Spectrum Sharing at 3.5 GHz

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National Institute of Standards and Technology
U.S. Department of Commerce

CTL Communications Technology Laboratory

Outline

Contributions to 3.5 GHz Citizens Broadband Radio Service (CBRS)

- Release 1 of Wireless Innovation Forum CBRS standards
  - NIST-led development of federal incumbent protection test procedures
- NIST reference model for federal incumbent protection
  - Used by regulator to test and certify commercial Spectrum Access Systems

Detection of Incumbent Signals in the 3.5 GHz Band

- Characterization of incumbent signals
  - 3.5 GHz radar waveform measurements (NASCTN)
- Machine-learning radar detection and classification algorithms
- RF signal data sets
- Sensor placement and configuration

Citizens Broadband Radio Service

Standards and Reference Model

National Institute of Standards and Technology
U.S. Department of Commerce

Communications Technology Laboratory

Citizens Broadband Radio Service (CBRS)

Opens **150 MHz** of prime spectrum to traditional mobile operators and **new entrants**; shared access to **3.5 GHz** band (3550 MHz to 3700 MHz)

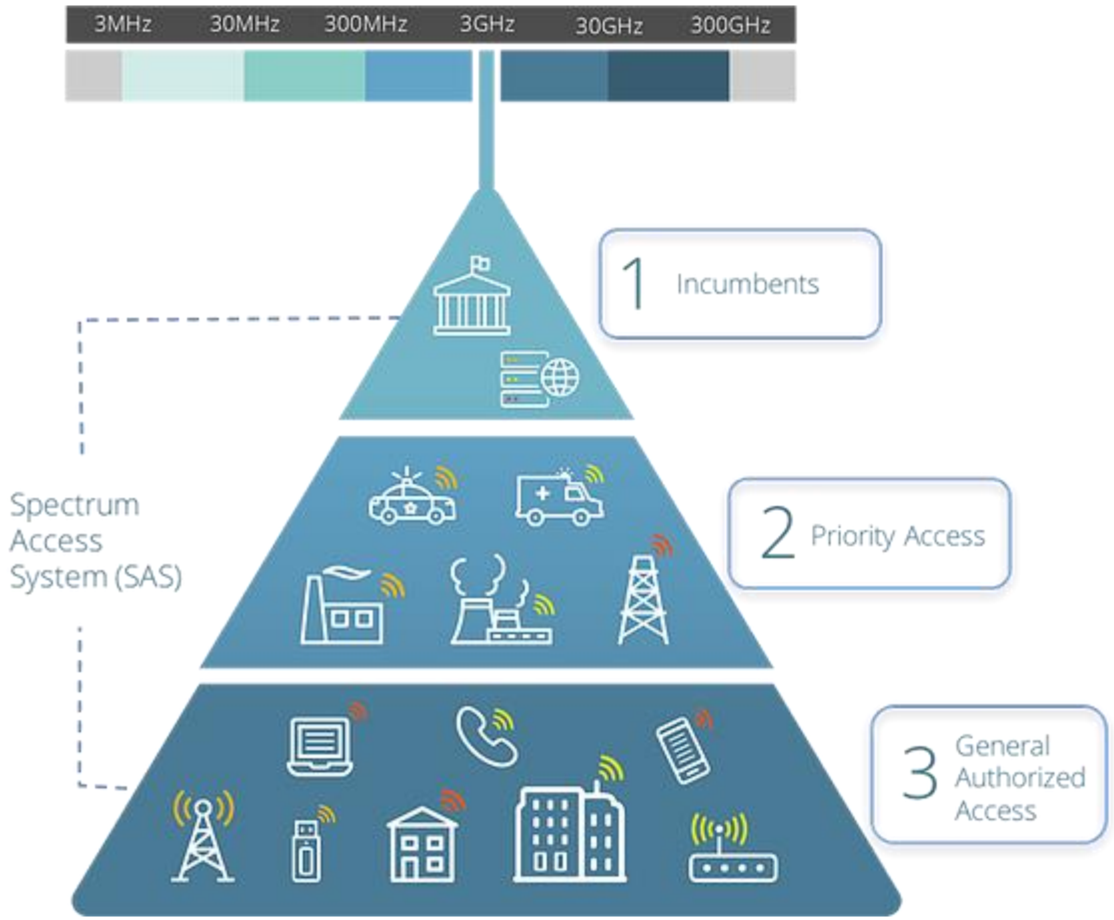
- Jan 2015: CBRS standards process begins under the auspices of the **Wireless Innovation Forum** (WINNF).
- April 2015: FCC finalizes CBRS rules.
- Jan 2016: **NIST** joins the WINNF as a full member.
- Jan 2018: Completion of **Release 1** specifications

CBRS Architecture

NIST

Three Tiers of Spectrum Users

1. **Incumbent**
   - Federal (e.g., U.S. Navy radars)
   - Fixed satellite service earth stations
   - Grandfathered wireless broadband licensees
2. **Priority access licensee (PAL)**
3. **General authorized access (GAA)**



Source: https://www.cbrsalliance.org/blog

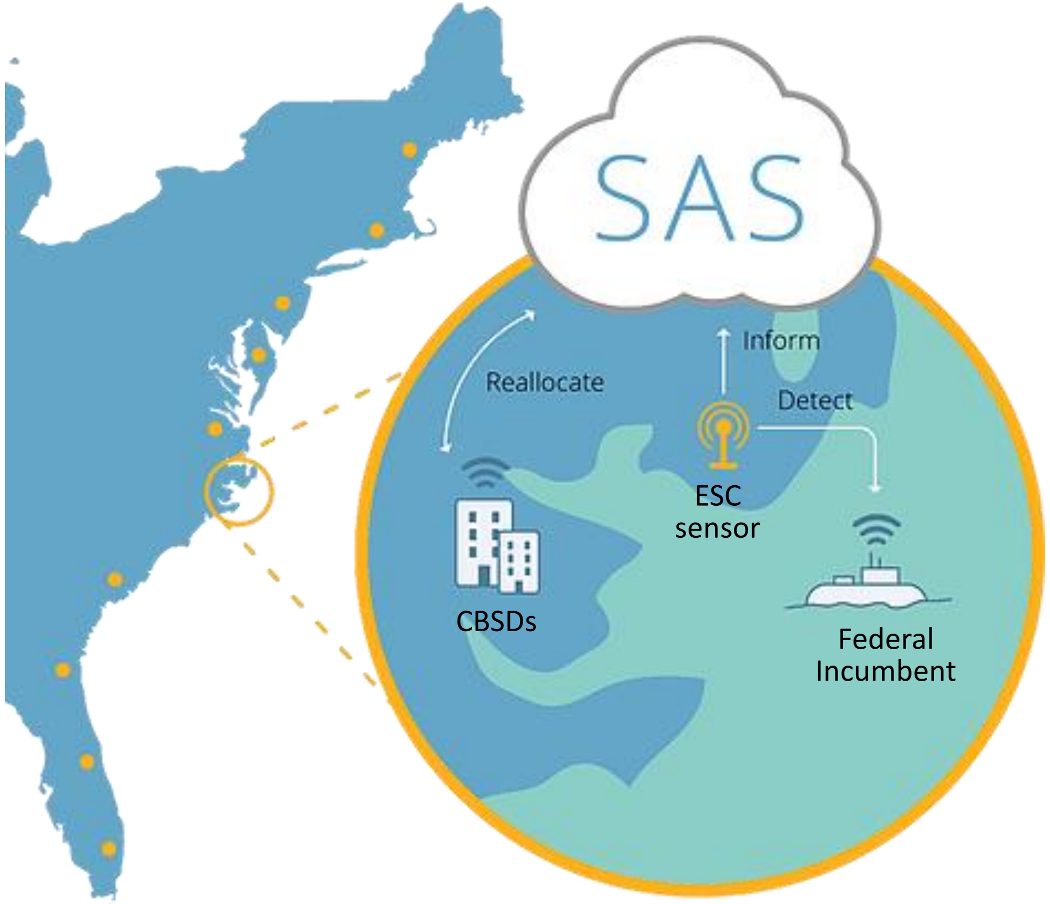
CBRS Architecture

NIST

<u>CBRS devices</u> (**CBSDs**): fixed base stations/access points operating as PALs and GAAs (typically LTE cells) providing mobile broadband service to end user devices

<u>Spectrum Access System</u> (**SAS**): allocates spectrum resources (frequencies, power) to CBSDs; manages interference of lower tiers to higher tiers and among Tier 2

<u>Environmental Sensing Capability</u> (**ESC**): sensor network that monitors CBRS band for federal incumbent signals (military radar); upon detecting an incumbent in a Dynamic Protection Area (DPA), SAS reconfigures CBSDs to mitigate interference in the DPA within 300 s



Source: https://www.cbrsalliance.org/blog

Federal Incumbent Dynamic Protection Areas (DPAs)

East Coast
West Coast
Gulf Coast
Alaska
Hawaii
Puerto Rico
Guam
Inland sites

USS George H.W. Bush. *Credit: U.S. Navy photo by Mass Communication Specialist 3rd Class Nicholas Hall [Public domain], via Wikimedia Commons*

52% of the U.S. population lives in coastal watershed counties [NOAA].

NIST Contributes to CBRS Standards

- WINNF-TS-0112, CBRS Operational and Functional Requirements
- WINNF-TS-0016, SAS to CBSD Protocol Specification
- WINNF-TS-0061, SAS Test and Certification Specification

Part of suite of 10 standards completed 2018

https://cbrs.wirelessinnovation.org/release-1-standards-specifications

Spectrum Sharing Committee Work Group 4 (Test and Certification)
CBRS Test and Certification TS – SAS as UUT
WINNF-TS-0061-V1.5.0

Contributors

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NIST Contributes to Spectrum Access System (SAS) Testing

