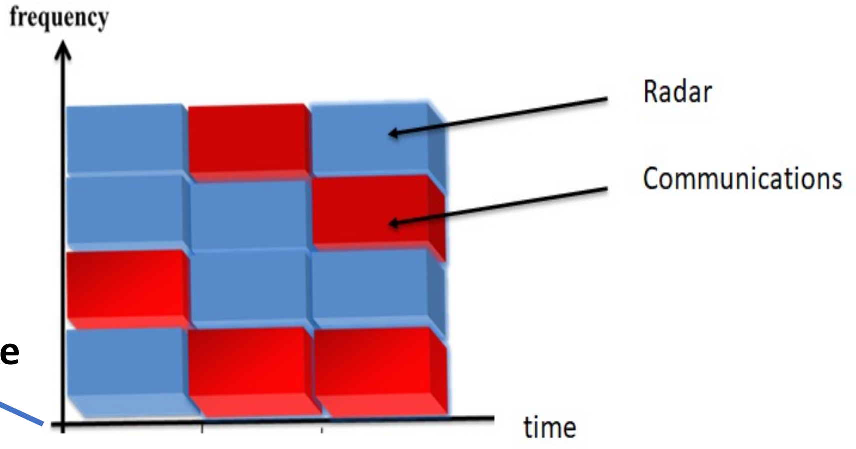
Cognitive Radar Techniques for Spectrum Sharing

Dr. Anthony Martone, IEEE Fellow
DEVCOM Army Research Laboratory

February 22, 2023

Cognitive Radar for Spectrum Sharing: Challenges, Methodologies, and a Path Towards Operation!

- **Outline:**
  - **Spectrum challenges and opportunities: new paradigms for spectrum sharing**
  - **Coexistence definitions**
  - **ARL capability trends**
    - **Non-cooperative coexistence for *radar dynamic spectrum access (DSA)***
  - **Spectrum sensing multi-objective optimization (SS-MO) and how to balance performance trade-off**
  - **Techniques for practical implementation**
  - **The software defined radar (SDRadar) for DSA**
  - **Cognitive loss and the need for cognitive radar technique selection**



Example of spectrum sharing and DSA between radar and communication systems. Both systems access a frequency allocation for a time, then vacant for the others use.

A. Martone, M. Amin, "A view on radar and communication systems coexistence and dual functionality in the era of spectrum sensing," *Digital Signal Processing*, Volume 119, 2021.

- **Thank you!**
  - **IEEE, ARL, AFRL, Syncopated Engineering, National Instruments, Huntington Ingalls Industries, Penn State, University of Kansas, Virginia Tech, Baylor University, Villanova, New York Institute of Technology, University of Oklahoma, Georgia Tech Research Institute, Fraunhofer FKIE**

Spectrum Sharing Challenges

… we will make more

megahertz available f

deployments …. https://

tes, the AWS 3 auction of service licenses raised over

andwidth …

15-131, 2015.

orks *frequency bands*, …

uitous

ines, i.e.,

ternet of

… FAA Sets 5G Flight Restrictions to Avoid Possible Hazards …

The Wall Street Journal 12/7/2021

… mid-band spe

for 5G buildout

and capacity c

https://www.fcc.gov/5G

… more recent C-band auction of se

raised over $81 billion to promote 5G ….

