SPECTRUMX

Teaming Up to Advance Monitoring and Sharing of the Radio Frequency Spectrum

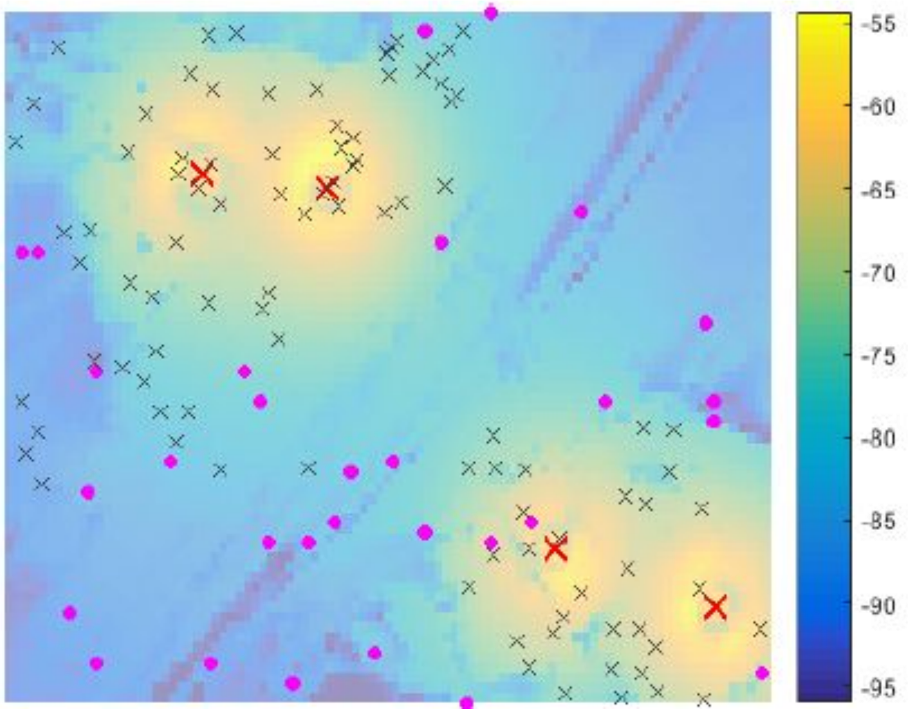
Dr. Nick Laneman, Center Director, Professor EE

IEEE ICC Workshop on Spectrum Sharing Technology for Next-Generation Communications
Seoul, Korea, May 16, 2022

WIRELESS INSTITUTE

UNIVERSITY OF NOTRE DAME

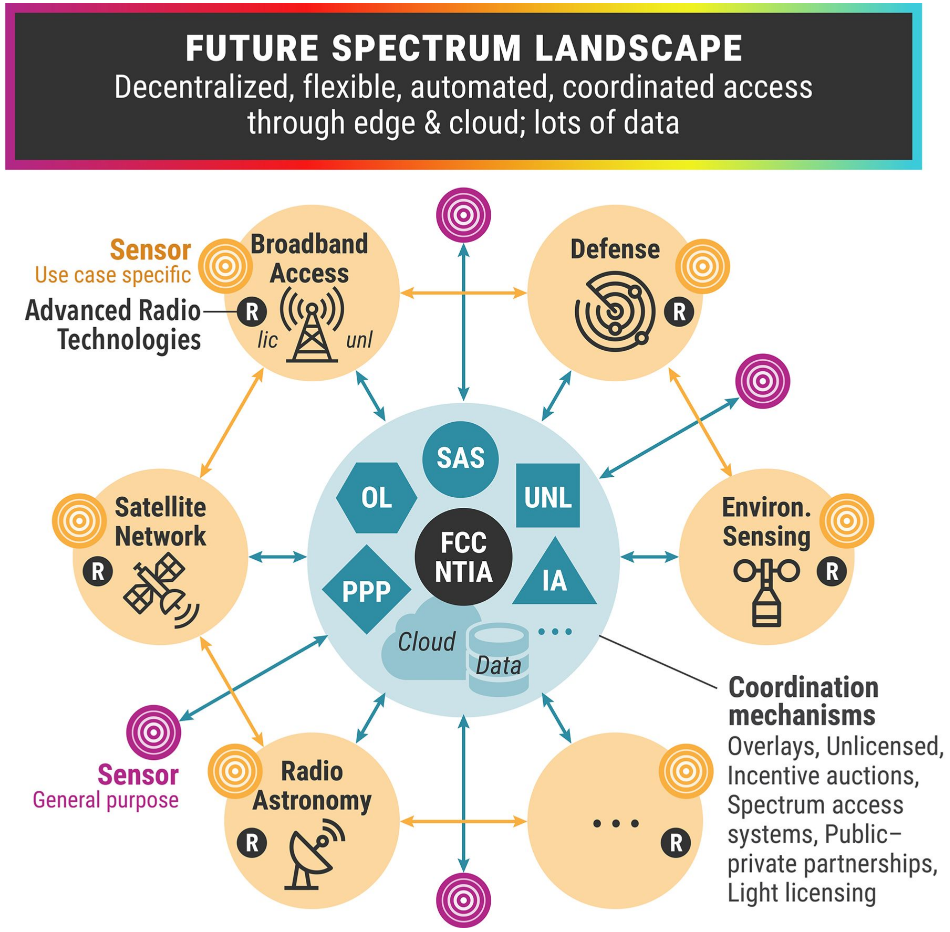
Vision: Widespread Spectrum Monitoring & Sharing



Many, Distributed Sensors
Measuring RF Spectrum Across
Frequency, Space, & Time

Low-SWaPC
Sensors,
Software,
Big Data

Models,
Algorithms,
Architectures,
Tradeoffs



Acknowledgements - ND Wireless Team

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Ph.D. Alum EE

Arash Ebadi Shahrivar
Ph.D. Alum EE

Nikolaus Kleber
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Co-Director, Prof EE

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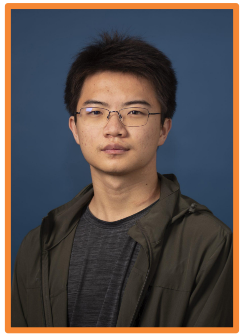
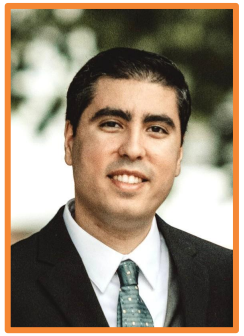
Asst Professor EE

Siddarth Joshi
Asst Professor CSE



Xiangbo Meng
Ph.D. Student EE



Gonzalo Martinez
Ph.D. Alum CSE

Xiwen Kang
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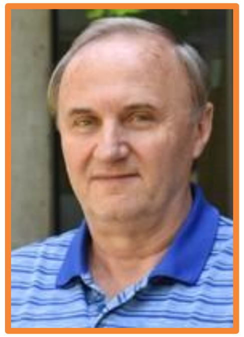
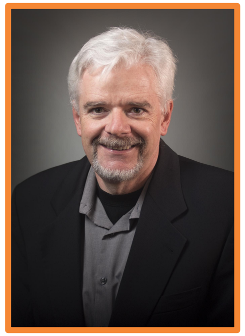


Pavle Kirilov
Hardware Engineer

Aaron Striegel
Professor CSE

Paul Brenner
Professor CSE

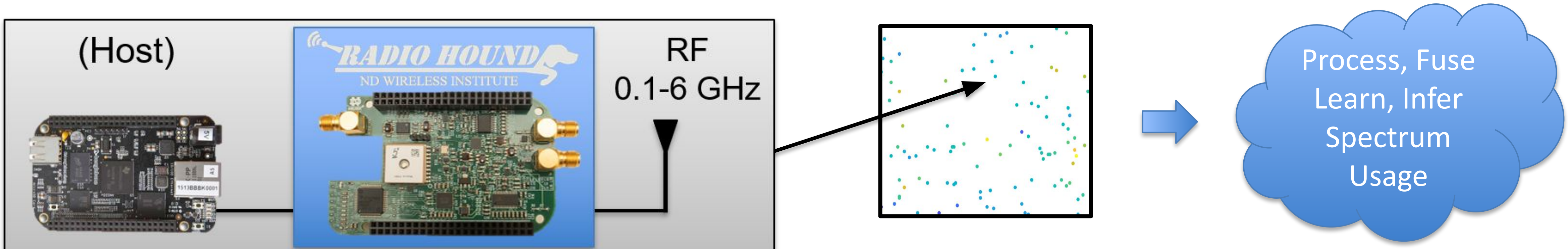


Martin Haenggi
Professor EE

Acknowledgements - Sponsors & Partners

RadioHound Project: Low-Cost Sensors + System

Sensor (V3)



Deployment

Motivation

- Understand spectrum usage patterns in time and space
  - Spectrum situational awareness to inform sharing mechanisms as well as regulatory policy
  - Requires truly large-scale deployments with hundreds or thousands of sensors

Objective

- Create a scalable spectrum sensing system to learn, detect and predict spectrum usage patterns

Approach

- Use low-cost, low-power sensors with a signal processing & machine learning backbone