NIST

Wireless Innovation Forum

Published test and certification specifications

NIST/CTL

Created the federal incumbent (DPA) protection reference model

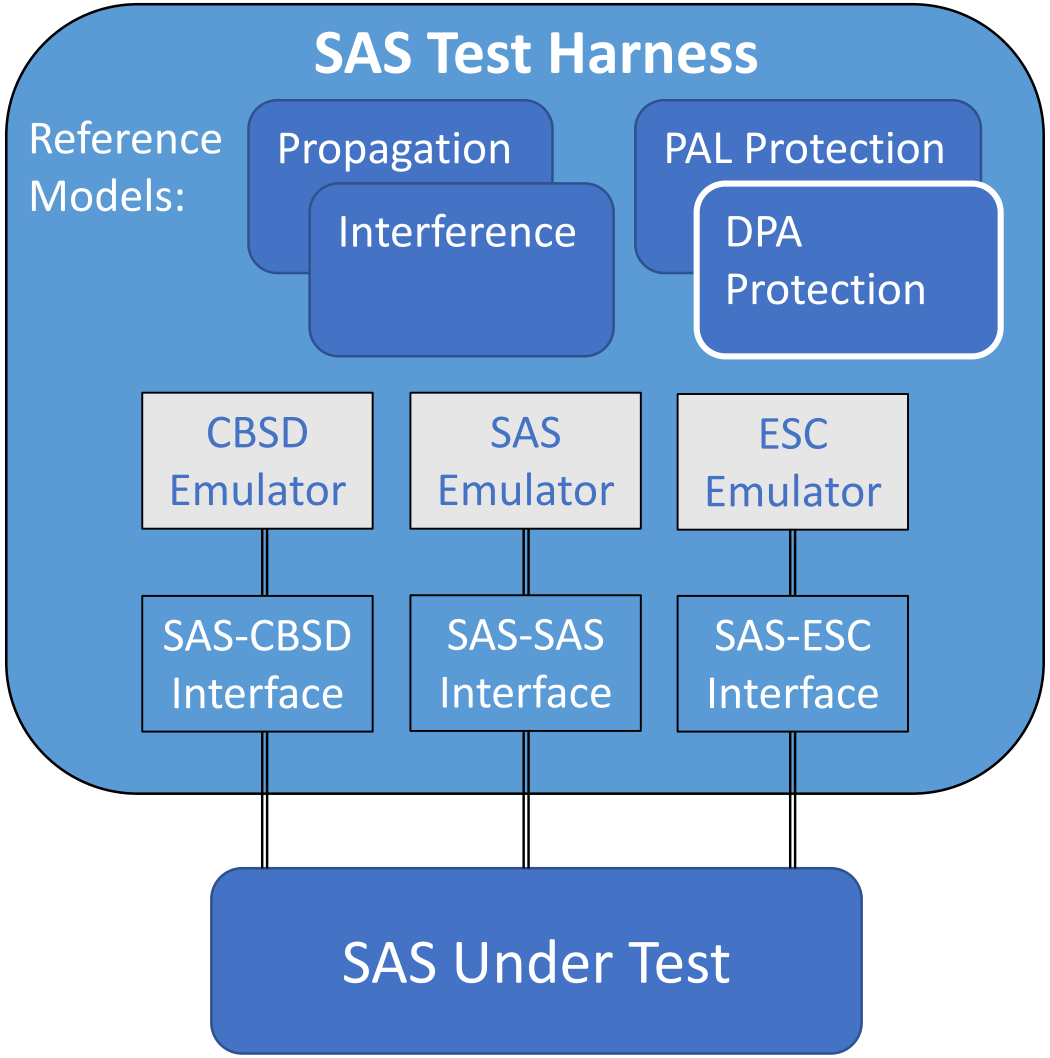
SAS Industry

Developed the SAS Test Harness

Google COMMSCOPE RED TECHNOLOGIES federated wireless

NTIA

Performed certification testing of commercial SASs



https://github.com/Wireless-Innovation-Forum/

Federal Incumbent Protection Procedure

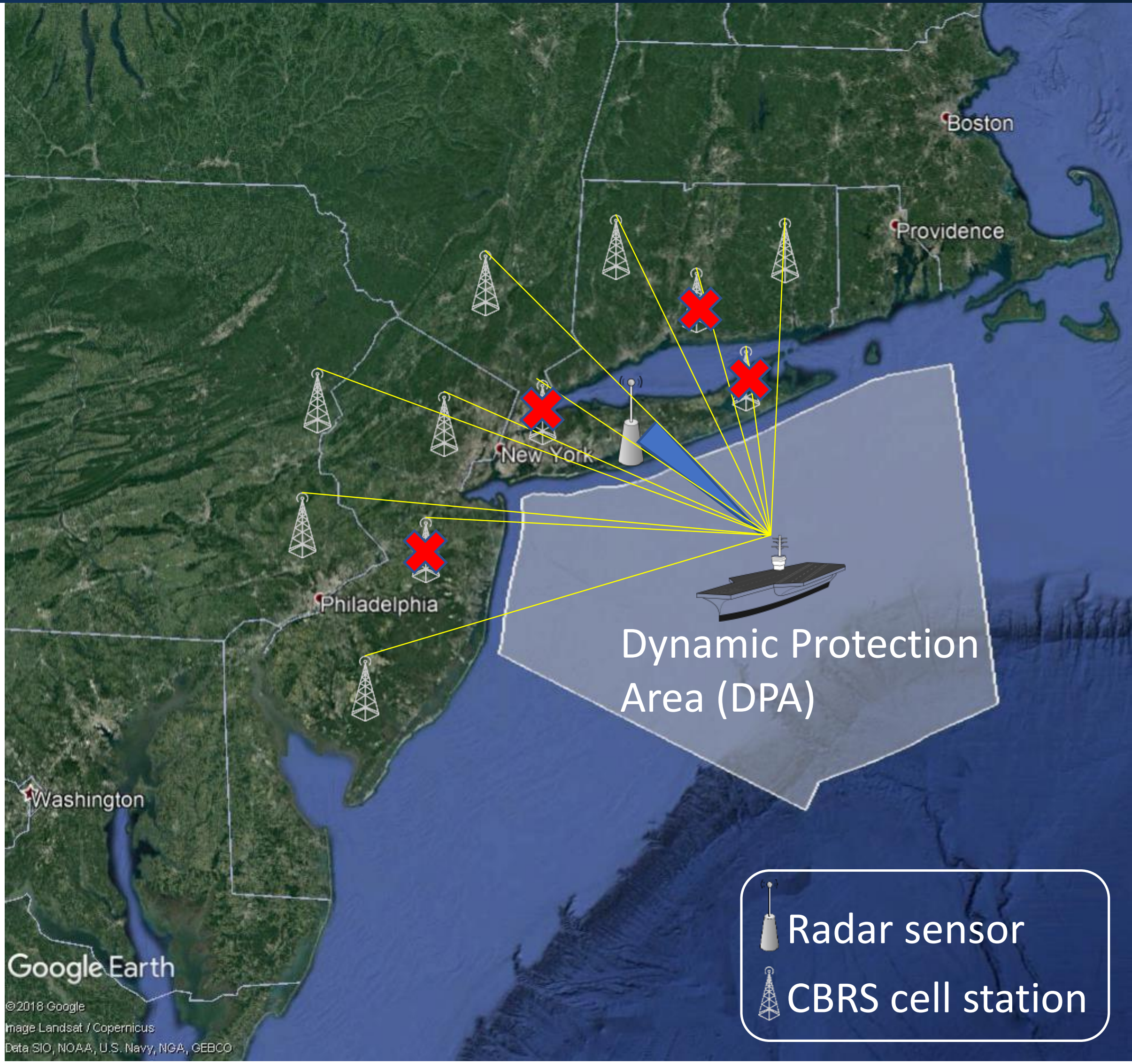
NIST

- Sensor detects offshore shipborne radar and informs SAS of activated DPA and channel
- SAS reallocates spectrum resources to mitigate interference to active DPA
  - Uses a pre-calculated “move list” of CBSDs
  - Moves CBSDs off the protected channel in the vicinity of the DPA
- Move list is designed to meet the required interference protection level:

  95th percentile of aggregate interference into radar receiver antenna ≤ –144 dBm/10 MHz

  at every point in the DPA

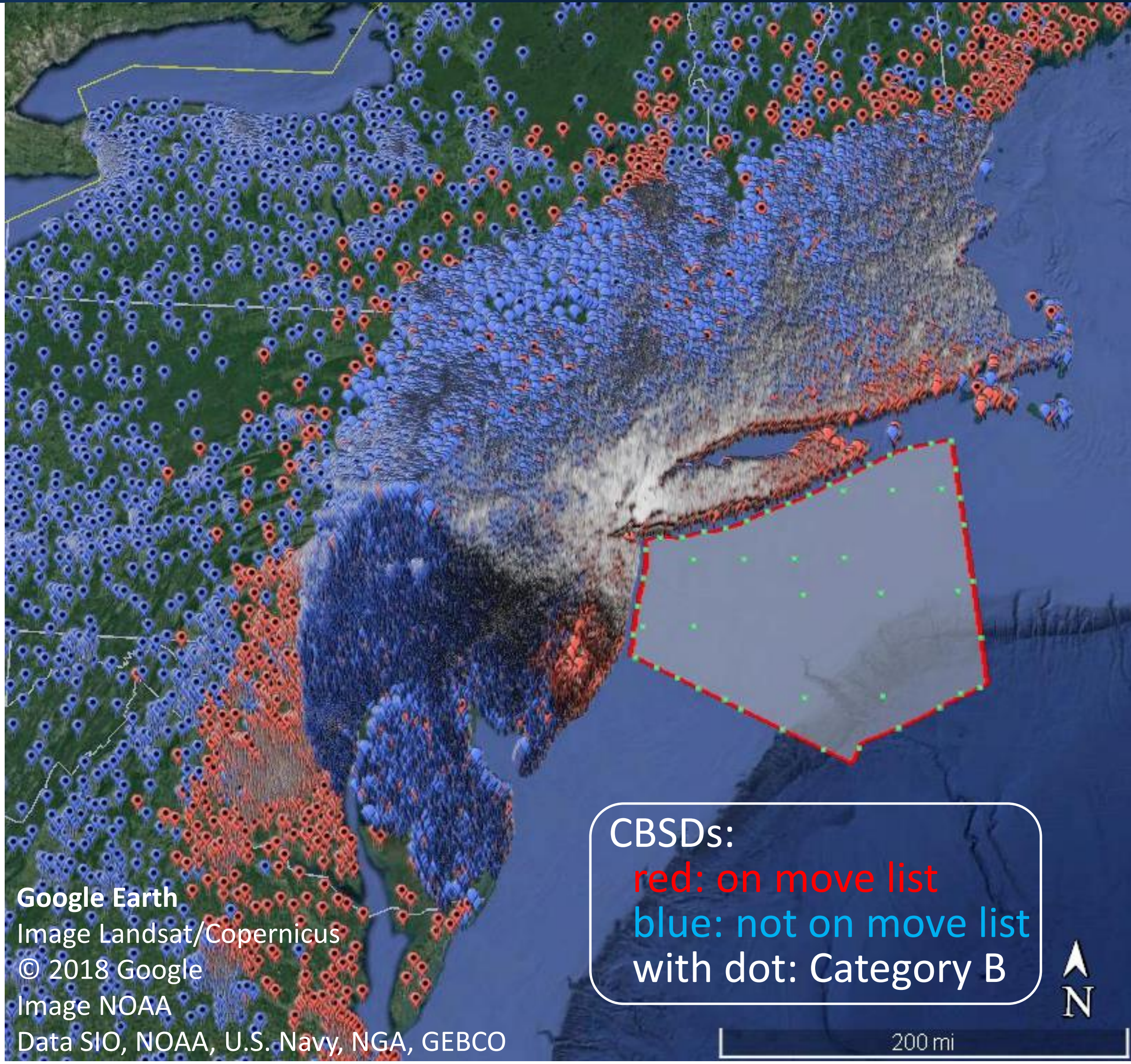
DoD-defined protection level



Move-List Example: New York Offshore DPA

NIST

- Simulated deployment of 80K CBSDs (generated with NTIA/OSM software)
- "Move list" calculated by NIST reference model of DPA protection algorithm
  - Using ITM reference propagation model
  - Based on 2000 Monte Carlo realizations of each path (modeling time variability of path loss)

