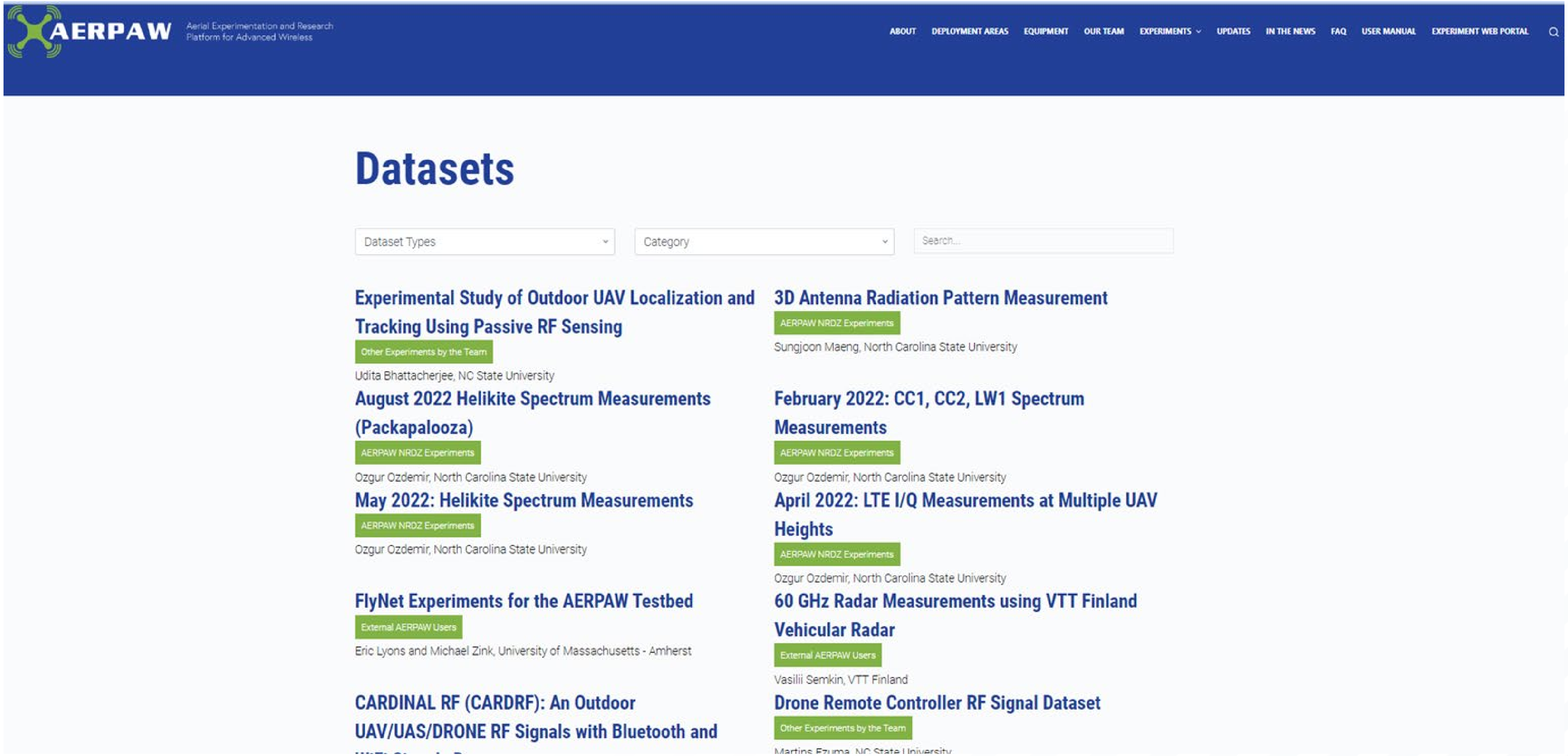


LTE band 12 (DL, Urban)

Rural vs. Urban Spectrum Utilization:

- Spectrum occupancy increases more gradually w.r.t. altitude in rural vs. urban
- Lower spectrum activity in rural areas vs. urban
- There may be pockets of spatio-temporal sharing opportunities in both, especially for uplink
- Similar observations in 5G bands

AERPAW Data Repository


AERPAW Aerial Experimentation and Research Platform for Advanced Wireless

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Datasets

Dataset Types | Category | Search...