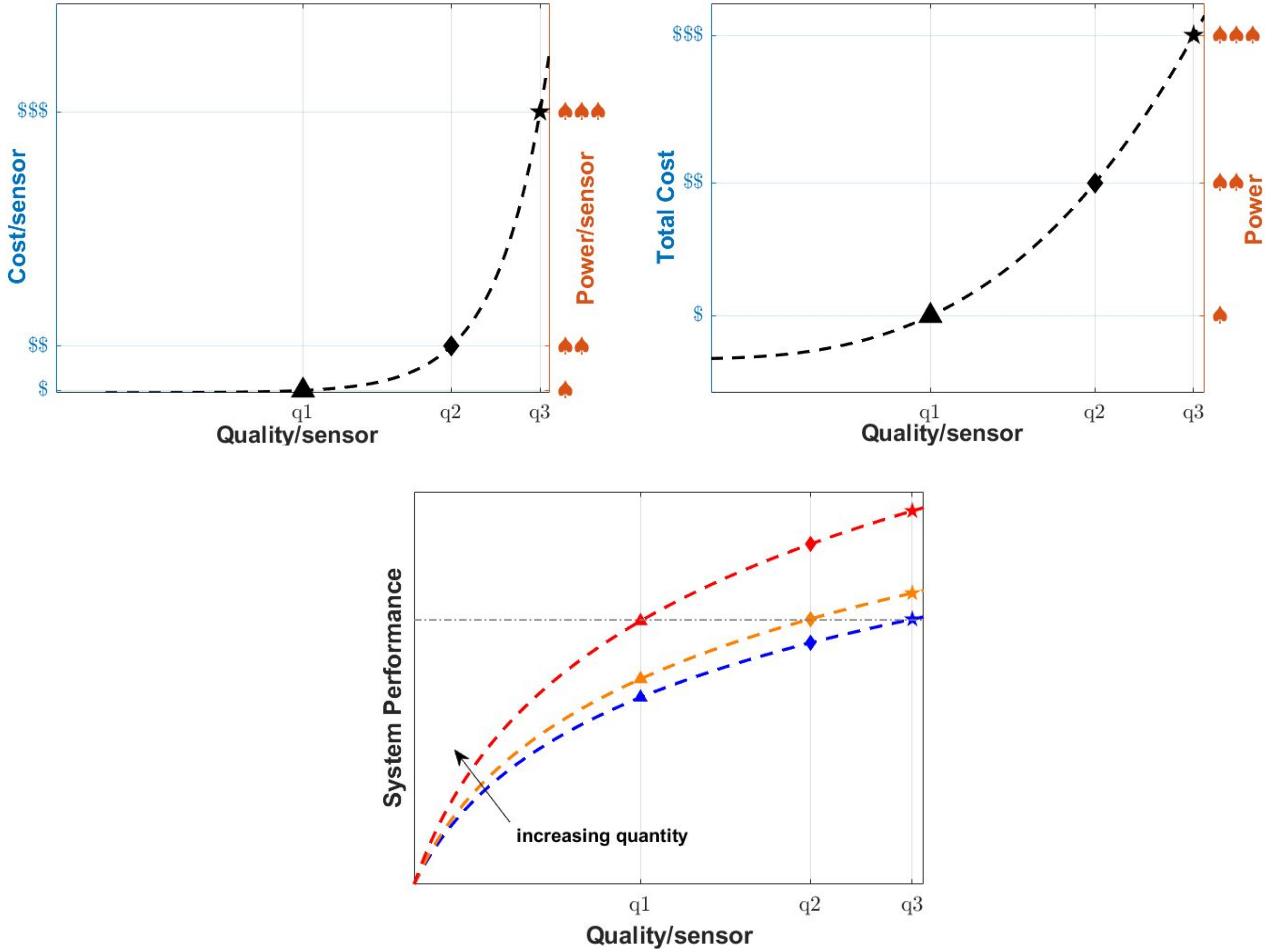
Quantity over Quality: Intuition

Intuition

- Lowering quality
  - reduces performance
  - decreases power consumption
  - cuts cost exponentially

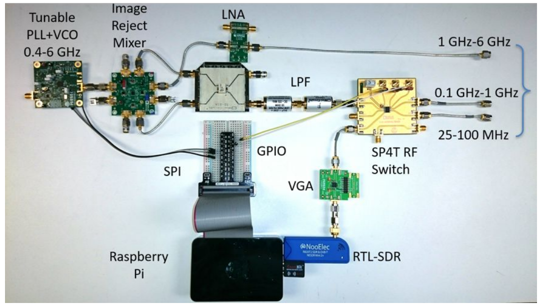
- Increasing quantity
  - compensates lost performance
  - does not affect power
  - increases cost linearly

Claim: Quantity increases slowly as quality decreases for a given performance.

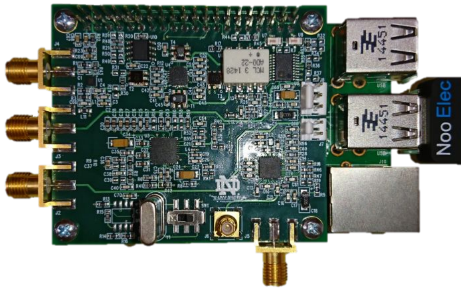


Work Stream 1: Sensor Development

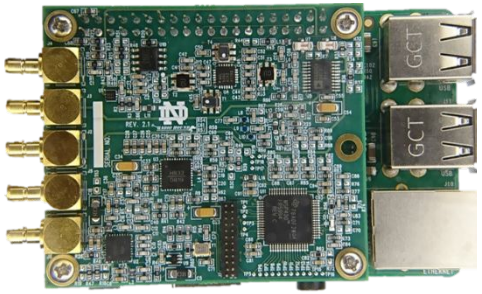
Initial V1 Prototype



V1



V2.1

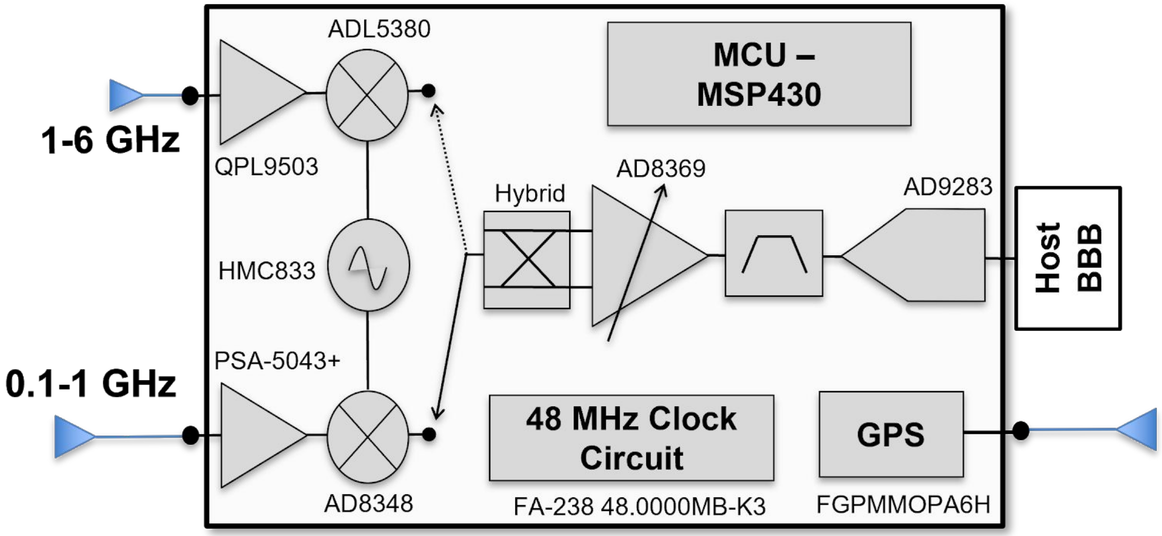


V3.3

	V1 (Nov 2016)	V2.1 (Apr 2018)	V3.3 (July 2022)
Tunable Range	25 MHz–6 GHz	25 MHz–6 GHz	100 MHz–6 GHz
Bandwidth	2 MHz	2 MHz	20 MHz
Power	5 W	4 W	3.5 W
Cost in parts	~$75	~$50	~$35
Key Features	Raspberry Pi	Raspberry Pi, MSP for Fast Tune	BeagleBone Black, On-board GPS and ADC
Status	20 units	100 units	100’s of units

Design & Specs V3.2

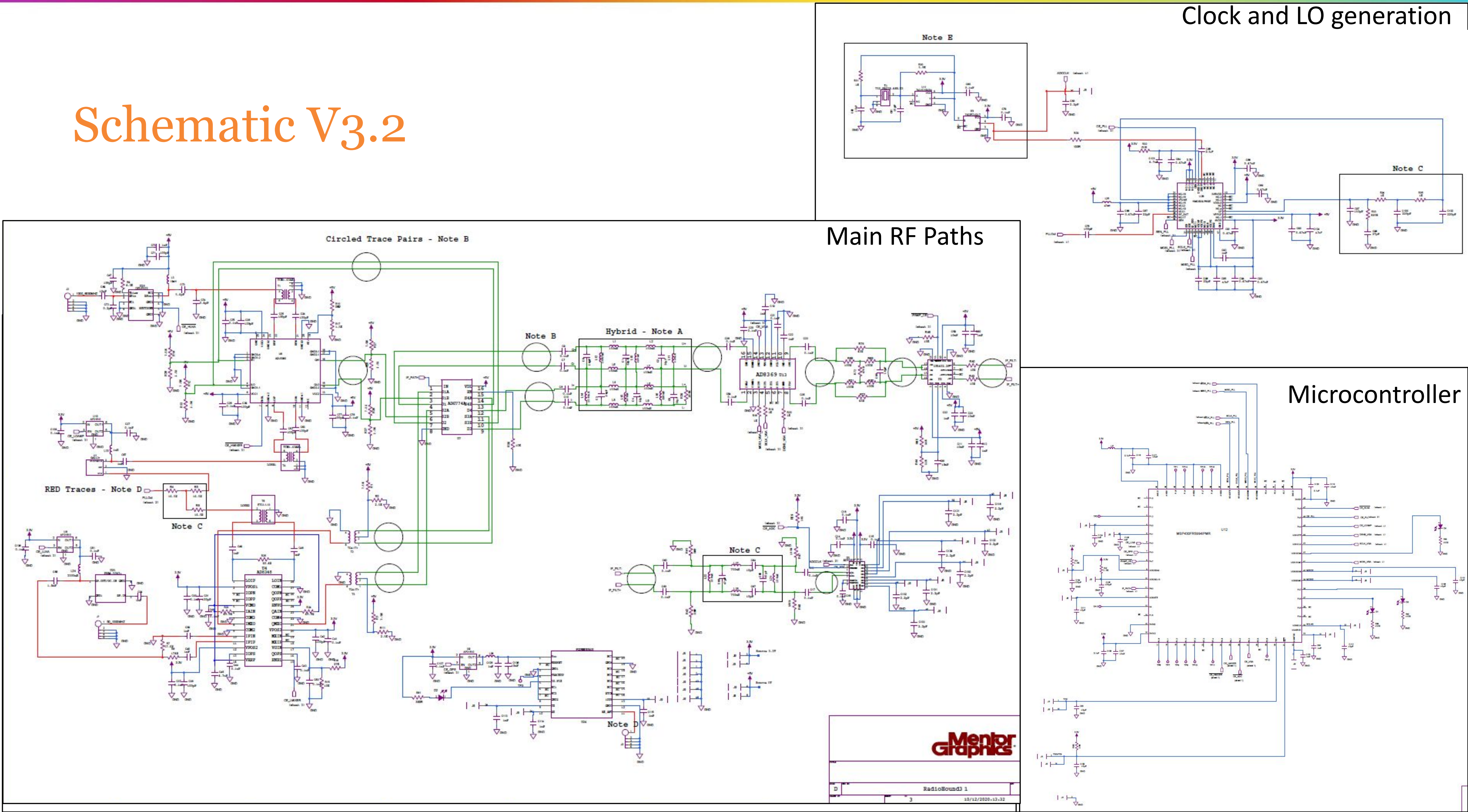
Parameter	Min	Typ	Max	Units	Comments
Supply Voltage		5		V	
RF Input Power	-110		-18	dBm	Variable gain adjusted to access entire range
RF Frequency	100		6000	MHz	Split across two antennas
IF Frequency		60		MHz	
Tunable Gain	-5		40	dB	On-Board VGA tunable gain
MDS		-110		dBm	
P1dB		-15		dBm	
Board Gain	35		80	dB	Decreases with frequency
Noise Figure	2		20	dB	Increasies with frequency