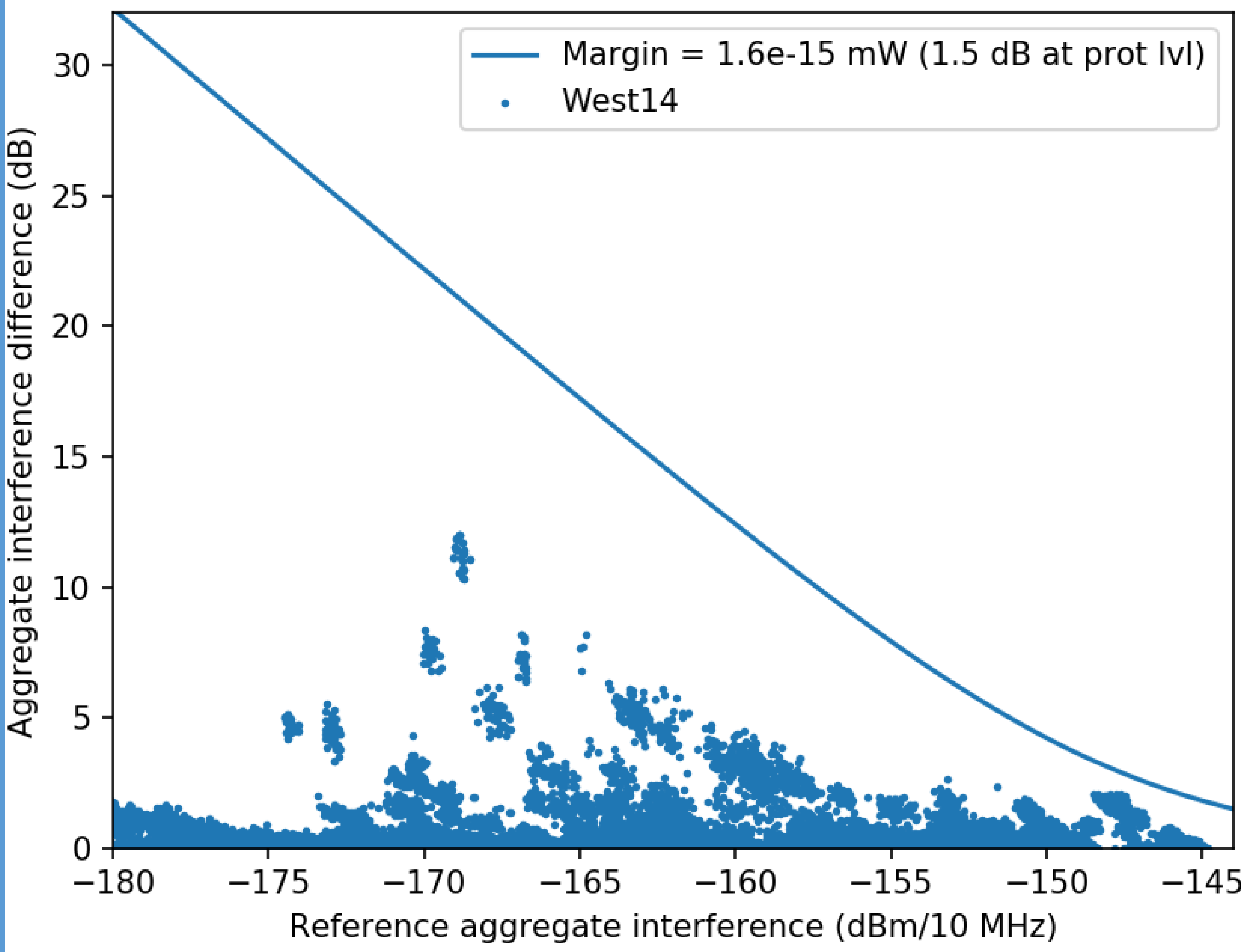


NIST Brings Uncertainty Analysis to SAS Testing

- Federal incumbent protection test procedure includes an interference margin to account for move-list uncertainty.
- NIST proposed a methodology adopted by the WINNF for quantifying this margin.

Example: San Diego DPA ("West 14")

- Simulated deployment of 22K CBSDs.
- Generated 100 independent move lists.
- 1.5 dB margin relative to protection level is sufficient in this case.



Industry Statements Following CBRS Standards Release

"… it is now possible to make major changes in how we approach managing spectrum resources …
… flexible, cloud-based management can … relegate the exclusive, command and control vision of spectrum allocation to history." **Eric Schmidt, Executive Chairman of Google parent company Alphabet Inc.**

"… 150MHz of spectrum in a continuous block. This spectrum will enable cost effective coverage and capacity expansion at large scale." **Ricky Corker, Executive Vice President, Nokia**

"Ericsson's commitment to supplying LTE equipment for the band will ensure strong commercial support for the ecosystem." **Paul Challoner, VP Network Product Solutions, Ericsson Inc., USA**

"We look forward to offering innovative new products and services in this new shared CBRS spectrum." **Ed Chan, Chief Technology Architect and Network Planning, Verizon**

Industry Statements Following CBRS Standards Release

“The efforts of our company, NIST and the other members of the WINNF SSC to establish standards, testing and certification for spectrum sharing are setting the stage for improving wireless service indoors, expanding broadband services to rural areas, and providing private wireless capabilities for industrial users. It’s an outstanding example of public-private collaboration,”
Kurt Schaubach, Chief Technology Officer, Federated Wireless

Detection of RF Signals in Shared Spectrum

National Institute of Standards and Technology
U.S. Department of Commerce

Communications Technology Laboratory

Detection of RF Signals in Shared Spectrum

NIST

Improved Detectors

Leveraging state-of-the-art machine learning models, including deep-learning neural networks

Data Sets

Disseminating curated RF signal waveforms for training AI models, derived from both measurements and synthesis

Sensor Deployment

Algorithms for efficient placement and configuration of sensors to detect incumbent signals

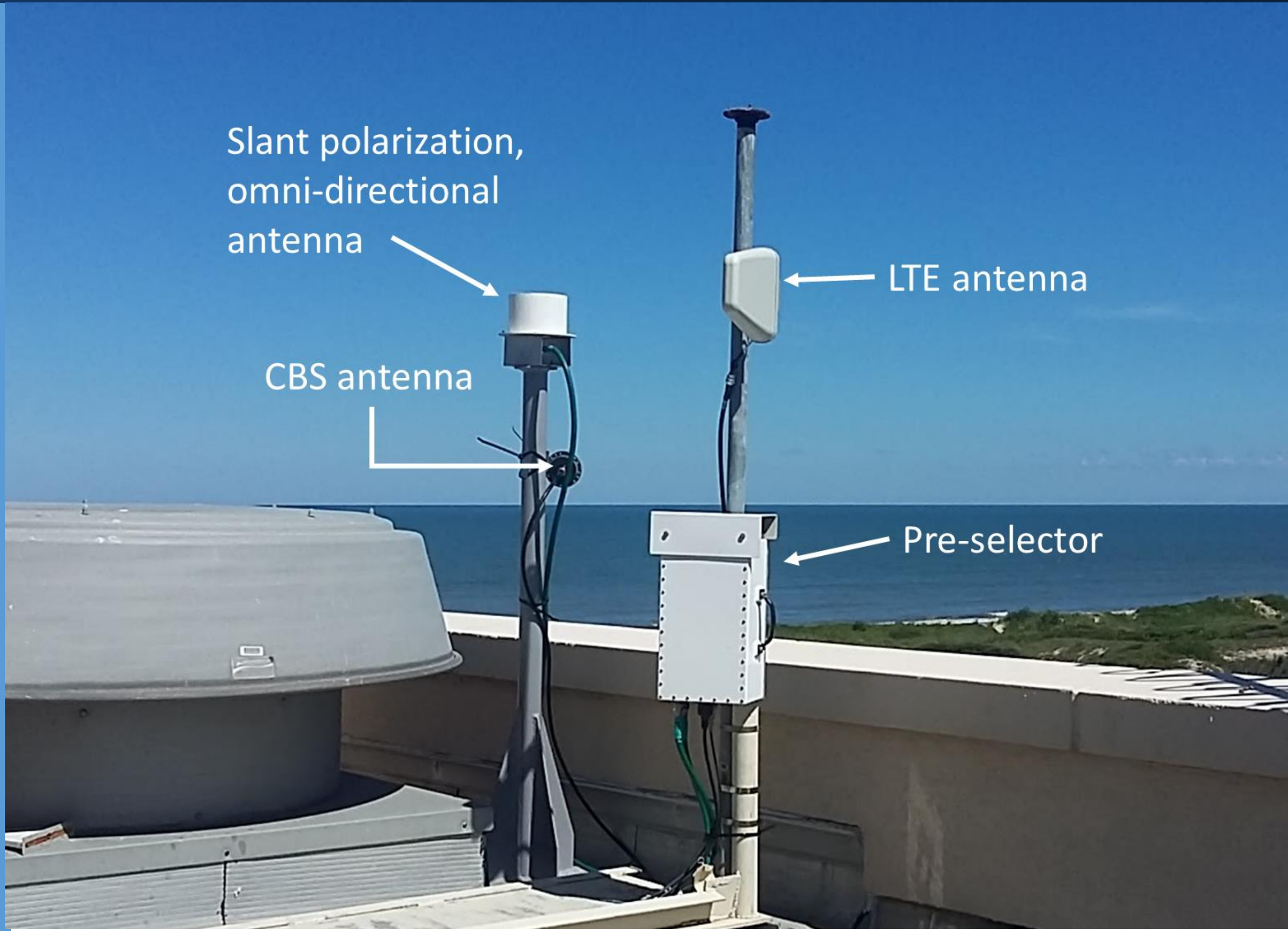
NASCTN 3.5 GHz Radar Waveform Measurements

NIST

Objectives
- Characterize shipborne SPN-43 radar
- Create waveform library

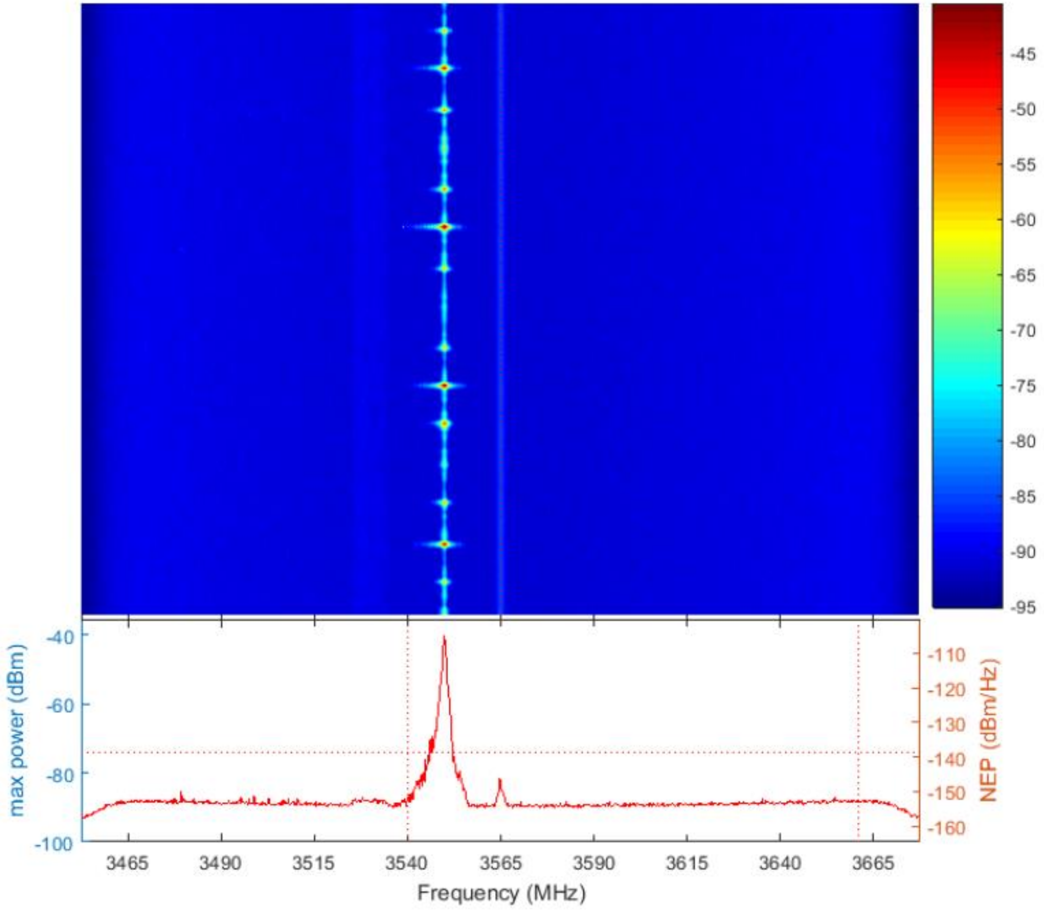
Measurements collected
- Two naval bases: San Diego, Norfolk
- 2 months at each location