Experimental Study of Outdoor UAV Localization and Tracking Using Passive RF Sensing
Other Experiments by the Team
Udita Bhattacherjee, NC State University

3D Antenna Radiation Pattern Measurement
AERPAW NRDZ Experiments
Sungjoon Maeng, North Carolina State University

August 2022 Helikite Spectrum Measurements (Packapalooza)
AERPAW NRDZ Experiments
Ozgur Ozdemir, North Carolina State University

February 2022: CC1, CC2, LW1 Spectrum Measurements
AERPAW NRDZ Experiments
Ozgur Ozdemir, North Carolina State University

May 2022: Helikite Spectrum Measurements
AERPAW NRDZ Experiments
Ozgur Ozdemir, North Carolina State University

April 2022: LTE I/Q Measurements at Multiple UAV Heights
AERPAW NRDZ Experiments
Ozgur Ozdemir, North Carolina State University

FlyNet Experiments for the AERPAW Testbed
External AERPAW Users
Eric Lyons and Michael Zink, University of Massachusetts - Amherst

60 GHz Radar Measurements using VTT Finland Vehicular Radar
External AERPAW Users
Vasilii Semkin, VTT Finland

CARDINAL RF (CARDRF): An Outdoor UAV/UAS/DRONE RF Signals with Bluetooth and

Drone Remote Controller RF Signal Dataset
Other Experiments by the Team

https://aerpaw.org/experiments/datasets/

IEEE VTS Connecting the Mobile World

Tutorial Videos on Example Experiments

Recording	Duration
Tutorial 1: Getting started with AERPAW	5:48
Tutorial 2: Creating a project (for PIs)	4:58
Tutorial 3: Creating experiment and initiating development	6:28
Tutorial 4: Part-1: Accessing virtual experiment nodes	5:12
Tutorial 4: Part-2: Accessing virtual experiment nodes	3:58
Tutorial 5: AERPAW OEO Overview	15:15
Tutorial 6 - Part 1: Programming AERPAW Vehicles	5:10
Tutorial 6 - Part 2: Preplanned Trajectory	8:28
Tutorial 7: Programming AERPAW Radio Software	7:35
Tutorial 8: Programming AERPAW Traffic Generation Software	4:01
Tutorial 9: SE1: Part-1: srsRAN LTE Radio Experiment without Vehicles	8:01
Tutorial 9: SE1: Part-2: srsRAN LTE Radio Experiment with Vehicles	5:33
Tutorial 10: GE1: Part-1: OFDM TX/RX Experiment without Vehicles	7:12
Tutorial 10: GE1: Part-2: OFDM TX/RX Experiment with Vehicles	4:39
Tutorial 11: GE2: GNU Radio Channel Sounder Experiment with Vehicles	1:01:42
Tutorial 12 Part-1: UHD2: I/Q Sample Collection Experiment with Vehicles and SE1: srsRAN LTE	8:23
Tutorial 12 Part-2: Post Processing I/Q Sample Collection Experiment Using Real World Data from IEEE Dataport Using Matlab's 4G Toolbox	13:29
Tutorial 13 Part-1: UHD2: I/Q Sample Collection Experiment with Vehicles and SE6: 5G NR	5:34
Tutorial 13 Part-2: Post Processing I/Q Sample Collection Experiment from 5G NR Ericsson Real-World Network Using Matlab's 5G Toolbox	12:10
Tutorial 14 - Manual Drone Flight (Optional)	6:03
Tutorial 15: SE4 srsRAN NB-IoT experiment with vehicles	4:57

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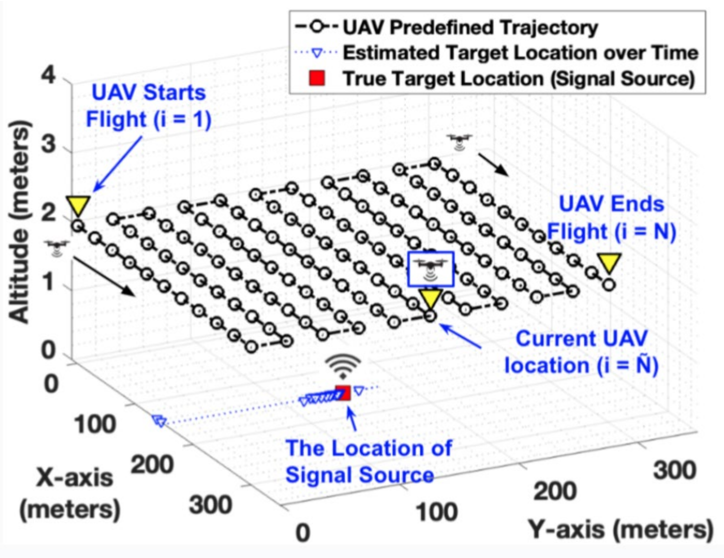
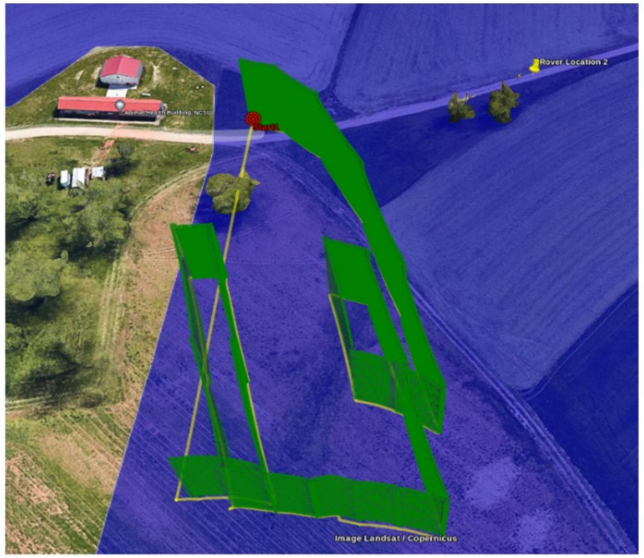
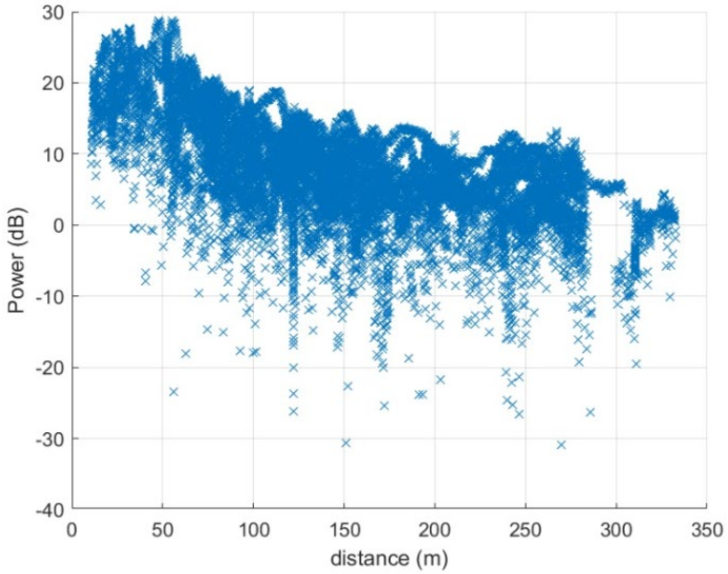
AERPAW Find a Rover (AFAR) Challenge