Dimensions set by BeagleBone Black footprint

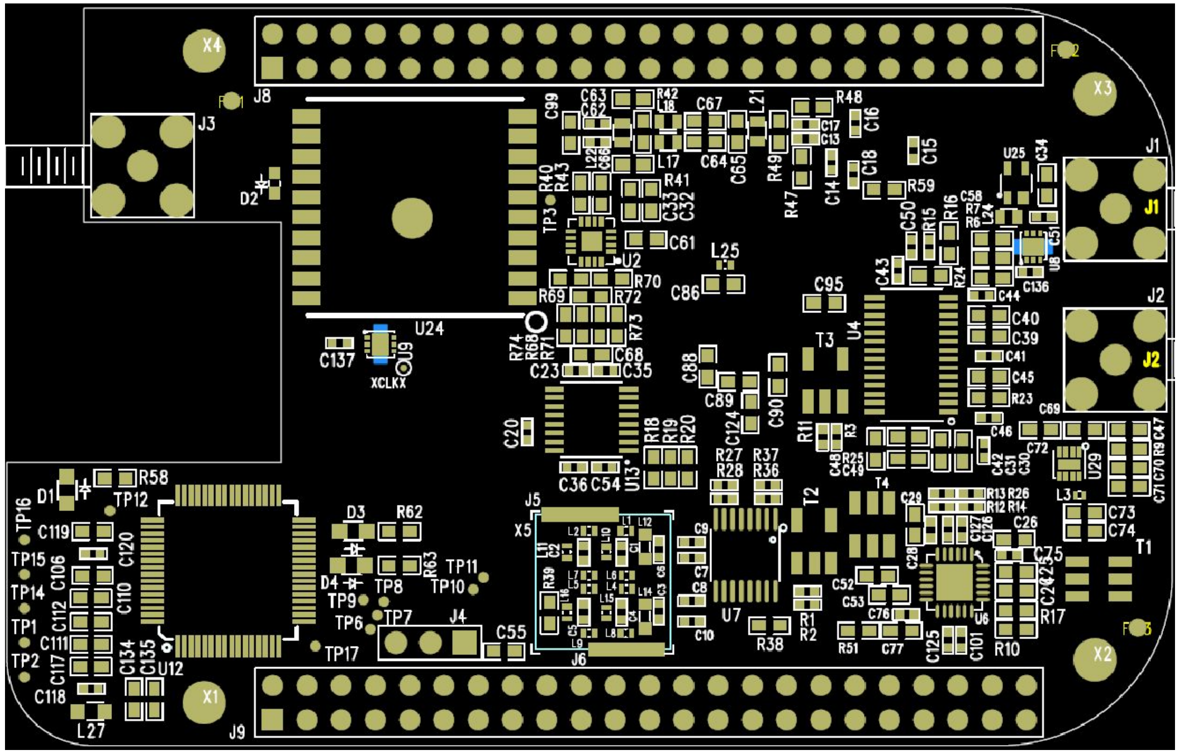
104mm x 55mm x 30mm (l, w, h)