Outcomes
- 14,739 spectrograms, every 10 min
- 3,336 sixty-second IQ waveform captures (200 MHz inst. bandwidth)

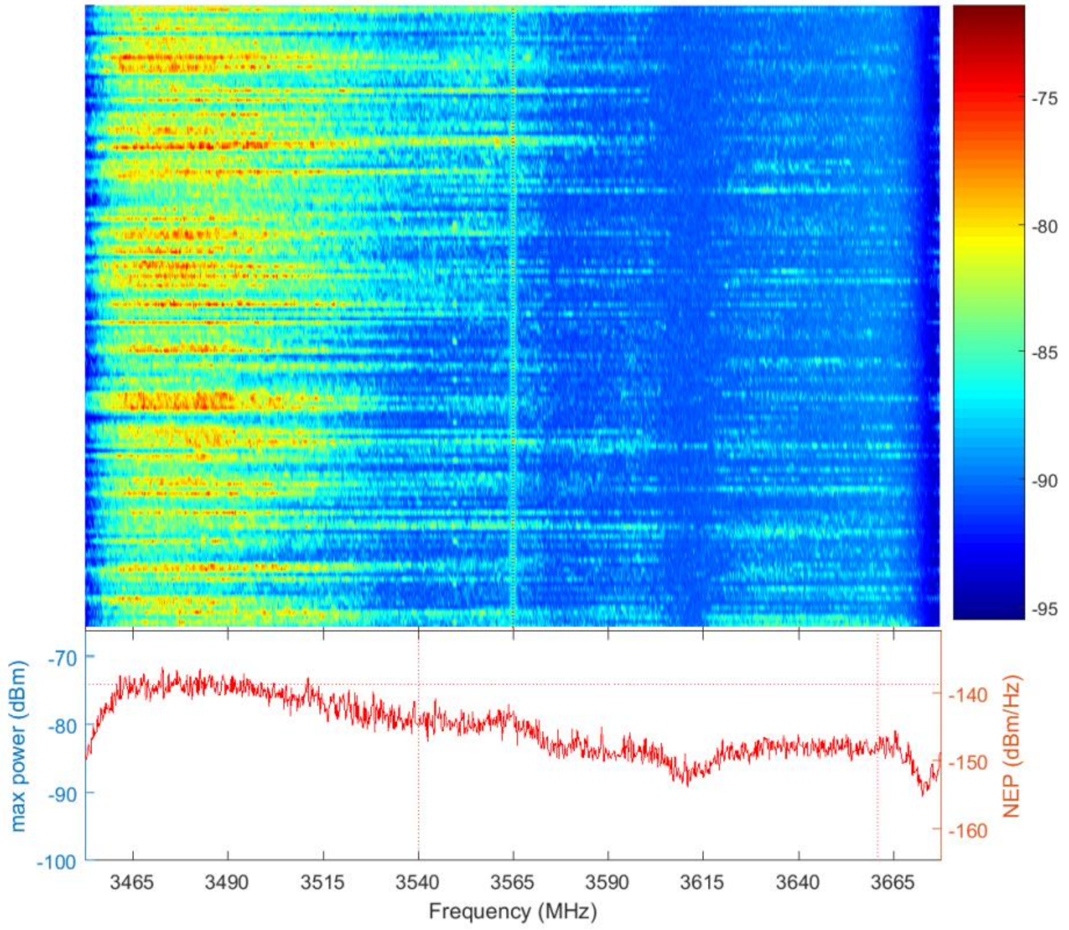


3.5 GHz Spectrograms

SPN-43 signal without adjacent-band radar emissions



SPN-43 signal embedded in adjacent-band radar emissions



ESC sensors are supposed to detect the SPN-43 signal in both cases.

from NASCTN Report 2, NIST Technical Note 1954, “3.5 GHz Radar Waveform Capture at Point Loma: Final Test Report”

Classifying and Labeling 3.5 GHz Spectrograms

- Evaluated 13 algorithms for classifying the spectrograms for SPN-43 presence
  - 8 deep learning architectures
  - 3 classical machine learning methods
  - 2 classical signal detection methods
- Found that 3-layer convolutional neural network (CNN) offered superior tradeoff between accuracy and computational complexity
- Trained CNN used to label the complete set of spectrograms for SPN-43 presence and derive channel occupancy and ambient power statistics

Publications:

W. M. Lees, A. Wunderlich, P. Jeavons, P. Hale, and M. Souryal, "Deep learning classification of 3.5 GHz band spectrograms with applications to spectrum sensing," *IEEE Transactions on Cognitive Communications and Networking*, June 2019.

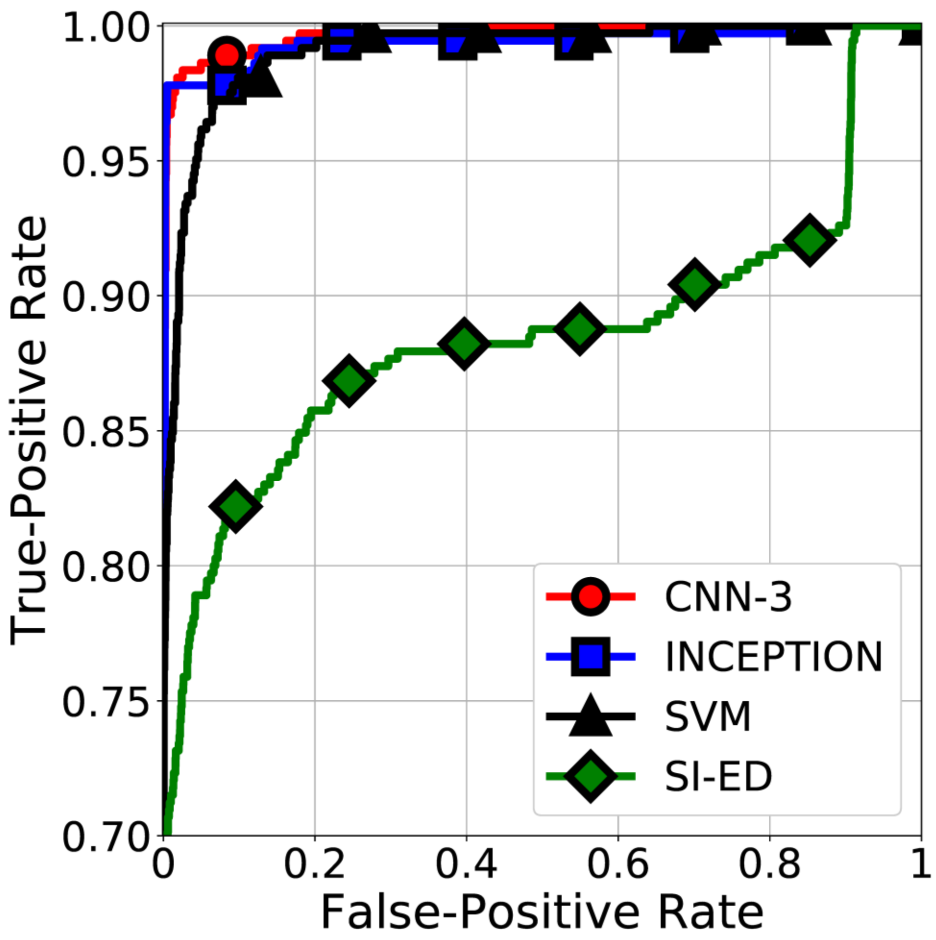
W. M. Lees, A. Wunderlich, P. Jeavons, P. Hale, M. Souryal, "Spectrum Occupancy and Ambient Power Distributions for the 3.5 GHz Band Estimated from Observations at Point Loma and Fort Story," NIST Technical Note 2016, Sept 2018.

Classifier Performance and Band Statistics

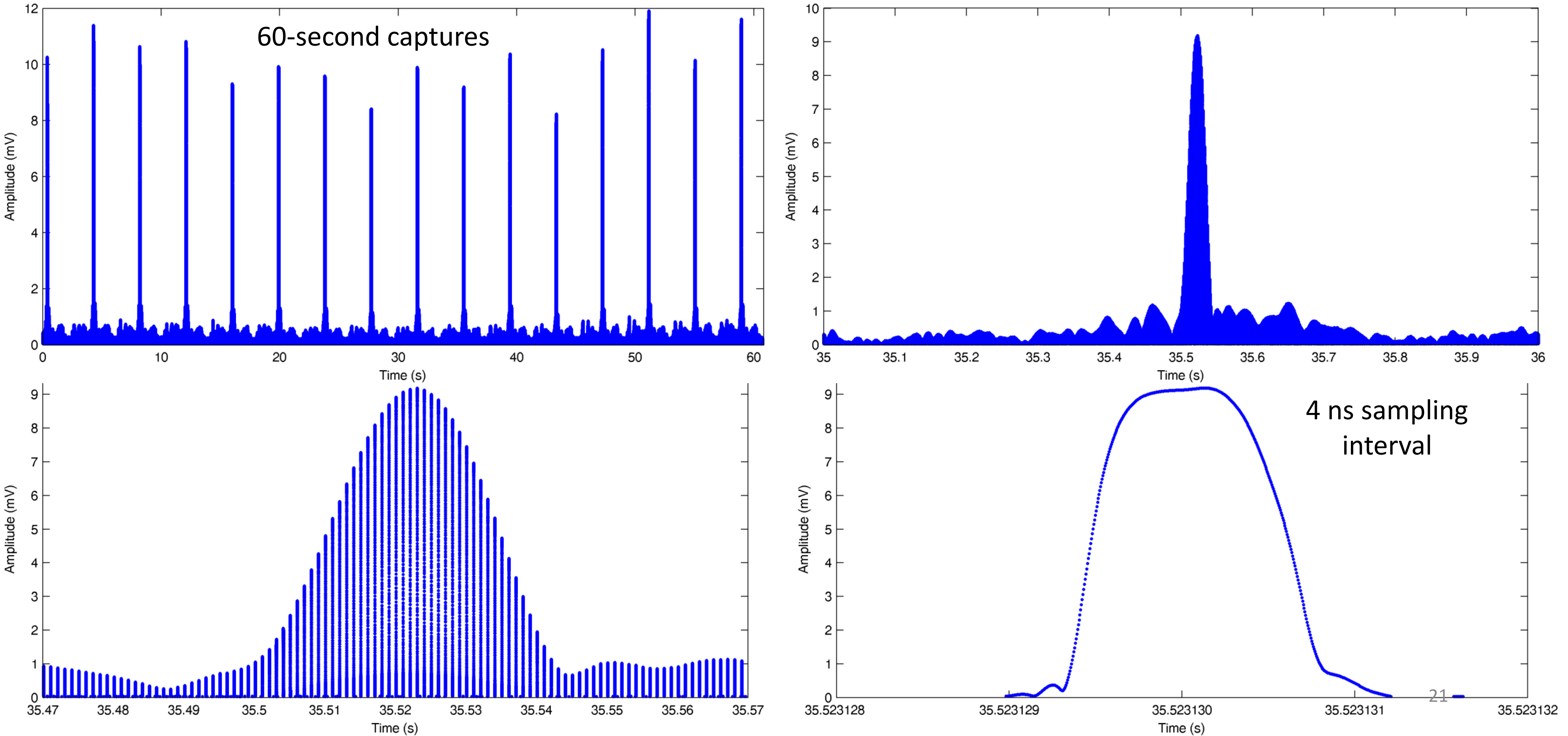
Among 13 algorithms tested, best in each class were:

- Convolutional neural network with three layers (CNN-3)
- Inception, a deep neural network developed for computer vision
- Support vector machine (SVM)
- Energy detection correlated with radar antenna sweep period (SI-ED)

CNN-labelled spectrograms used to derive statistics of CBRS channel occupancy, vacancy, and noise-plus-interference levels



3.5 GHz High-Resolution Waveforms



Test Waveform Generation

Field-measured radar signals

Field-measured interference signals

Synthetic interference signals and/or WGN

Test Waveform Generator

Test waveforms

Radar detection algorithm simulation

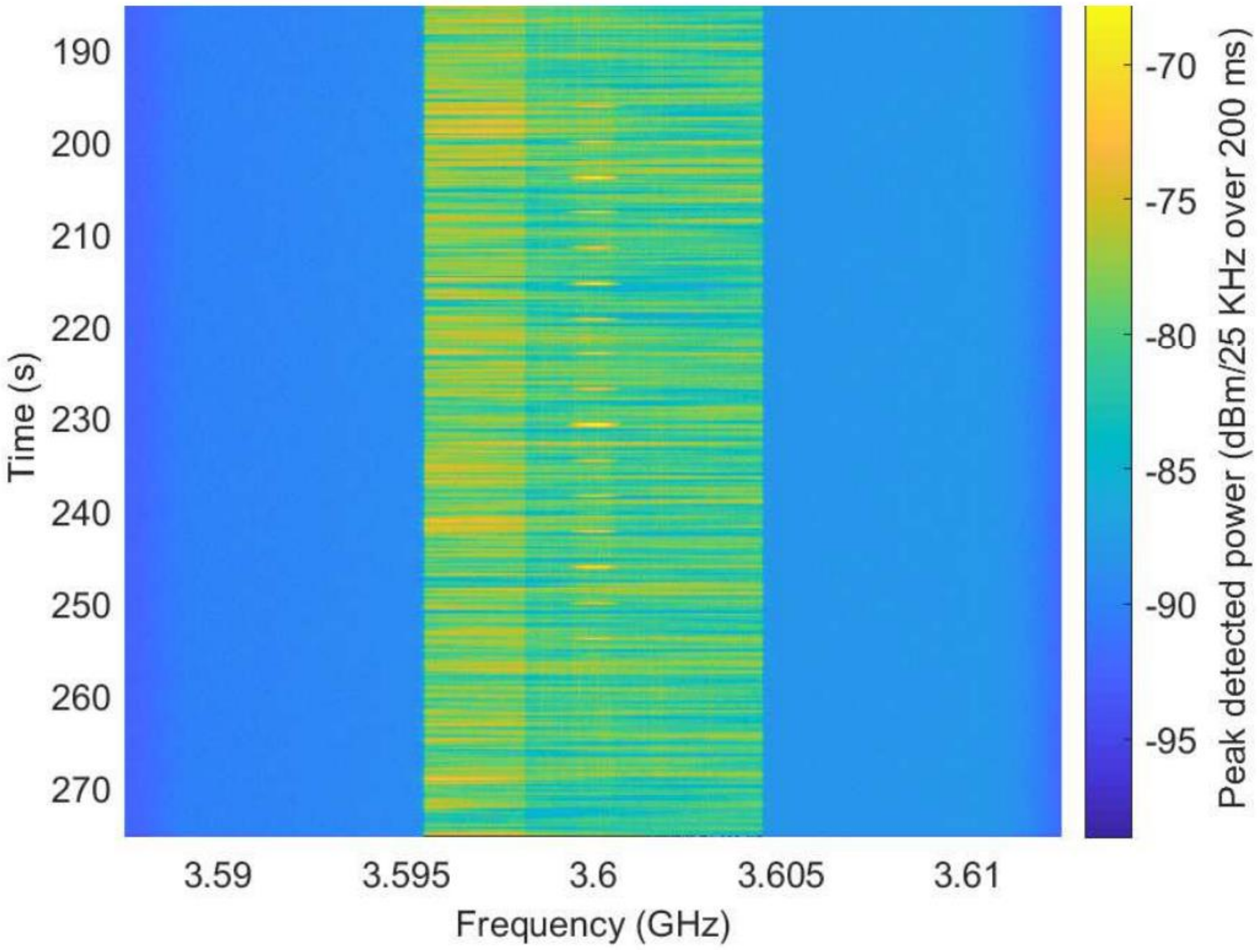
Signal Generator

RF sensor under test

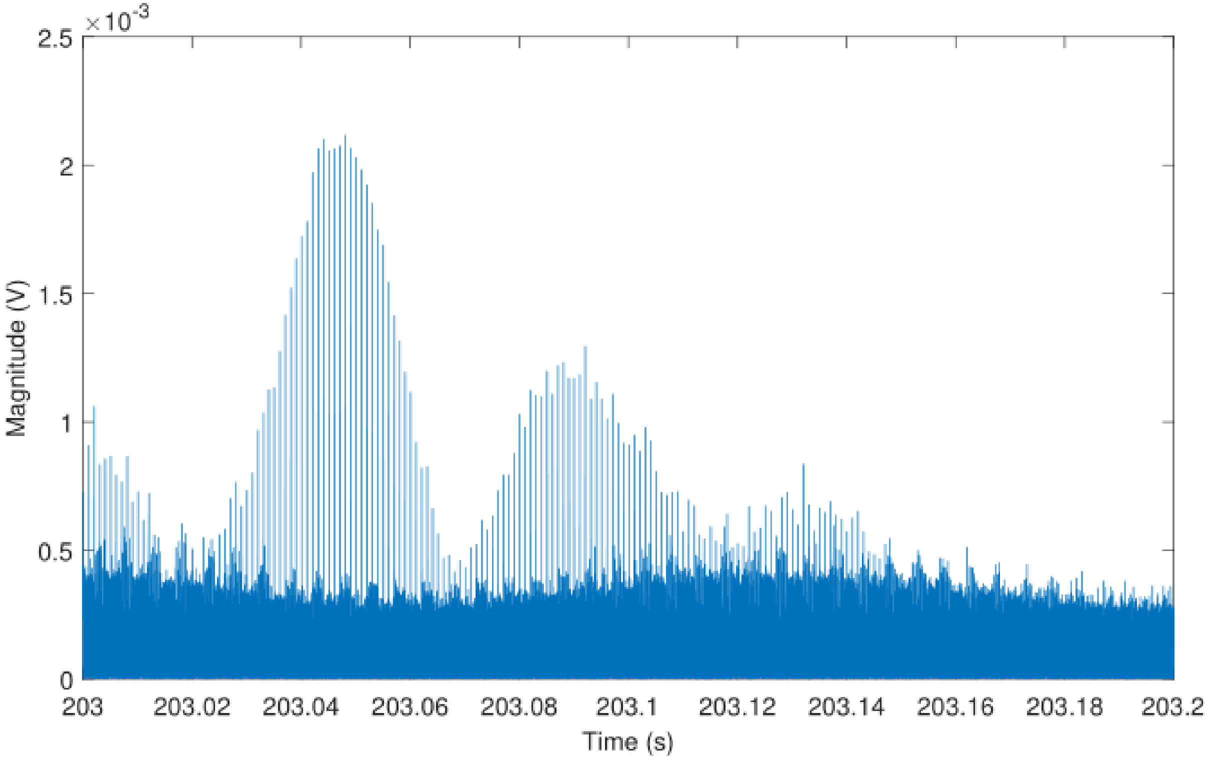
(e.g., 3.5 GHz ESC sensor)

Test Waveform Examples

Spectrogram of in-band radar signal with co-channel LTE



Time-domain plot of a 0.2s portion of the in-band radar signal with co-channel LTE (at the 203s mark of the test)



R. Caromi *et al.*, “3.5 GHz ESC Sensor Test Apparatus Using Field-Measured Waveforms,” in *Proc. Wireless Innovation Forum Summit on Wireless Communications Technologies* (WInnComm), Nov. 2018.

Radar Detection with Full IQ Waveforms

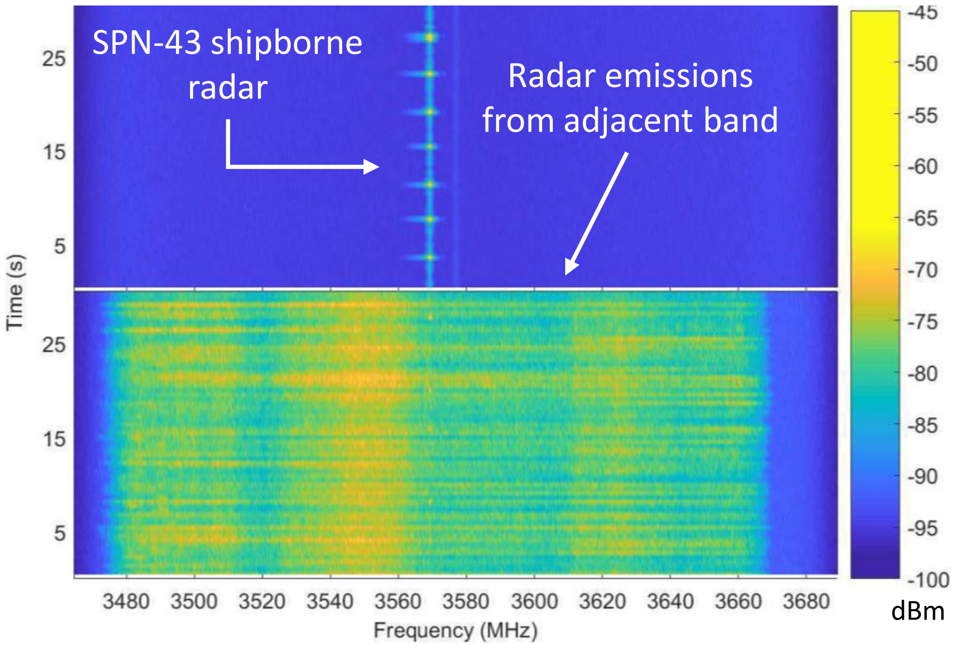
Motivation: Commercial-federal spectrum sharing relies on a network of commercial sensors that detect federal incumbent signals in presence of commercial signals and out-of-band emissions from adjacent bands.

Question: How well can sensors detect incumbent signals in the band?

Classical Approach: Filter matched to known parameters

Problem: Sensors may have only partial knowledge of incumbent waveforms and interference.