FCC, FCC Starts First 5G Mid-Band Spectrum Auction Today, Wash. D.C., Commis

… while commercial operators have paid annual

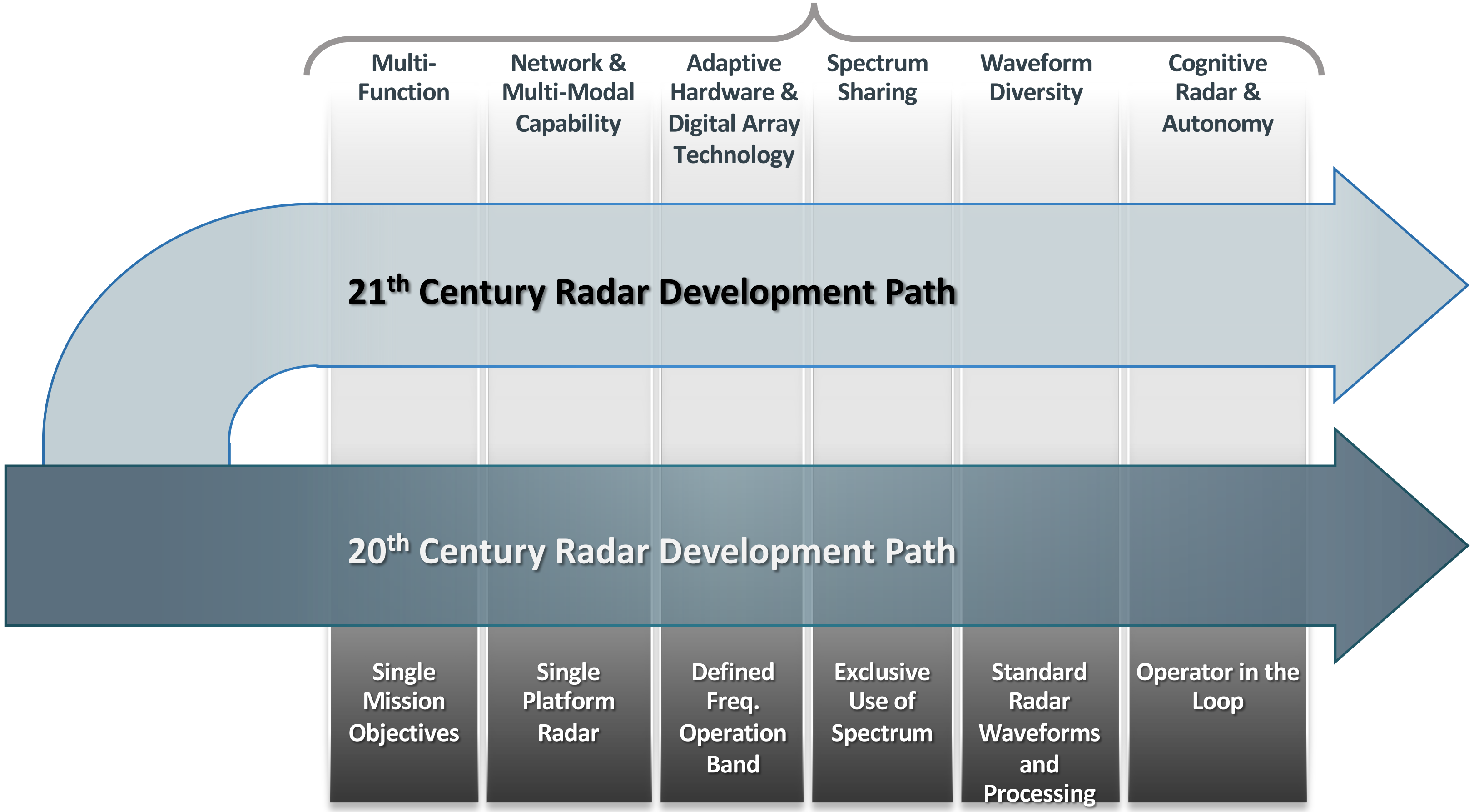
amounts of nearly *£200 million for conti* *data services* …

F. Liu, Joint radar and communication design: applications, state-of-the-art, d ahead, IEEE Trans. Commun. 68(6) (June 2020) 3834–3862

Trajectory for Future Radars

A paradigm shift is needed for future radars:

- Cognitive RF
- Modular, multi-band HW/SW
- Adaptable RF hardware
- COTS technology for radar
- Agile waveforms/DSP
- Networked radar/multi-statics