Schematic V3.2

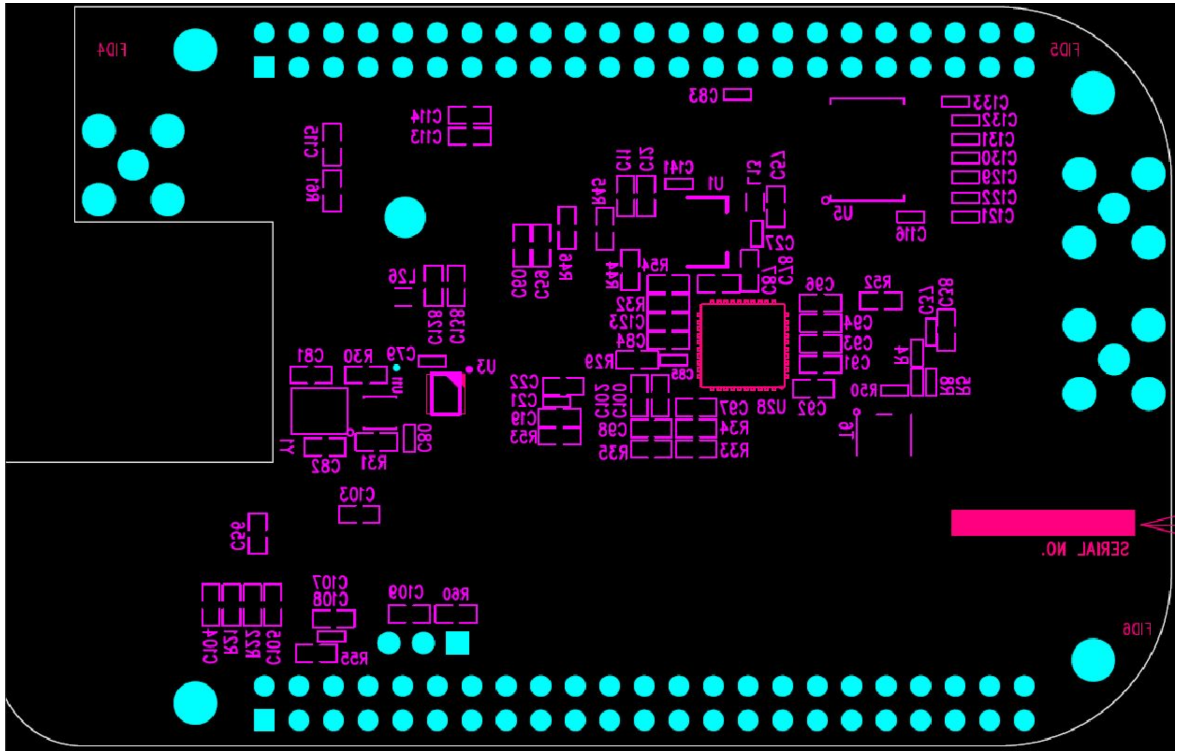


Layout V3.2: Assembly Layer

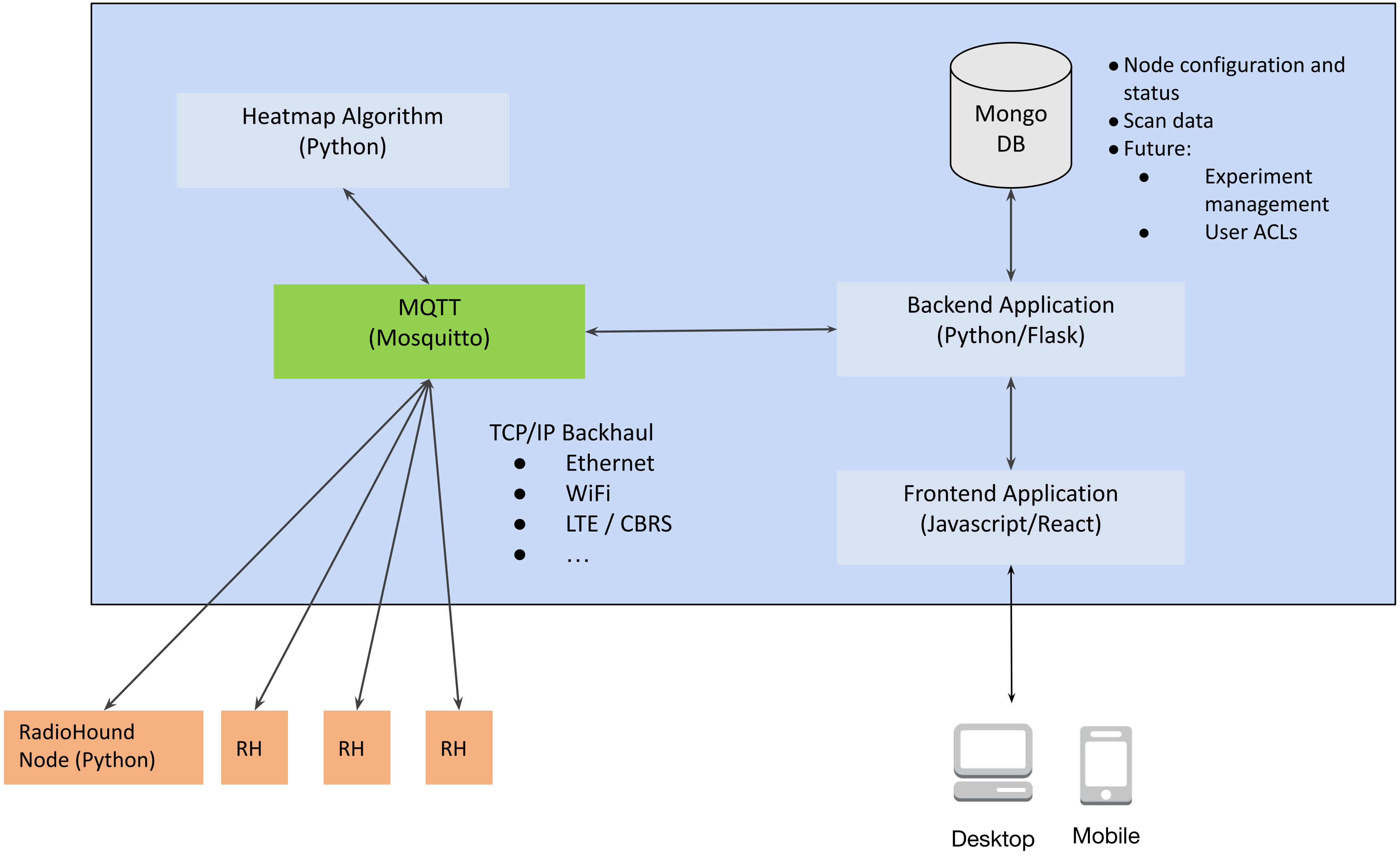
Top Side

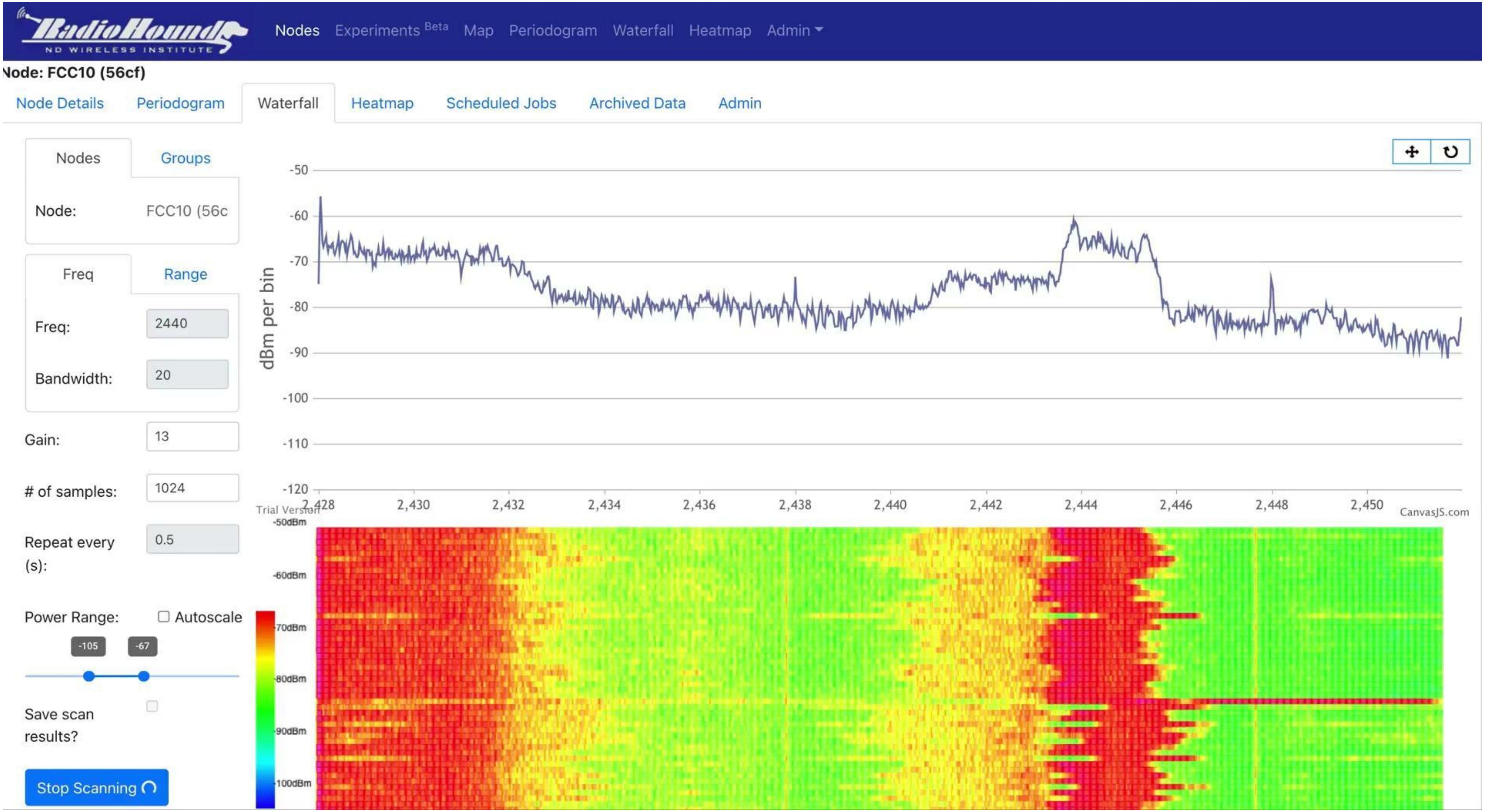


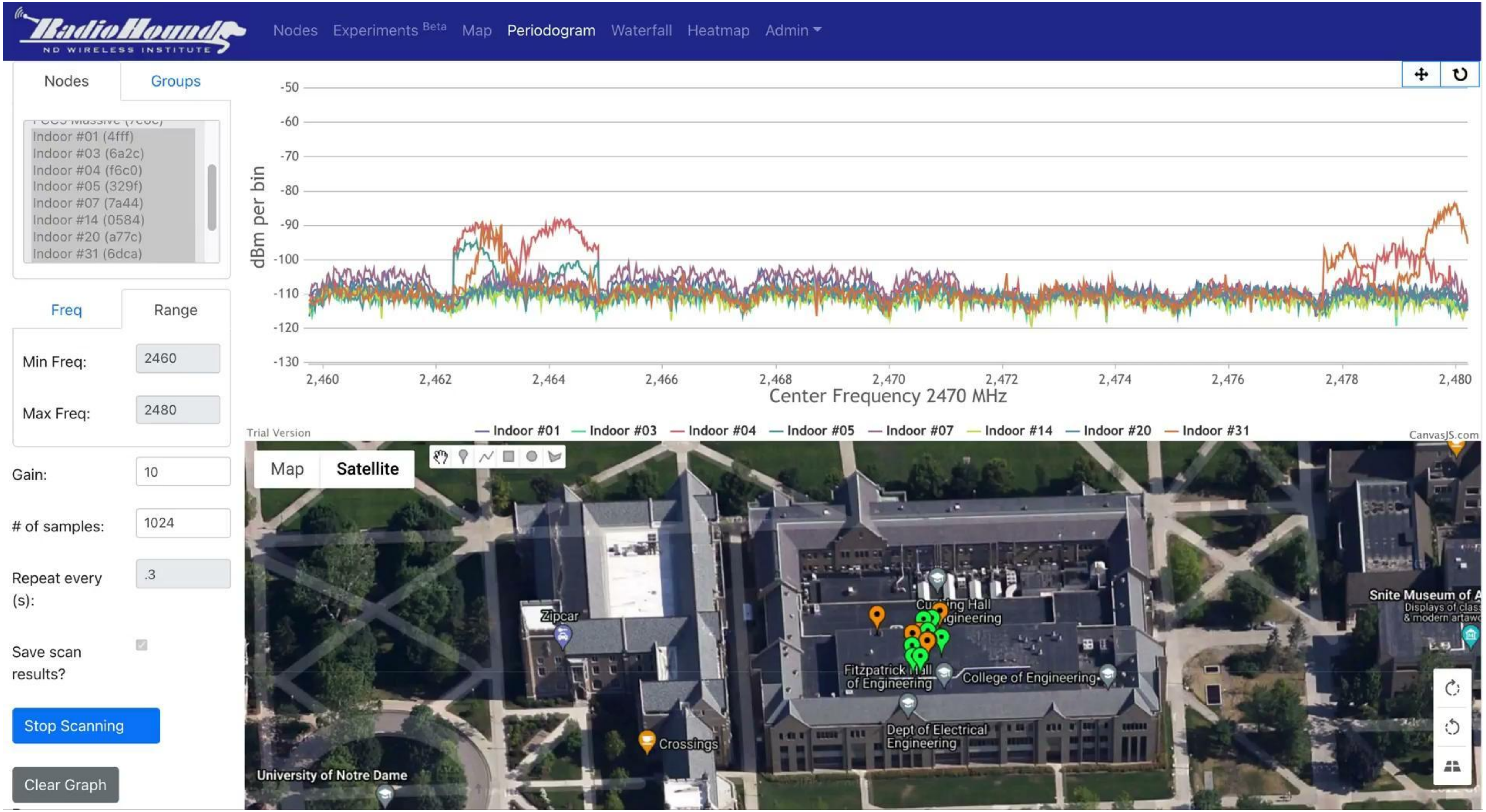
Bottom Side



Work Stream 2: Software Development




RadioHound
ND WIRELESS INSTITUTE
Nodes
Experiments Beta
Map
Periodogram
Waterfall
Heatmap
Admin
Node: FCC10 (56cf)
Node Details
Periodogram
Waterfall
Heatmap
Scheduled Jobs
Archived Data
Admin
Nodes
Groups
Node: FCC10 (56c
Freq
Range
Freq: 2440
Bandwidth: 20
Gain: 13
# of samples: 1024
Repeat every (s): 0.5
Power Range:
Autoscale
-105
-67
Save scan results?
Stop Scanning
dBm per bin
-50
-60
-70
-80
-90
-100
-110
-120
2,428
2,430
2,432
2,434
2,436
2,438
2,440
2,442
2,444
2,446
2,448
2,450
Trial Version
CanvasJS.com
-50dBm
-60dBm
-70dBm
-80dBm
-90dBm
-100dBm