New Approach: Machine learning model trained to identify incumbent signals embedded in noise/ interference



NIST is Applying Machine-Learning to RF Detection

NIST

Feature-based support-vector machines

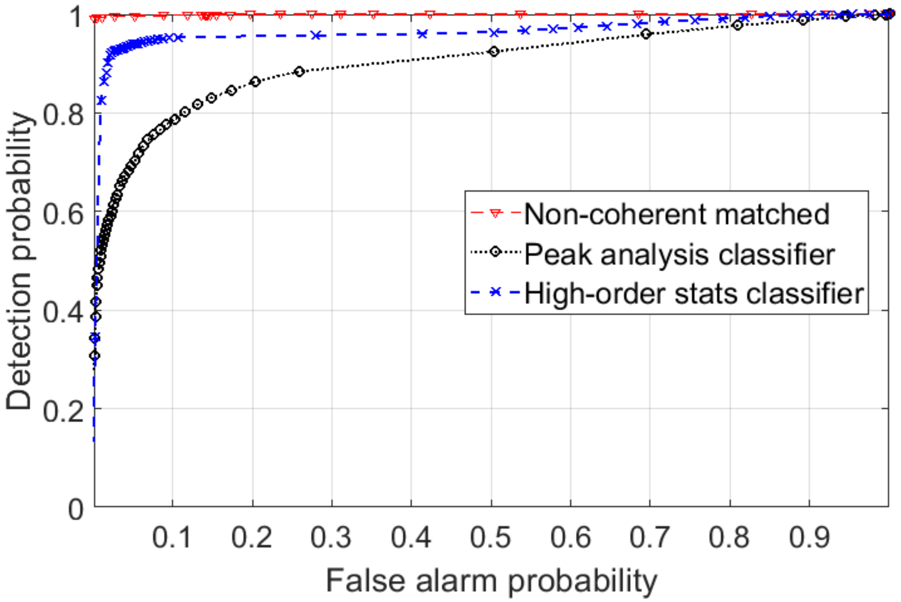
- Higher-order statistics classifier
- Peak-analysis classifier

Less computationally expensive to generalize than a matched filter (conventional)

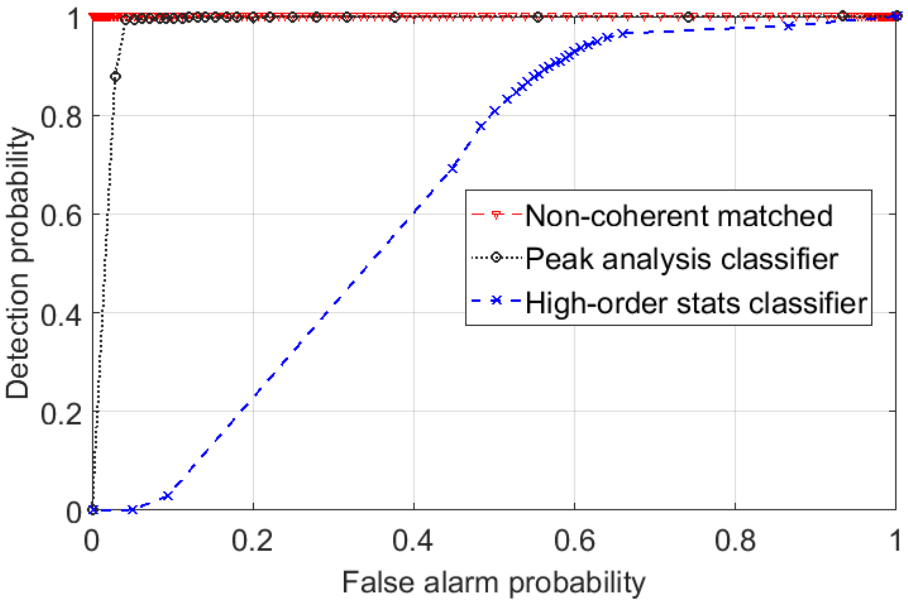
Evaluated with field measurements of 3.5 GHz band (+ simulated LTE)

Peak-analysis classifier excels at distinguishing in-band from adjacent-band radars.

Seeing promising results from deep learning neural networks



LTE Interference at –102 dBm/MHz



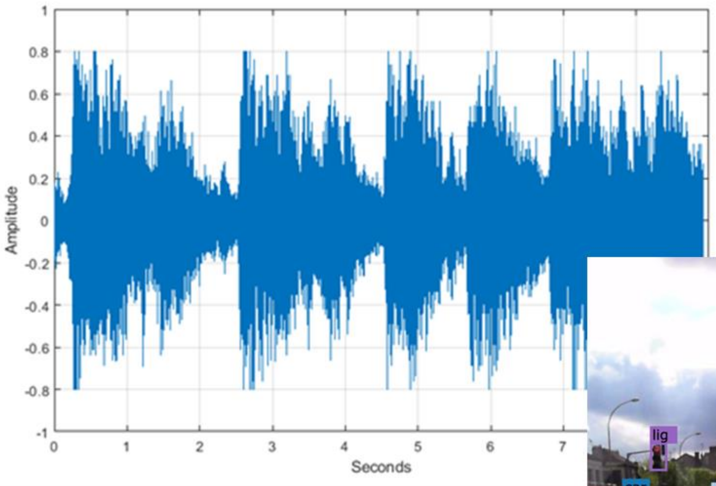
Adjacent-Band Radar Interference at 10 dB to 20 dB interference-to-noise ratio

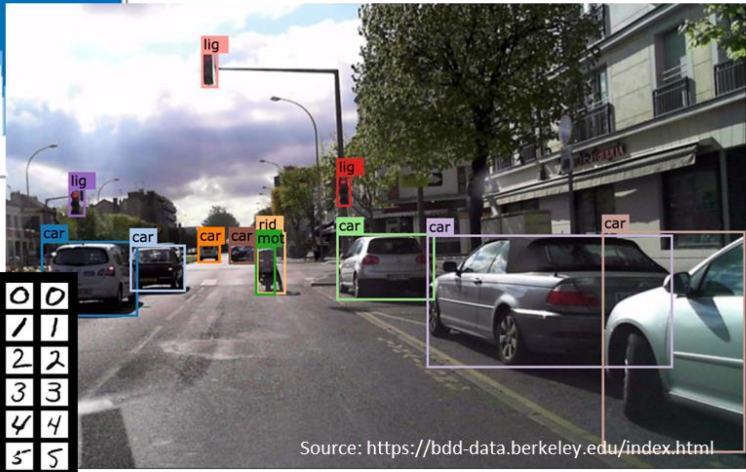
RF Signal Data Sets for Training AI Models

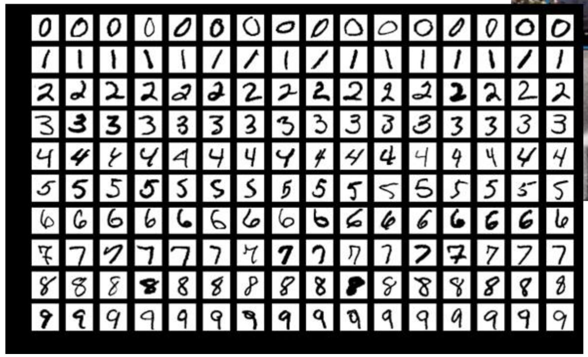
Recognized data sets exist in domains such as speech, object, and handwriting recognition.

“No robust competition data sets exist in the ... radio domain.”*

* T. J. O’Shea, J. Corgan, “Convolutional radio modulation recognition networks,” CoRR, 2016.







MNIST dataset [Josef Steppan under CC BY-SA 4.0]

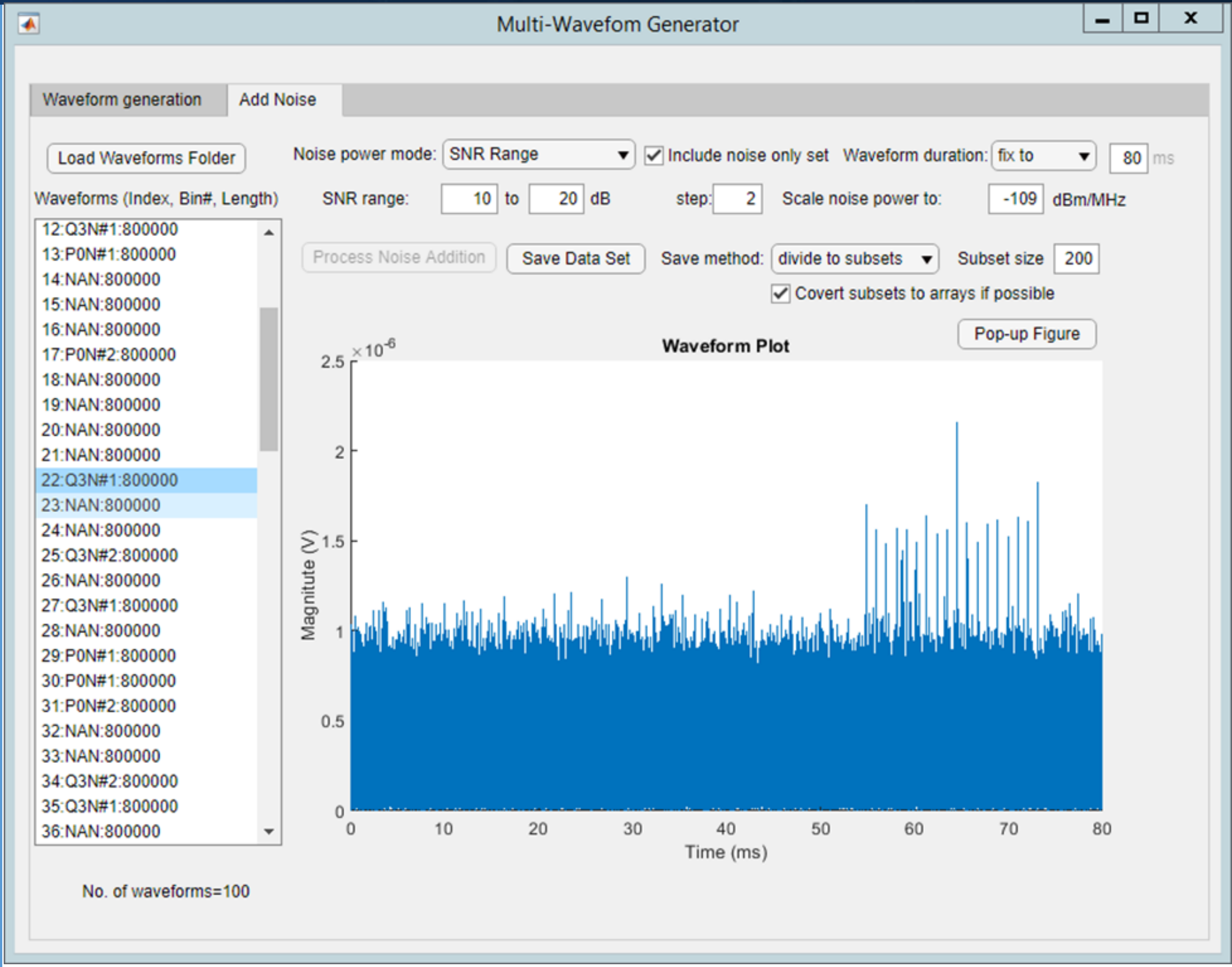
RF Signal Data: Characteristics and Sources

Goal: Publicly Available Database of RF Signal Data

- Targets next generation communication systems
- Composed of traceable data
- Curated to produce a representative range of signals, noise, and channels

