WEBINAR SERIES ON ADVANCED MOBILITY
Acknowledgement

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

June 6, 2023

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https://aerpaw.org/
Outline

- AERPAW Overview and Deployment Areas
- AERPAW Phase-2 Platform Updates
- Other Recent Platform Updates
Many promising academic ideas do not get tested in the field for long while (NOT low-hanging fruit)
“Valley of Death” for Wireless Research

“ALL models are wrong, but SOME models are useful.” – George Box

Driven by publications and citations

Driven by revenue
NSF Platforms for Advanced Wireless Research (PAWR)

**POWDER**
Salt Lake City, UT
Software defined networks and massive MIMO
AVAILABLE TODAY !!

**COSMOS**
West Harlem, NY
Millimeter wave and backhaul research
AVAILABLE TODAY !!

**COLOSSEUM**
Northeastern University, MA
Large-scale wireless emulation
AVAILABLE TODAY !!

**ARA**
Ames, IA
Rural broadband wireless
To be Available in 2023

Phase-1 Availability: Nov. 2021
Phase-2 Availability (Expected): Aug. 2023
Advanced Wireless Research for Unmanned Aerial Vehicles

Image source: Ericsson
AERPAW Project Team and Partners

- Ismail Guvenc: PI, NC State (SDRs, 4G/5G standards, PhyzMAC)
- Rudra Dutta: NC State (SDN, architecture, CentIMesh)
- Mihail Sichitiu: NC State (drones, architecture, CentIMesh)
- 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)

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 Gorgie
- 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

- 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., WRC (RF, Towers, & Platform Ops.))
- Mike Barts: WRC (4G/5G Ericsson deployment)
- Asokan Ram: WRC (4G/5G Ericsson deployment)

- Alphan Sahin, USC: mmWave Development
- Andrew Balmos, Purdue: LoRa Development
- Mark Funderburk, NC State: UAV/UGV Development
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
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
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)

- Traffic Generator
- Vehicle Control Application
- IQ Wireless Channel Emulator (CHEM)
- Radio Software
- Vehicle Software In The Loop (SITL)
- E-VM - Portable Node
- E-VM - Fixed Node

- Traffic Out → Traffic In
- Radio Signals Out → Radio Signals In
- Commands
- Status

- Ping, iPerf
- srsRAN, OAI, GNURadio, Python scripts
- QGroundControl
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

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
AERPAW Sample Plan Files for Phase-1 Fixed Node Footprint

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

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

Vehicle Control Application
  - AERPAW Vehicle Library
  - DroneKit
  - pymavlink

MAVLink
  - MAVLink Commands
  - MAVLink Filtered Commands
  - MAVLink Status

Autopilot Firmware (ArduPilot)

MAVLink
  - MAVLink Commands
  - MAVLink Status

Increased Flexibility

Experimenter Code
  - AERPAW Code
  - Open Source Code
LoRa and Keysight RF Sensor Phase-2 Deployments

Keysight RF Sensors

LoRa Gateways

Lake Wheeler Field Labs

Centennial Campus
4G/5G NSA Ericsson Network at AERPAW
mmWave SDR Experiments (to be available in late Phase-3)

# AERPAW’s FCC Innovation Zone and Experimental Licenses

## Phase-1 GA Frequencies

### SDR Experiments
- 3.3-3.55 GHz
- 902-928 MHz

## New Phase-3 GA Frequencies

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

## 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

## Frequency Table

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Type of operation</th>
<th>Allocation</th>
<th>Fixed Station Maximum EIRP (dBm)</th>
<th>Mobile Station Maximum EIRP (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>617-634.5 MHz (DL)</td>
<td>Fixed</td>
<td>Non-federal</td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>663-698 MHz (UL)</td>
<td>Mobile</td>
<td>Non-federal</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>907.5-912.5 MHz</td>
<td>Fixed &amp; Mobile</td>
<td>Shared</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>1755-1760 MHz (UL)</td>
<td>Mobile</td>
<td>Shared</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>2155-2160 MHz (DL)</td>
<td>Fixed</td>
<td>Non-federal</td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>2390-2483.5 MHz</td>
<td>Fixed &amp; Mobile</td>
<td>Shared</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>2500-2690 MHz</td>
<td>Fixed &amp; Mobile</td>
<td>Non-federal</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>3550-3700 MHz</td>
<td>Fixed &amp; Mobile</td>
<td>Shared</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>3700-3980 MHz</td>
<td>Mobile</td>
<td>Non-federal</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>5850-5925 MHz</td>
<td>Fixed &amp; Mobile</td>
<td>Shared</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>5925-7125 MHz</td>
<td>Fixed &amp; Mobile</td>
<td>Non-Federal</td>
<td>65</td>
<td>20</td>
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<tr>
<td>27.5-28.35 GHz</td>
<td>Fixed &amp; Mobile</td>
<td>Non-federal</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>38.6-40.0 GHz</td>
<td>Fixed &amp; Mobile</td>
<td>Non-federal</td>
<td>65</td>
<td>20</td>
</tr>
</tbody>
</table>

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.

### AERPAW’s FCC Call Sign: WK2XQH (searchable at: [https://apps.fcc.gov/oetcf/els/reports/CallsignSearch.cfm](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

20 ms (2 LTE frames, high SNR)

RSRP at different UAV altitudes

Improved Path loss models

Kriging interpolation

20 ms (2 LTE frames, low SNR)
NRDZ UAV Testbed Experiments with 5G NR
Spectrum Occupancy Measurements and Modeling in Rural & Urban Areas (1)
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

https://aerpaw.org/experiments/datasets/
## Tutorial Videos on Example Experiments

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

- [https://aerpaw.org/aerpaw-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/](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](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/](https://aerpaw.org/aerpaw-afar-challenge/)
Join IEEE VTS at www.vtsociety.org

Follow IEEE VTS on social media

Website
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LinkedIn
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