RadioHound
ND WIRELESS INSTITUTE
Nodes
Experiments Beta
Map
Periodogram
Waterfall
Heatmap
Admin
Nodes
Groups
Indoor #01 (4fff)
Indoor #03 (6a2c)
Indoor #04 (f6c0)
Indoor #05 (329f)
Indoor #07 (7a44)
Indoor #14 (0584)
Indoor #20 (a77c)
Indoor #31 (6dca)
Freq
Range
Min Freq:
2460
Max Freq:
2480
Gain:
10
# of samples:
1024
Repeat every (s):
.3
Save scan results?
Stop Scanning
Clear Graph
dBm per bin
-50
-60
-70
-80
-90
-100
-110
-120
-130
2,460
2,462
2,464
2,466
2,468
2,470
2,472
2,474
2,476
2,478
2,480
Center Frequency 2470 MHz
Trial Version
Indoor #01
Indoor #03
Indoor #04
Indoor #05
Indoor #07
Indoor #14
Indoor #20
Indoor #31
CanvasJS.com
Map
Satellite
Zipcar
Cushing Hall of Engineering
Fitzpatrick Hall of Engineering
College of Engineering
Dept of Electrical Engineering
Crossings
University of Notre Dame
Snite Museum of A

Work Stream 3: Deployment Collaborations

CRADAs between ND/FCC & FCC/USPS

- FCC WTB deployed 7 RadioHound V3.1 sensors on USPS vehicles in Denver, CO
- Scans of 800 MHz–2400 MHz in 15 kHz increments
- Correlated with phone throughput from three service providers
- Part of Congressional feasibility study on broadband mapping throughout the US

Results

- Partner obtained experience with the platform as well as datasets for further study
- HW feedback & testing informed V3.2 design to increase sensitivity & performance up to 3 GHz
- SW feedback led to “Experiments” framework
- Congressional report in May 2021 https://www.fcc.gov/sites/default/files/report-congress-usps-broadband-data-collection-feasibility-05242021.pdf

Only 7 USPS vehicles in this pilot study, but there are ~200,000 more! Many technical & logistical challenges cited in the report.

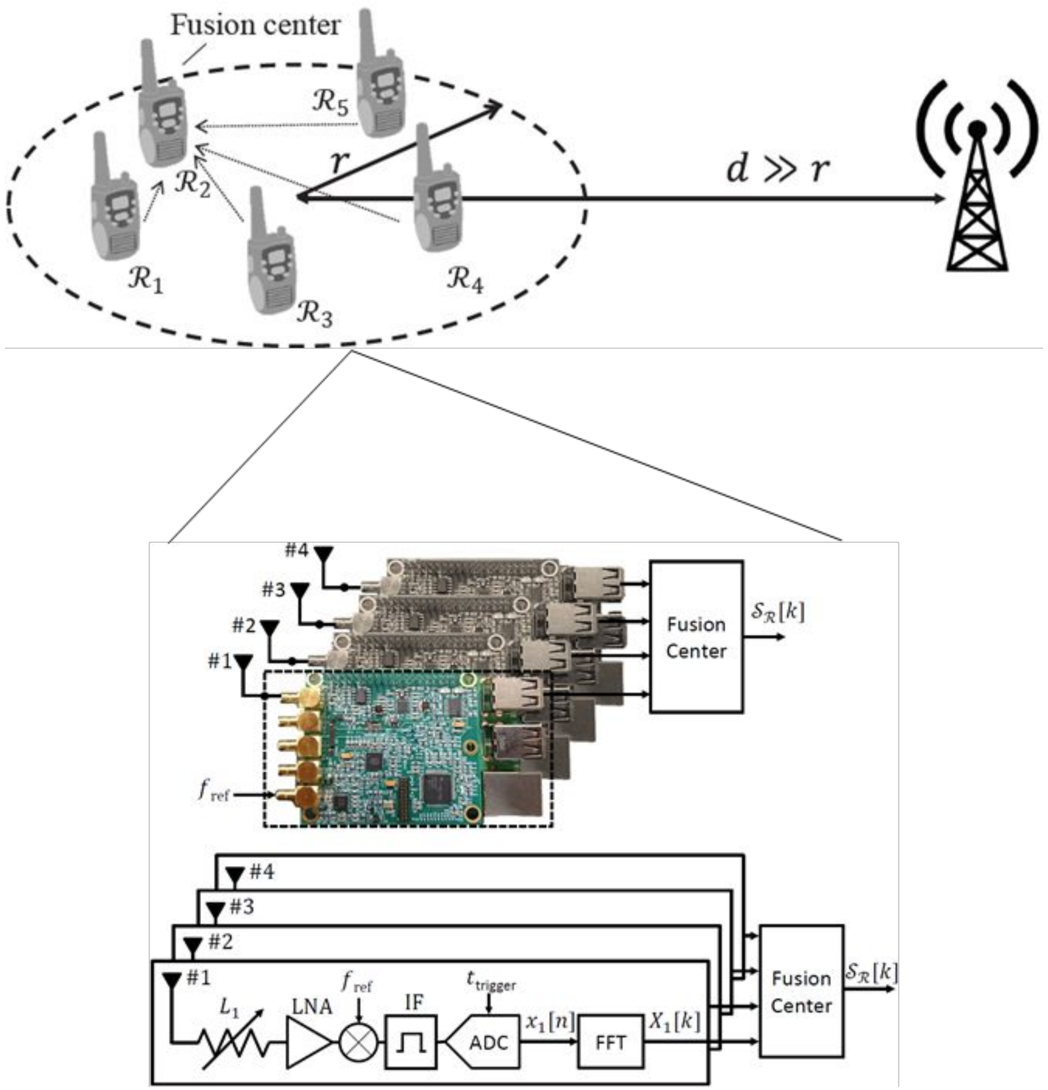
FCC Collaboration Timeline

- 06/2020: Initial Discussions
- 01/2021: Delivered V3.1 Sensors
- 03/2021: Project Plan & Formal Agreement
- 04/2021: Data Collection
- 05/2021: Report to Congress
- 07/2021: V3.2 sent for manufacture
- 09/2021: V3.2 received for testing

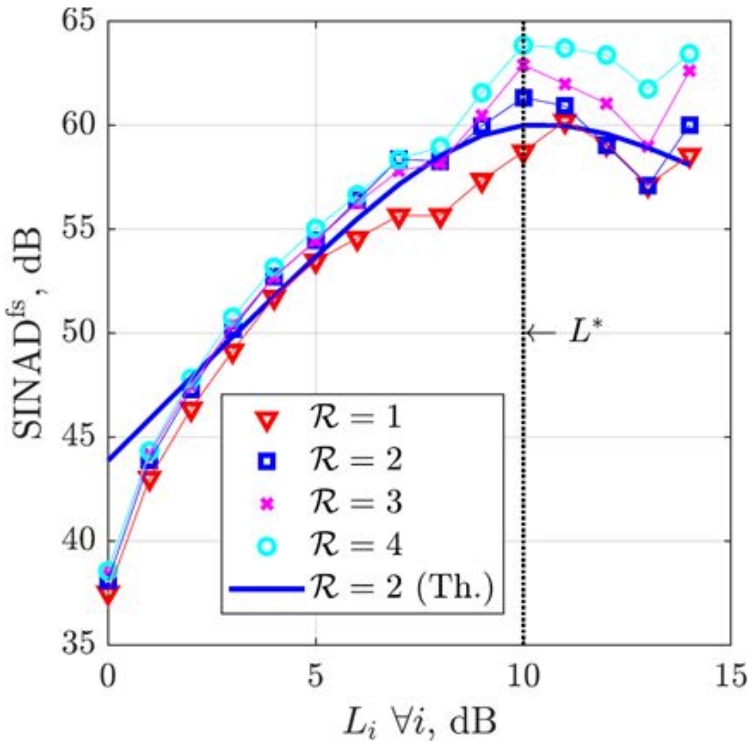
Work Stream 4: Basic Research & Publications

- Dr. Nikolaus Kleber (defended Ph.D. September 2020, now with Raytheon)
  - N. Kleber, C. R. Dietlein and J. D. Chisum, "Cooperative Cross-Correlation Algorithm to Optimize Linearity of Fused RF Sensors," in *IEEE Sensors Journal*, vol. 20, no. 7, pp. 3766-3776, April 1, 2020, doi: 10.1109/JSEN.2019.2959255.
  - N. Kleber, M. Haenggi, J. Chisum, B. Hochwald and J. N. Laneman, "Directivity in RF Sensor Networks for Widespread Spectrum Monitoring," in *IEEE Transactions on Cognitive Communications and Networking*, doi: 10.1109/TCCN.2021.3124523.
- Dr.. Abbas Termos (defended Ph.D. February 2022, joining Qualcomm)
  - A. Termos and B. Hochwald, "*Robust Neural Network-Based Spectrum Occupancy Mapping*," in *Proc. IEEE DySPAN 2021*, Virtual, 12/15