Sources

- Field measurements
- Testbeds
- Simulation
- Other organizations



NIST/CTL Surrogate Radar Waveform Generator

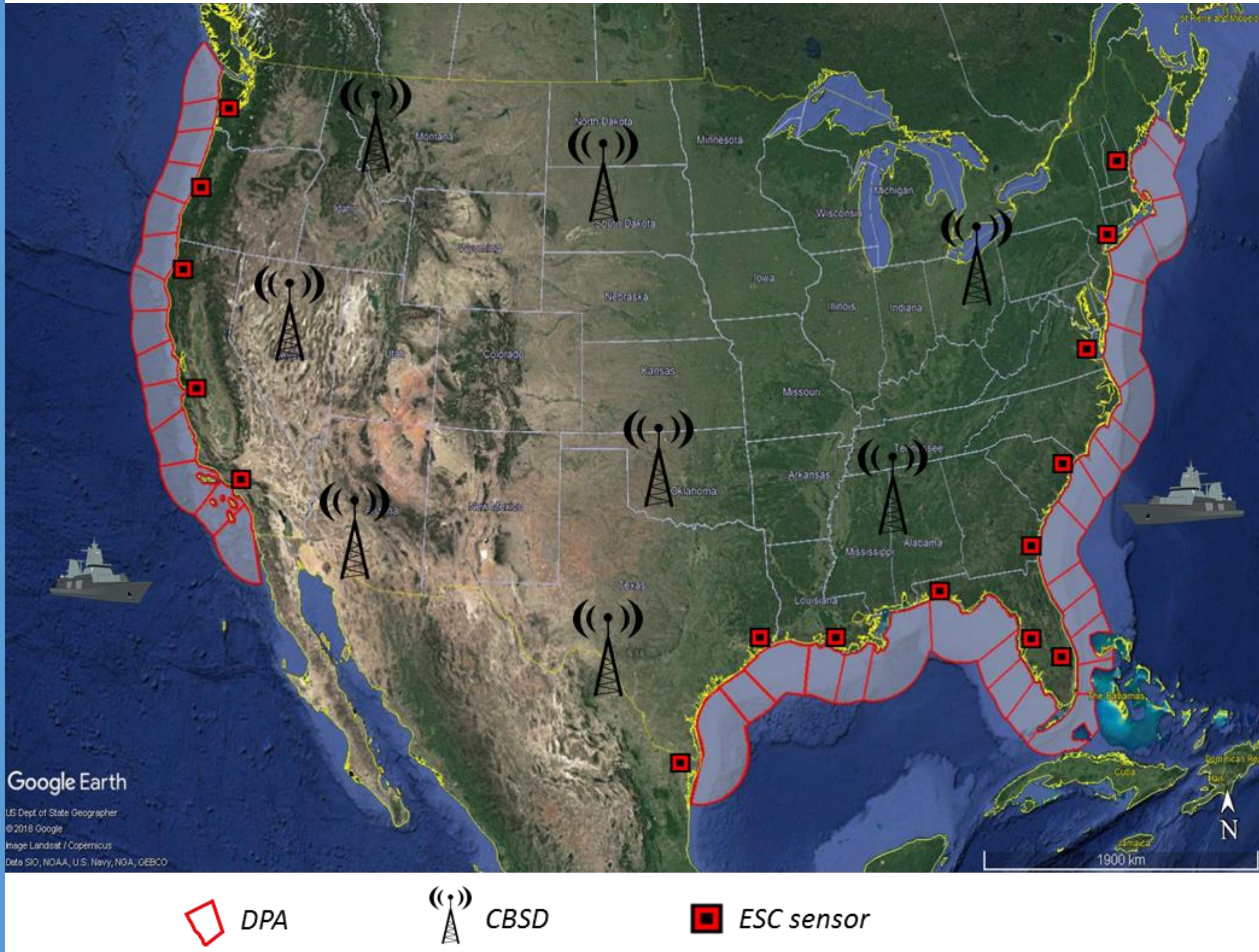
Deployment of RF Sensors for Incumbent Detection

Main Contribution

- **Methodology for determining placement and antenna configuration of sensors to detect incumbent operations, using:**
  - Existing tower sites as candidate locations for the sensors
  - Irregular Terrain Model (ITM) in point-to-point mode for path loss

Applications

- **Planning and deployment of sensors by commercial operators** (e.g., 3.5 GHz ESC)
- **Evaluation and certification of sensor network designs by regulators**



Deployment of RF Sensors: Technical Approach

Motivation – CBRS use case:
Environmental Sensing Capability (ESC) sensors deployed along the coasts are required to detect the presence of incumbent shipborne radar inside a Dynamic Protection Area (DPA).

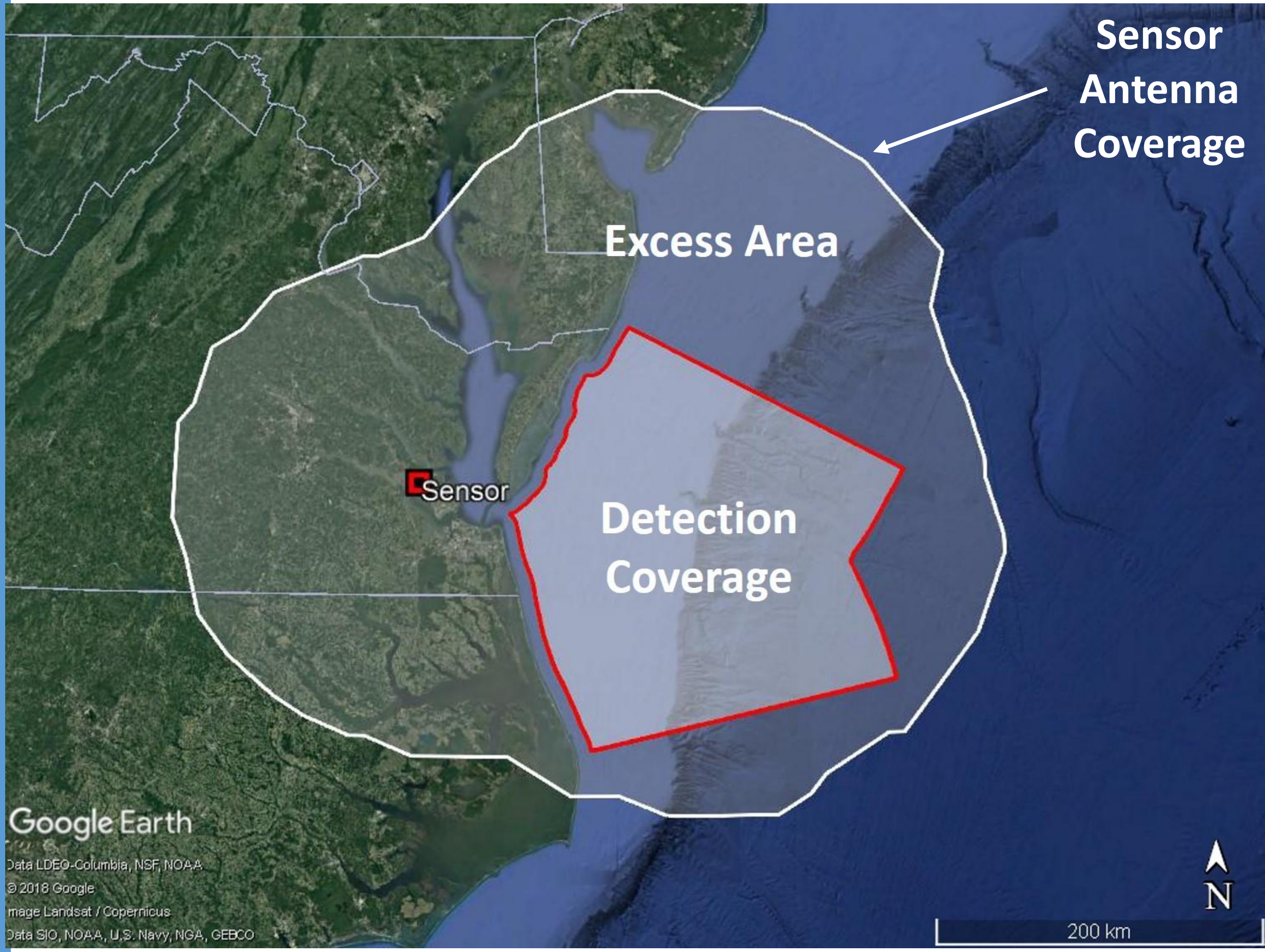
Definitions:

Detection coverage – area of DPA covered by sensor(s)

Excess area – area outside a DPA (neighboring DPAs, sea, land) detected by sensor(s)

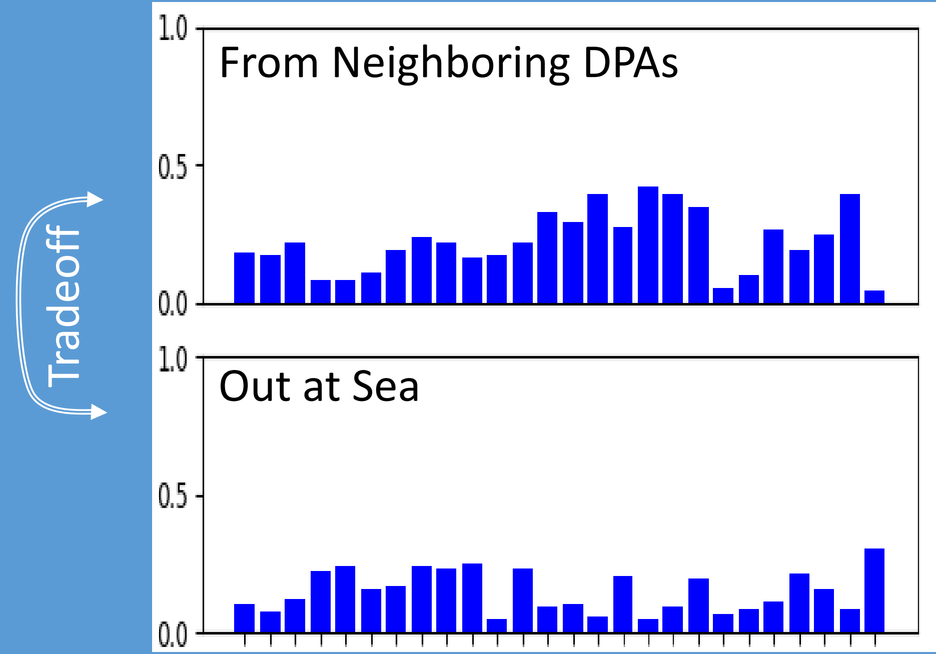
Objective: Determine locations and parameters of sensor antennas such that:

1. Detection coverage is maximized (protect incumbent)
2. Excess area is minimized (avoid unnecessary disruption of commercial operations)