Multi-Function

Network & Multi-Modal Capability

Adaptive Hardware & Digital Array Technology

Spectrum Sharing

Waveform Diversity

Cognitive Radar & Autonomy

21st Century Radar Development Path

20th Century Radar Development Path

Single Mission Objectives

Single Platform Radar

Defined Freq. Operation Band

Exclusive Use of Spectrum

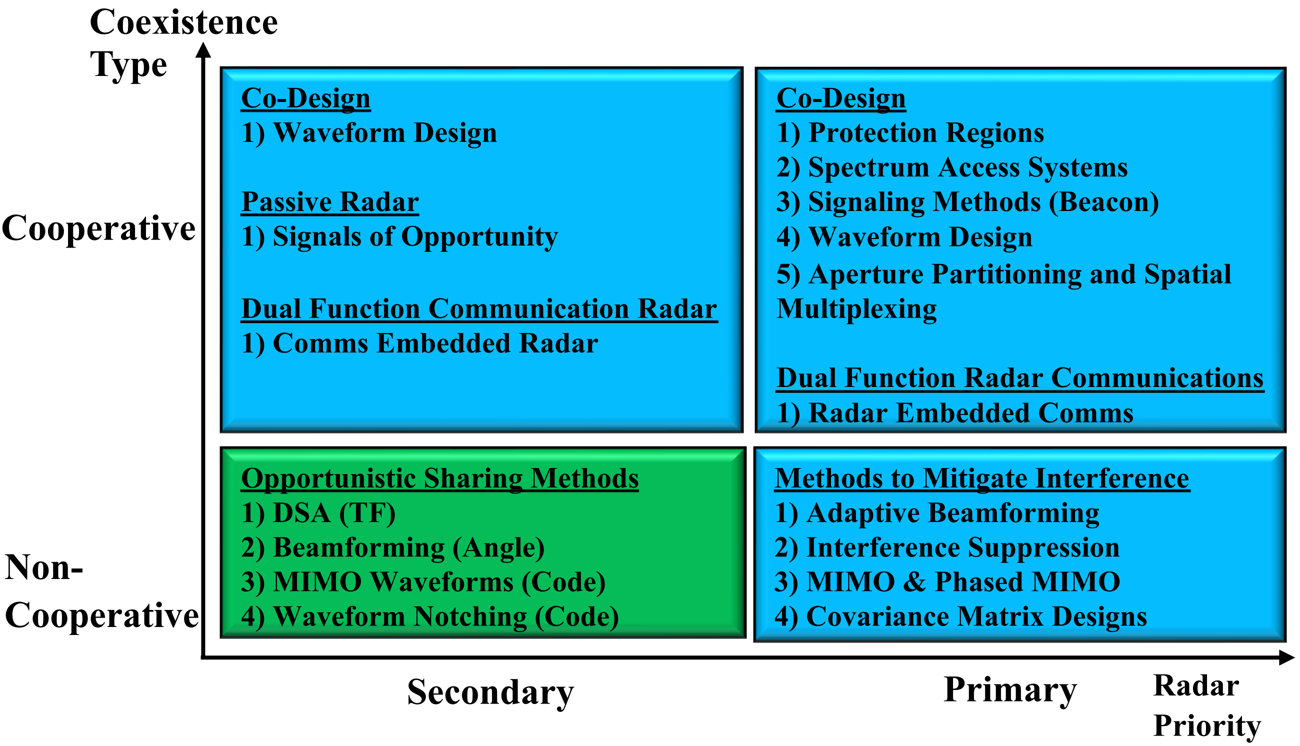
Standard Radar Waveforms and Processing

Operator in the Loop

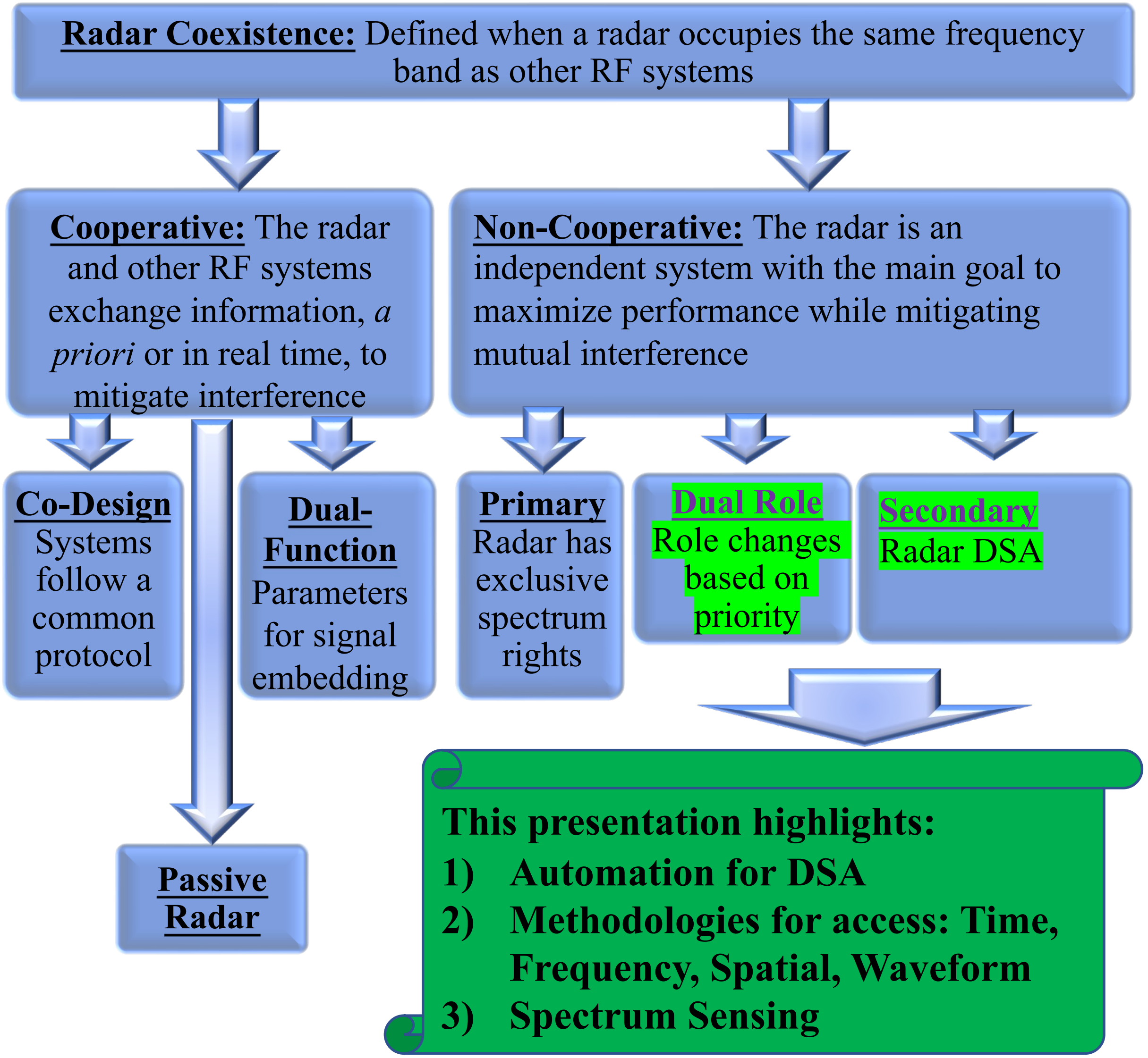
Network of Multifunction RF Sensors for Adaptation to Multiple Environments