Fusing Sensor Data to Improve Linearity



- Fusion improves SINAD
- SINAD increases with number of sensors



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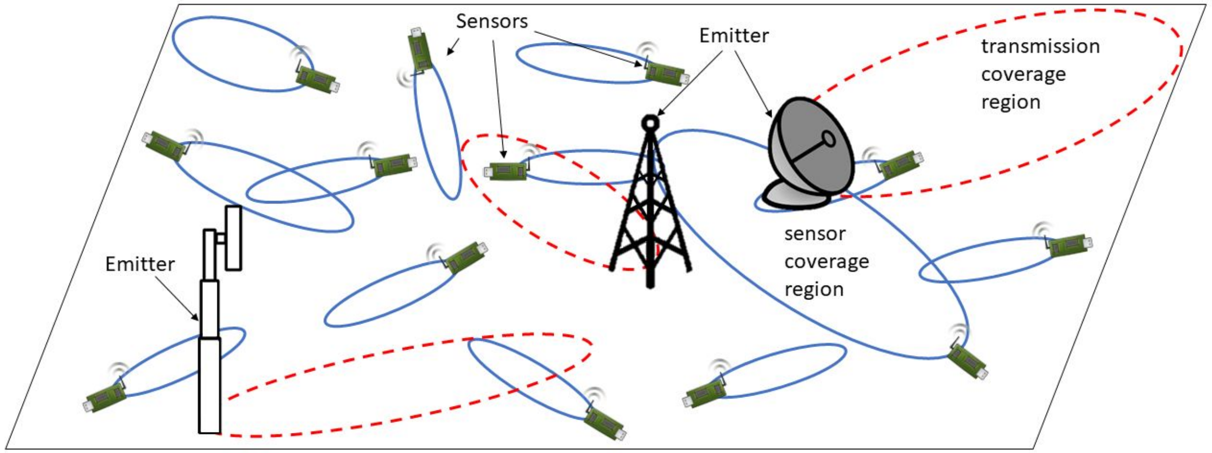
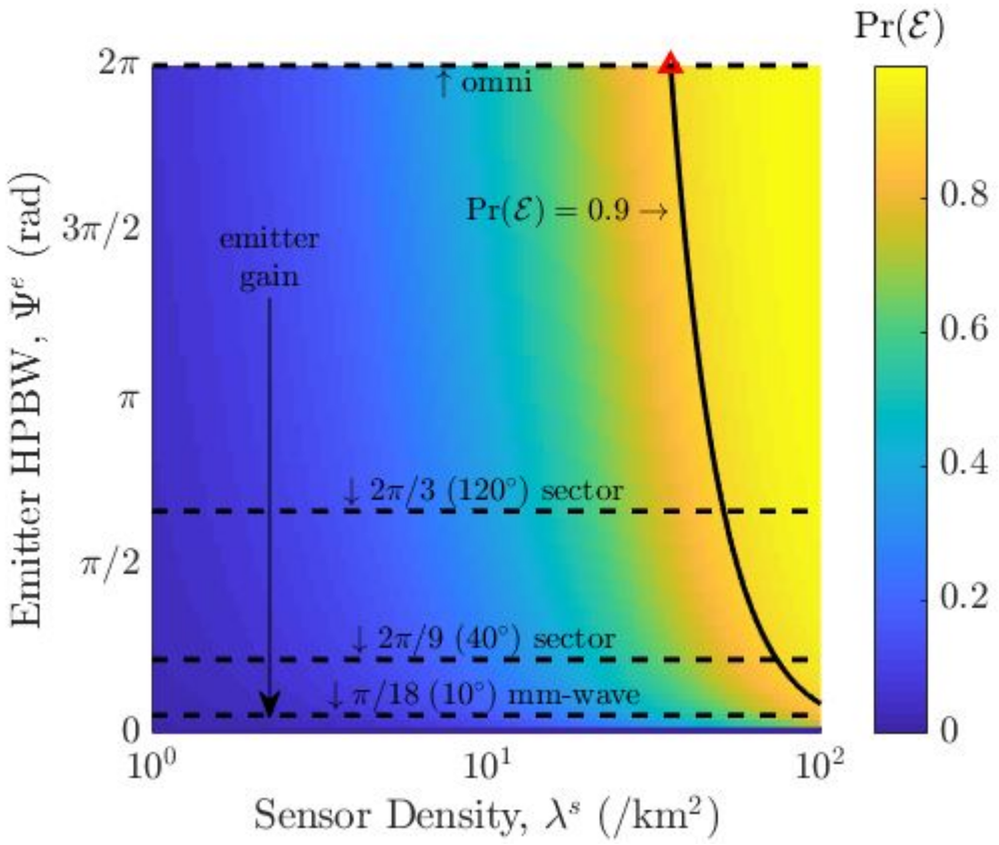
How Many Sensors for Emitter Detection?

- Model crowdsourced sensors as Poisson point process
- Closed-form expressions for detection probability enables analysis for design insights
- Need to account for emitter directivity





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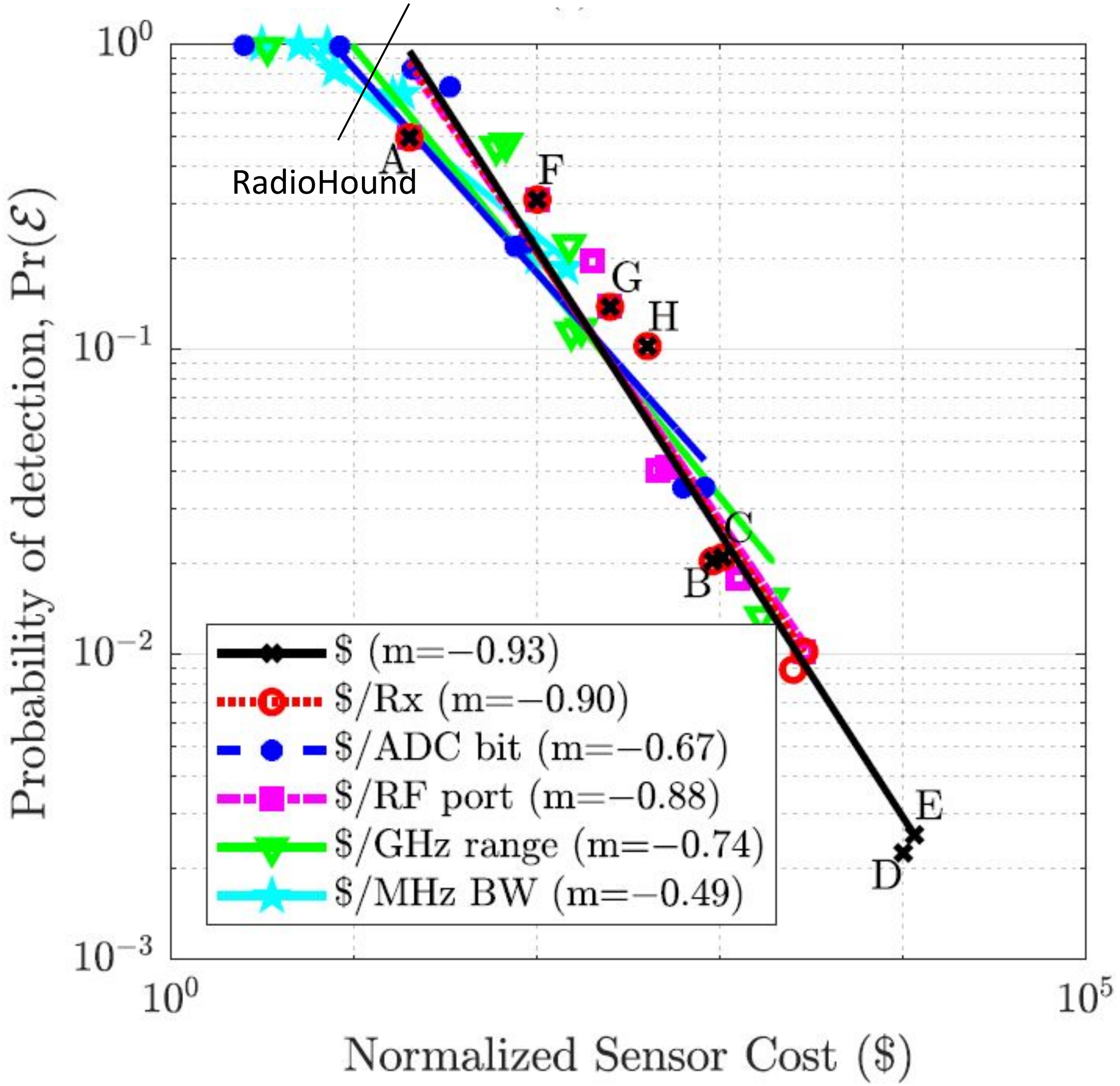
N. Kleber, J. Chisum, B. Hochwald and J. N. Laneman, "Three-Dimensional RF Sensor Networks for Widespread Spectrum Monitoring," submitted for publication.

Quantity versus Quality: Result

- Lower sensor quality/cost allows larger sensor quantity for a fixed budget
- Sensor quantity has larger effect on detection probability than sensor quality



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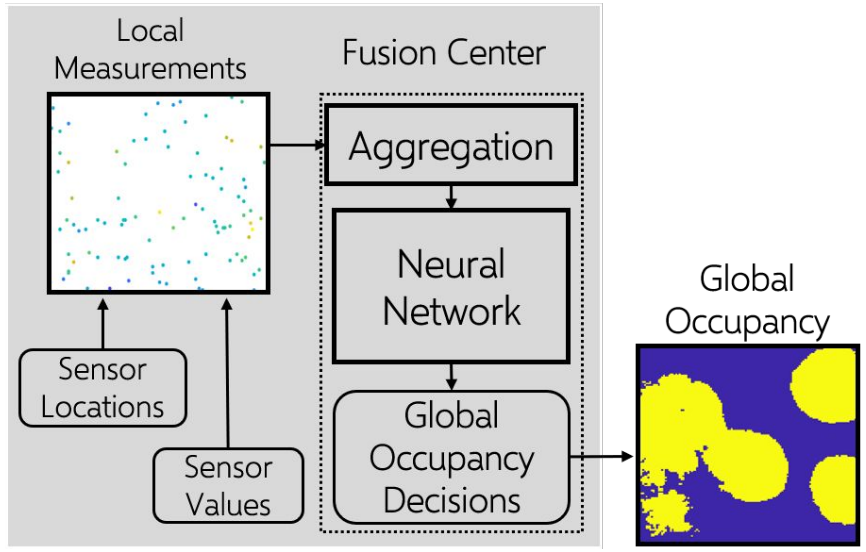
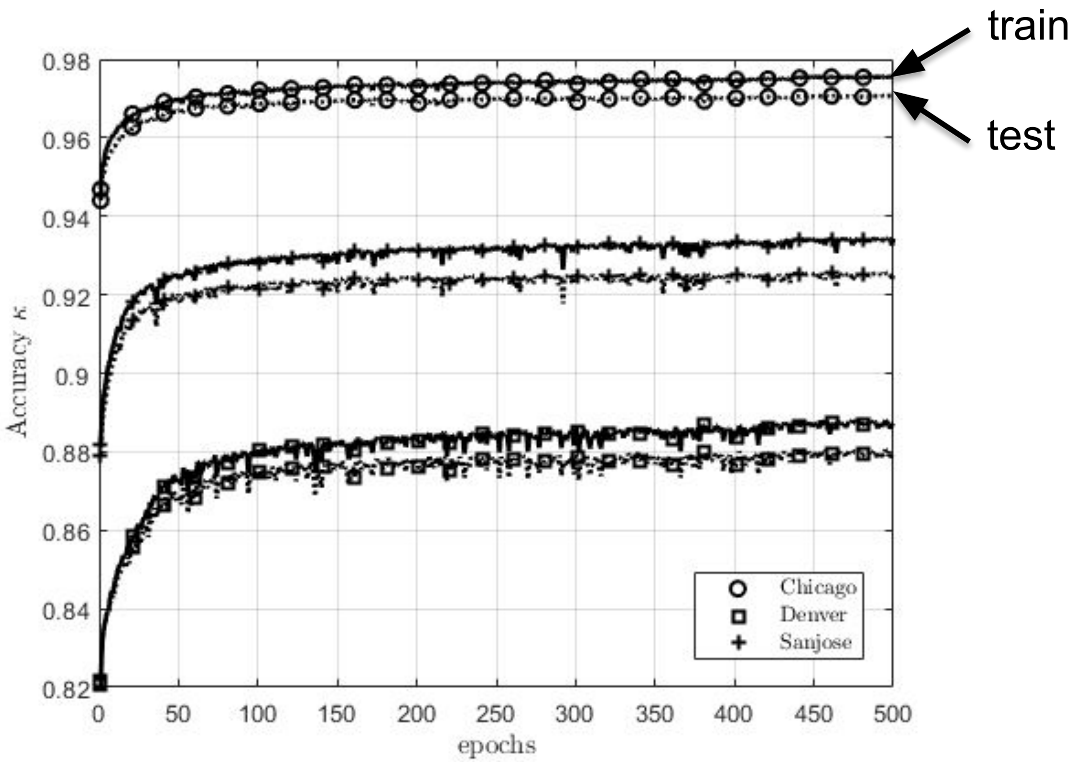
ML-Based Occupancy Maps