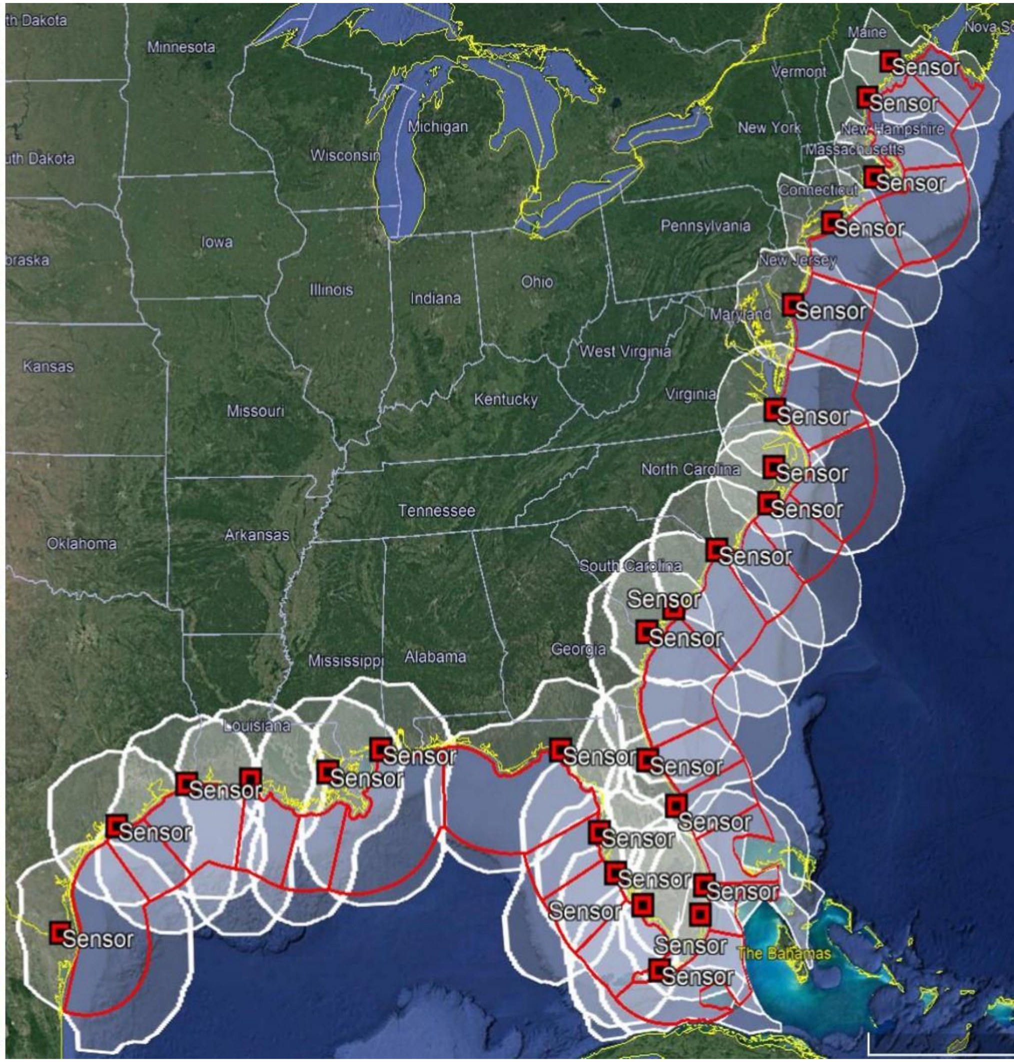
Sensor Deployment Along U.S. Coasts

Key Findings:
- A single antenna can fully cover each DPA.
- Most sensors employ:
  - A maximum antenna height of 100 m
  - Antennas with small beamwidths and high gains, e.g., (30°, 18 dBi) and (45°, 17 dBi)
- Probability of false alarm:



East Coast DPA

West Coast



East/Gulf Coasts

NIST Contributions to 3.5 GHz Spectrum Sharing

NIST

- ✓Requirements for SAS and ESC systems (in WINNF-TS-0112, CBRS Operational and Functional Requirements)
- ✓Procedures for testing CBRS protocols and interference management (in WINNF-TS-0061, SAS Test and Certification Specification)
  - ➢ Federal incumbent interference protection
  - ➢ Multiconstraint interference protection
- ✓Reference implementation of the CBRS federal incumbent protection algorithm (https://github.com/Wireless-Innovation-Forum/)
- ✓CBRS incumbent occupancy and noise statistics from CNN-labelled measurements
- ✓RF sensor test waveforms comprised of field measurements and generated signals
- ✓ML models for detection of radar signals embedded in LTE and OOB emissions
- ✓RF sensor deployment algorithms for efficient coverage of protection areas
- ✓Technical expertise on protocols, propagation models, and interference models to standards groups and to the Federal 3.5 GHz Joint Working Group

Recent Publications and Patents

1. "Deep Learning Classification of 3.5 GHz Band Spectrograms with Applications to Spectrum Sensing," W. M. Lees, A. Wunderlich, P. Jeavons, P. D. Hale, and M. R. Souryal, *IEEE Transactions on Cognitive Communications and Networking*, vol. 5, no. 2, pp. 224-236, June 2019.
2. "Detection of Incumbent Radar in the 3.5 GHz CBRS Band Using Support Vector Machines," R. Caromi and M. Souryal, in *Proc. IEEE Sensor Signal Processing for Defence* (SSPD), May 2019.
3. "Optimal Dynamic Spectrum Access Scheme for Utilizing White Space in LTE Systems," A. Sahoo, T. A. Hall, C. Hagwood, in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, April 2019.
4. "A Practical Approach to Place Coastal Sensors for Spectrum Sharing in the 3.5 GHz Band," A. Sahoo, T. T. Nguyen and T. A. Hall, in *Proc. IEEE WCNC,* April 2019.
5. "Analytical Modeling of White Space Utilization for a Dynamic Spectrum Access System," C. Hagwood, A. Sahoo, T. A. Hall, in *Proc. IEEE WCNC,* April 2019.
6. "Detection of Incumbent Radar in the 3.5 GHz Band," R. Caromi, M. Souryal, and W.-B. Yang, in *Proc. IEEE Global Conference on Signal and Information Processing* (GlobalSIP), Nov. 2018.
7. "3.5 GHz ESC Sensor Test Apparatus Using Field-Measured Waveforms," R. Caromi, J. Mink, C. Wedderburn, M. Souryal, and N. El Ouni, in *Proc. Wireless Innovation Forum Summit on Wireless Communications Technologies* (WInnComm), Nov. 2018.
8. U. S. Patent Application Pub. No. US 2018/0302920, "Apparatus and Method for Dynamically Controlling Spectrum Access," T. A. Hall, A. Sahoo, C. Hagwood, S. Streett, Oct. 2018.
9. "3.5 GHz Federal Incumbent Protection Algorithms," M. R. Souryal, T. T. Nguyen, and N. J. LaSorte, in *Proc. IEEE International Symposium on Dynamic Spectrum Access Networks* (DySPAN), Oct. 2018.
10. "Sensor Placement and Detection Coverage for Spectrum Sharing in the 3.5 GHz Band," A. Sahoo, M. Ranganathan, T. Nguyen, and T. Hall, in *Proc. IEEE PIMRC*, Sept. 2018.

Recent Publications and Patents (cont.)

11. “Spectrum Occupancy and Ambient Power Distributions for the 3.5 GHz Band Estimated from Observations at Point Loma and Fort Story,” W. M. Lees, A. Wunderlich, P. Jeavons, P. Hale, and M. Souryal, NIST Technical Note 2016, Sept. 2018.
12. “Dynamic Spectrum Access Algorithms Based on Survival Analysis,” T. Hall, A. Sahoo, C. Hagwood, and S. Streett, *IEEE Transactions on Cognitive Communications and Networking*, vol. 3, no. 4, pp. 740-751, Dec. 2017.
13. "3.5 GHz Environmental Sensing Capability Detection Thresholds and Deployment," T. T. Nguyen, M. R. Souryal, A. Sahoo, and T. A. Hall, *IEEE Transactions on Cognitive Communications and Networking*, vol. 3, no. 3, pp. 437-449, Sept. 2017.
14. “3.5 GHz Radar Waveform Capture at Fort Story: Final Test Report,” P. Hale, J. Jargon, P. Jeavons, M. Souryal, A. Wunderlich, and M. Lofquist, NIST Technical Note 1967, NASCTN Report 3, July 2017.
15. “3.5 GHz Radar Waveform Capture at Point Loma: Final Test Report,” P. Hale, J. Jargon, P. Jeavons, M. Souryal, A. Wunderlich, and M. Lofquist, NIST Technical Note 1954, NASCTN Report 2, May 2017.
16. “Exploiting LTE White Space Using Dynamic Spectrum Access Algorithms based on Survival Analysis,” T. Hall, A. Sahoo, C. Hagwood, and S. Streett, in *Proc. IEEE International Conference on Communications* (ICC), May 2017.
17. “3.5 GHz Environmental Sensing Capability Sensitivity Requirements and Deployment,” T. Nguyen, A. Sahoo, M. Souryal, and T. A. Hall, in *Proc. IEEE DySPAN*, Mar. 2017.
18. “Fair Resource Allocation in the Citizen Broadband Radio Service Band,” A. Sahoo, in *Proc. IEEE DySPAN*, Mar. 2017.
19. “An Analytical Model for Inference Attacks on the Incumbent's Frequency in Spectrum Sharing,” A. Ben Mosbah, T. A. Hall, M. Souryal, and H. Afifi, Best Poster Award, in *Proc. IEEE DySPAN*, Mar. 2017.
20. “Analysis of the Vulnerability of the Incumbent Frequency to Inference Attacks in Spectrum Sharing,” A. Ben Mosbah, T. A. Hall, M. Souryal, and H. Afifi, in *Proc. IEEE Consumer Communications & Networking Conference* (CCNC), Jan. 2017.

Standards Contributions

1. “Requirements for Commercial Operation in the U.S. 3550-3700 MHz Citizens Broadband Radio Service Band,” WINNF-TS-0112, Version V1.7.0, May 7, 2019.
2. “Test and Certification for Citizens Broadband Radio Service (CBRS); Conformance and Performance Test Technical Specification; SAS as Unit Under Test (UUT),” WINNF-TS-0061, Version V1.5.0, Apr. 29, 2019.
3. “Signaling Protocols and Procedures for Citizens Broadband Radio Service (CBRS): Spectrum Access System (SAS) - Citizens Broadband Radio Service Device (CBSD) Interface Technical Specification,” WINNF-TS-0016, Version V.1.2.3, Oct. 31, 2018.
4. “Revisions to Federal Incumbent Protection Tests for Inland DPAs,” M. Souryal, WINNF-18-I-00101, WG4, May 22, 2018.
5. “Procedures for Calculating DPA Protection Test Pass/Fail Criteria,” M. Souryal, WINNF-17-I-0289, WG4, Dec. 12, 2017.
6. “Revision to Interference Margin Allocation Path Loss Calculation Requirement,” M. Souryal, WINNF-17-I-0278, WG1, Dec. 4, 2017.
7. “SAS Functional Tests of Interference Protection with Multiple Constraints,” M. Souryal, A. Sahoo, and T. Nguyen, WINNF-17-I-00186, WG4, Aug. 2017.
8. “SAS Functional Tests of Federal Incumbent Protection,” M. Souryal, WINNF-17-I-00167, WG4, Aug. 2017.
9. “Proportional Fair Allocation of Interference Budget,” A. Sahoo, WINNF-17-I-00061, WG1 Coexistence Task Group, Feb. 2017.
10. “ESC Requirements,” S. MacMullan and M. Souryal, WINNF-16-I-0263, Rev. 1, WG4 ESC Certification Task Group, Jan. 25, 2017.
11. “Methodology for Defining a Protection Zone,” M. Souryal and T. Nguyen, WINNF-16-I-00264, WG4 ESC Certification Task Group, Dec. 7, 2016.
12. “Fairness Considerations for Coexistence of GAA users,” A. Sahoo, WINNF-16-I-0218, WG1 Coexistence Task Group, Oct. 2016.