Single Platform Radar with Fixed Solutions

Radar Spectrum Sharing Paradigms: Overview and Definitions



Coexistence Type	Secondary	Primary
Cooperative	**Co-Design** 1) Waveform Design **Passive Radar** 1) Signals of Opportunity **Dual Function Communication Radar** 1) Comms Embedded Radar	**Co-Design** 1) Protection Regions 2) Spectrum Access Systems 3) Signaling Methods (Beacon) 4) Waveform Design 5) Aperture Partitioning and Spatial Multiplexing **Dual Function Radar Communications** 1) Radar Embedded Comms
Non-Cooperative	**Opportunistic Sharing Methods** 1) DSA (TF) 2) Beamforming (Angle) 3) MIMO Waveforms (Code) 4) Waveform Notching (Code)	**Methods to Mitigate Interference** 1) Adaptive Beamforming 2) Interference Suppression 3) MIMO & Phased MIMO 4) Covariance Matrix Designs



Radar Coexistence: Defined when a radar occupies the same frequency band as other RF systems

Cooperative: The radar and other RF systems exchange information, *a priori* or in real time, to mitigate interference

Co-Design Systems follow a common protocol

Dual-Function Parameters for signal embedding

Passive Radar

Non-Cooperative: The radar is an independent system with the main goal to maximize performance while mitigating mutual interference

Primary Radar has exclusive spectrum rights

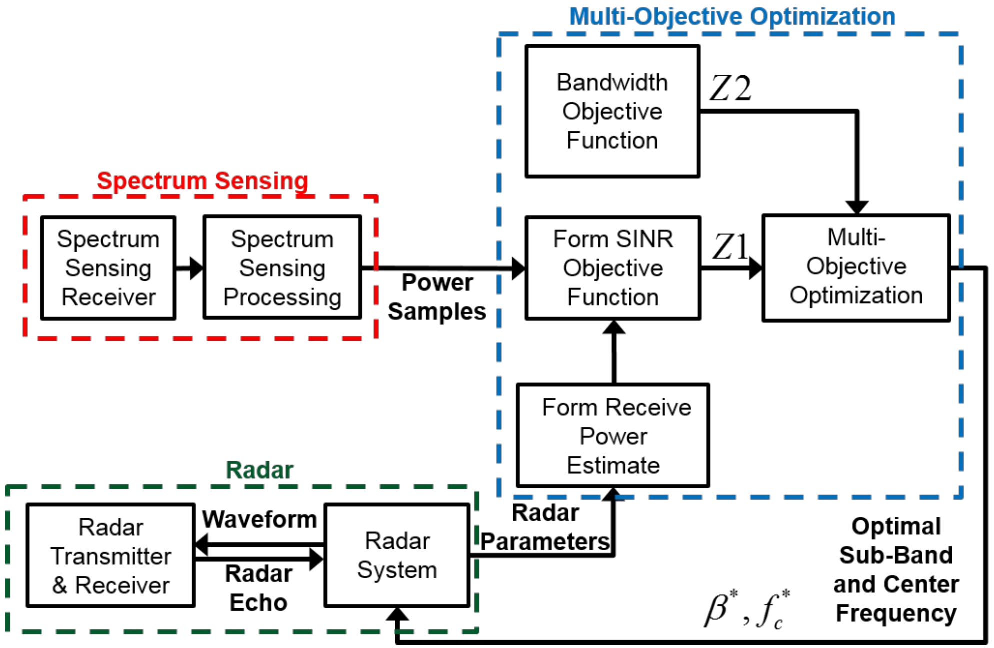
Dual Role Role changes based on priority

Secondary Radar DSA

This presentation highlights:
1) **Automation for DSA**
2) **Methodologies for access: Time, Frequency, Spatial, Waveform**
3) **Spectrum Sensing**

A. Martone, M. Amin, "A view on radar and communication systems coexistence and dual functionality in the era of spectrum sensing," *Digital Signal Processing*, Volume 119, 2021.