- Define *occupancy* as RF power exceeding a fixed threshold, function of frequency and location
- Given sparse power measurements at a given frequency, estimate occupancy over more dense grid
- Apply latest neural network techniques, train and test with commercial propagation model (Atoll)
- Highly accurate!





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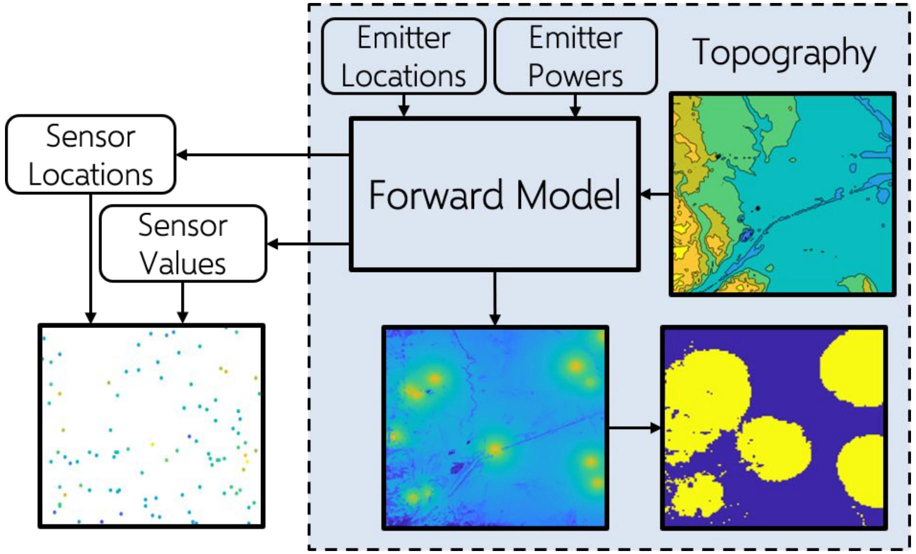

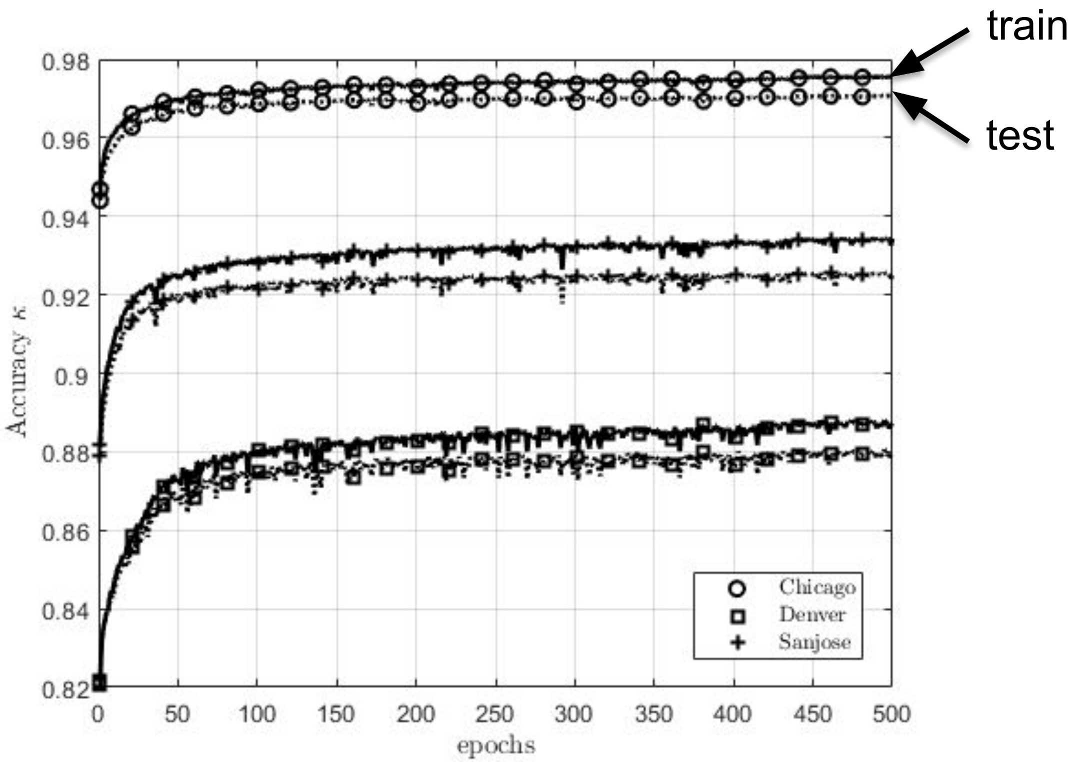

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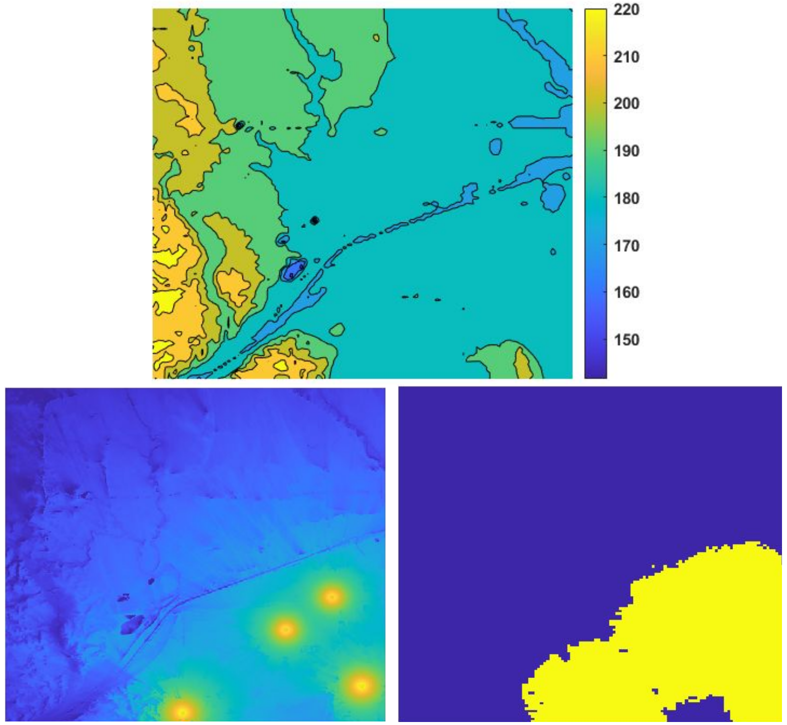
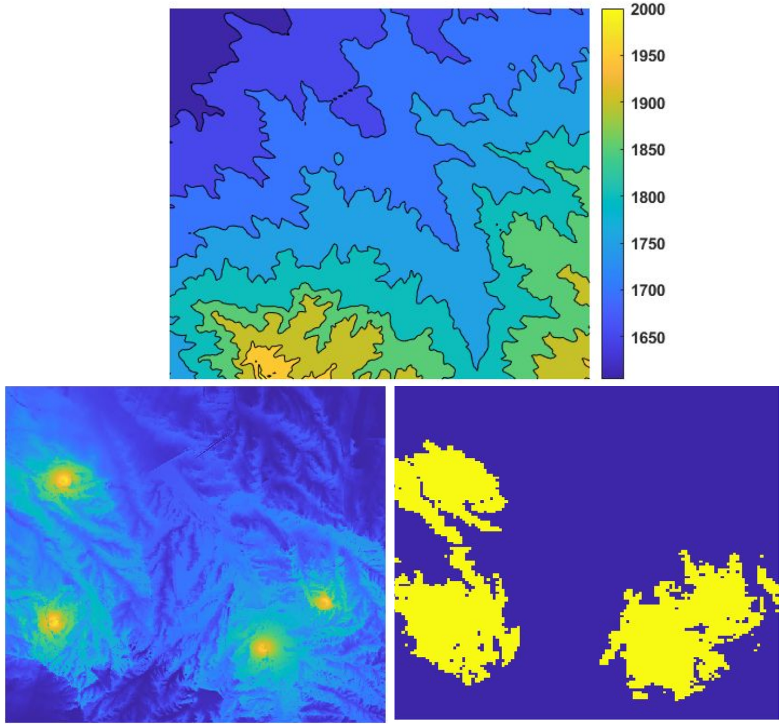
Different Topology, Different Occupancy