- https://aerpaw.org/aerpaw-afar-challenge/
  - **1st Place Award:** $1500, **2nd Place Award:** $1000, and **3rd Place Award:** $500
  - **Application Deadline:** June 15, 2023
  - **First Round Submissions in Emulation Environment:** August 15, 2023
  - **Final Round (Testbed) Evaluation:** September 1, 2023
    - Criteria-1: Localization accuracy with fixed flight time (LAFFT)
    - Criteria-2: Localization time with fixed localization accuracy (LTFLA)







AERPAW Community Workshop (ACW)

May 8-11, 2023, Raleigh, NC

Website: https://aerpaw.org/acw2023/

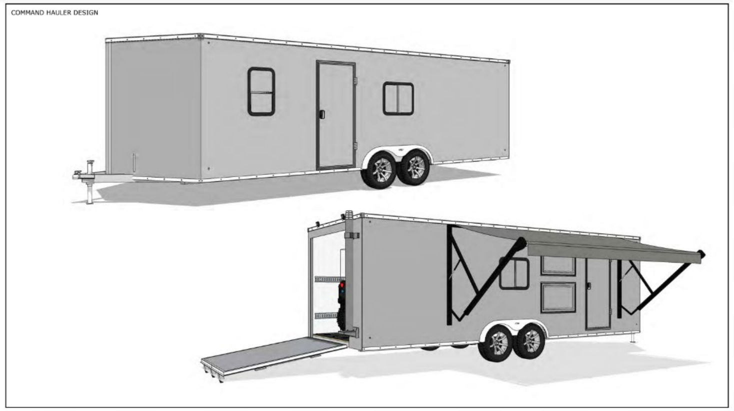
AERPAW Phase-3 Plans (Exp: Aug. 2024)

New SDR Example Experiments

- Multi-UAV communication (3 UAVs)
- UAV-UGV communication (2 UAVs + 1 UGV)
- High-speed (up to 30 m/s) UAV flight for channel quality evaluation
- RF monitoring with UAV accessing prohibited band
- UAV as a base station for UGV communication
- Handover between Ericsson base station (BS) and SDR base station
- O-RAN and UAV slicing and trajectory control experiment

Non-SDR Example Experiments and New Hardware

- Tracking UAVs passively using Keysight RF sensors
- mmWave beam tracking with Sivers phased arrays and UAVs
- LoRa and UAV based sensor data acquisition and UAV trajectory optimization
- New Ericsson 5G experiments

Drone Operations Center (Trailer)

AERPAW Sandbox

New Drone Competitions

Questions

- **AERPAW Website:** https://aerpaw.org/
- **AERPAW Contact Email:** aerpaw-contact@ncsu.edu
- **AERPAW Users Email Group (User Manual Section 2.7):** https://sites.google.com/ncsu.edu/aerpaw-wiki/aerpaw-user-manual/2-experiment-lifecycle-workflows/2-7-user-support
- **AERPAW AFAR Competition:** https://aerpaw.org/aerpaw-afar-challenge/

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