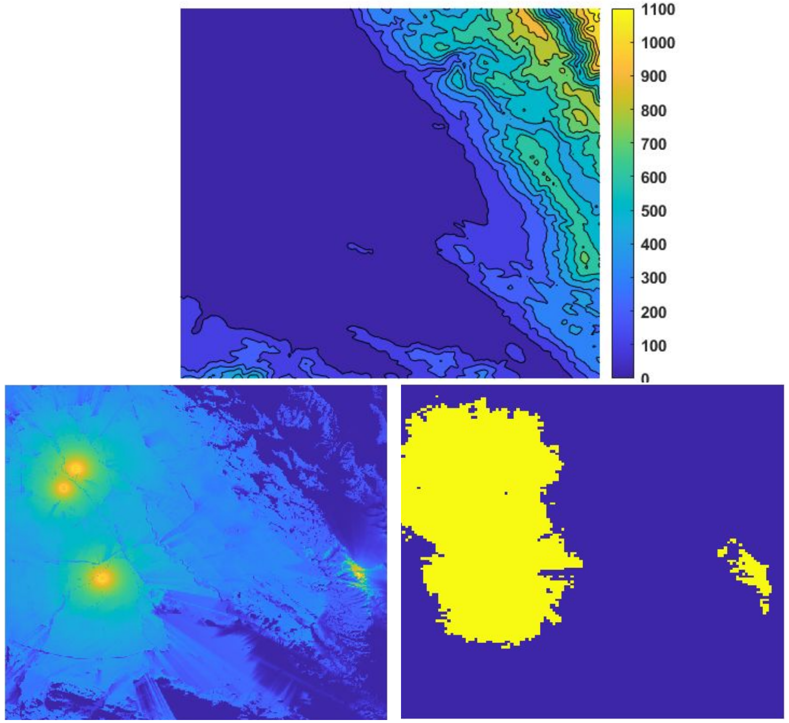
Chicago



Denver



San Jose



Direction 1: Simplify Sensor

Reduce mixer quality

- Introduces harmonics, but save ~69% power and ~66% cost

Remove LNA

- Reduces the SNR of the received signal, but saves ~79% power and ~71% cost

Remove VGA

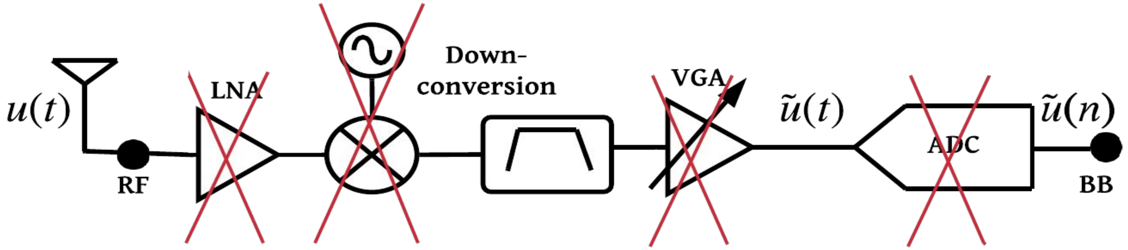
- Introduces clipping (under/over-flow) at the ADC, but saves ~86% power and ~85% cost

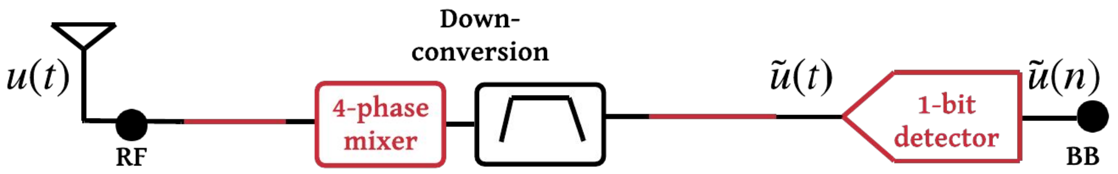
Reduce ADC resolution

- Provides 1-bit information, but saves ~89% power and ~95% cost

How many more streamlined sensors are needed?
Preliminary: ~4x

How are effects modelled and accounted for in ML system?





A. Termos *Spectrum Occupancy Mapping With Minimal Assumptions and Simple Sensors*, PhD Dissertation, University of Notre Dame, February 2022. https://doi.org/10.7274/3x816m3421g

Direction 2: Enhance Sensor

Maximum Tuning Frequency

- 12 GHz, or 60 GHz (instead of 6 GHz)

Bandwidth

- Sampling rate of A/D 100 MHz (instead of 48 MHz)

Multiple RF Chains

- Stack RF chains to enable MIMO, BF, TDOA, …

Targeted Bands

- CBRS + C-Band
- 6 GHz ISM Band
- Scientific Sensing
- …

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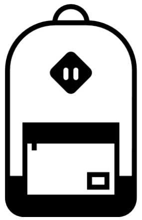
Direction 3: Platform Integrations



Student Backpack

Small size
Limited power
Medium Protection

Drones

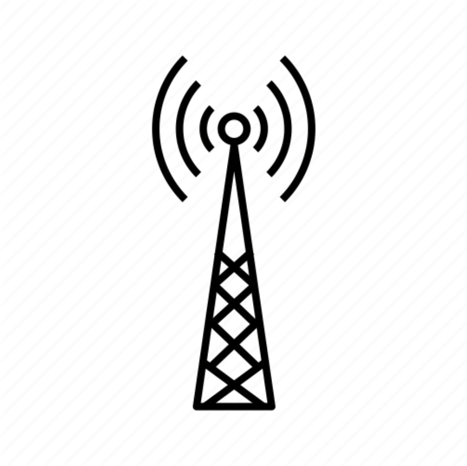
Small size
Some power
Medium Protection

CRC has built 3 drones for prototyping

Delivery Vehicles

Medium Size
Reasonable Power
Extra Protection

Campus vehicles, student or faculty vehicle can serve as a proxy for prototyping



Telecom Tower

Medium Size
Reasonable Power
Long-Term Deployment
Little Protection

No proxy, need a tower partner

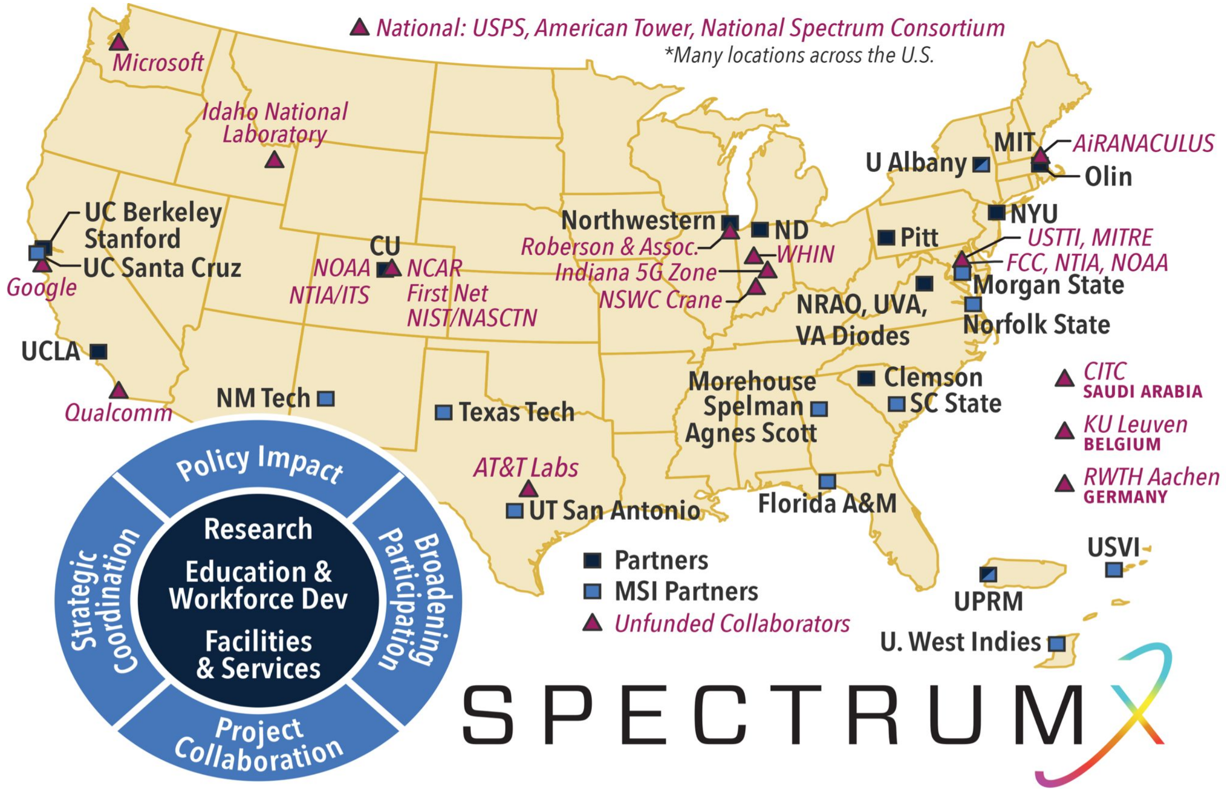
Call for Sensor Requirements & Evaluations

- ND has standardized an Equipment Evaluation agreement for RadioHounds
- To help us plan activities for the coming year, please send us a brief writeup including:
    - Sensor / software feature requests / requirements
    - Summary of desired application / deployment scenario(s)
    - Number of sensors and delivery date desired
        - Availability of RadioHound V3.2: ~10 today, 2 months to order
        - Availability of RadioHound V3.3: June 2021 (estimated)
    - Availability of funding, if any, and / or opportunities to pursue joint funding
    - Team contact information and main point of contact
- Email to sensors@spectrumx.org

SPECTRUMX

SpectrumX - An NSF Spectrum Innovation Center

- 5-year, $25M center award from the US National Science Foundation (NSF)
- Part of the new NSF Spectrum Innovation Initiative (SII)
- 27 top universities, including 14 Minority-Serving Institutions (MSIs)
- Numerous industry & government collaborators
- Led by ND Wireless Institute



Get Involved in SpectrumX!!

Bookmark the Website

spectrumx.org

Follow on LinkedIn

www.linkedin.com/company/spectrumx-center

Email Interests & Feedback

info@spectrumx.org

SPECTRUMX

Wrap Up

- Wide-band, wide-area spectrum sensing is within reach for data-driven spectrum access & management
- We have a sensor platform (RadioHound), development & collaboration experience (ARL, FCC), and a national center (SpectrumX) to realize this vision
- Let’s team up to advance spectrum monitoring and sharing!!