Spectrum Sensing Multi-Objective Optimization (SS-MO)



Multi-Objective Optimization

Bandwidth Objective Function

$Z2$

Spectrum Sensing

Spectrum Sensing Receiver

Spectrum Sensing Processing

Power Samples

Form SINR Objective Function

$Z1$

Multi-Objective Optimization

Form Receive Power Estimate

Radar

Radar Transmitter & Receiver

Waveform

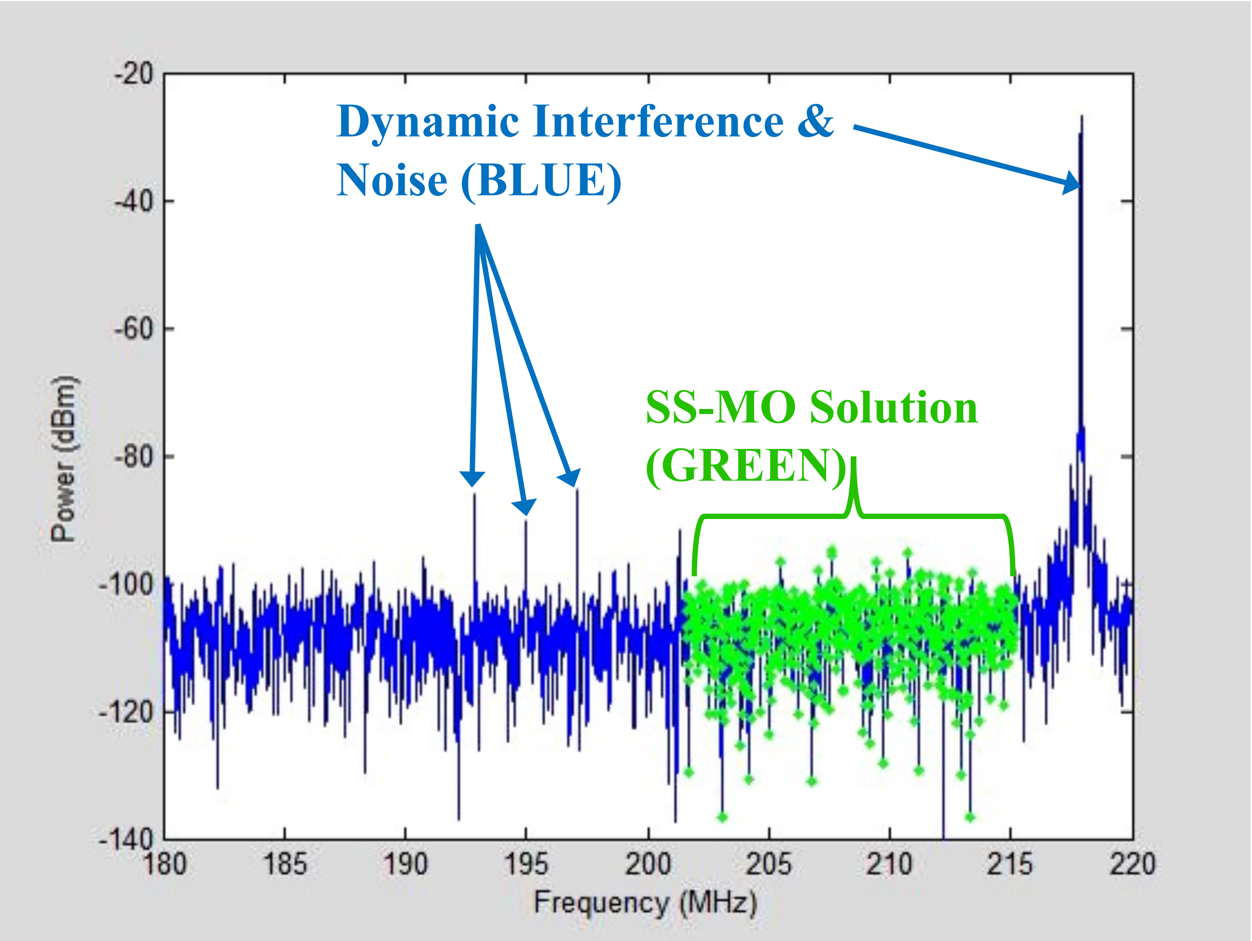
Radar Echo

Radar System

Radar Parameters

Optimal Sub-Band and Center Frequency

β^*, f_c^*



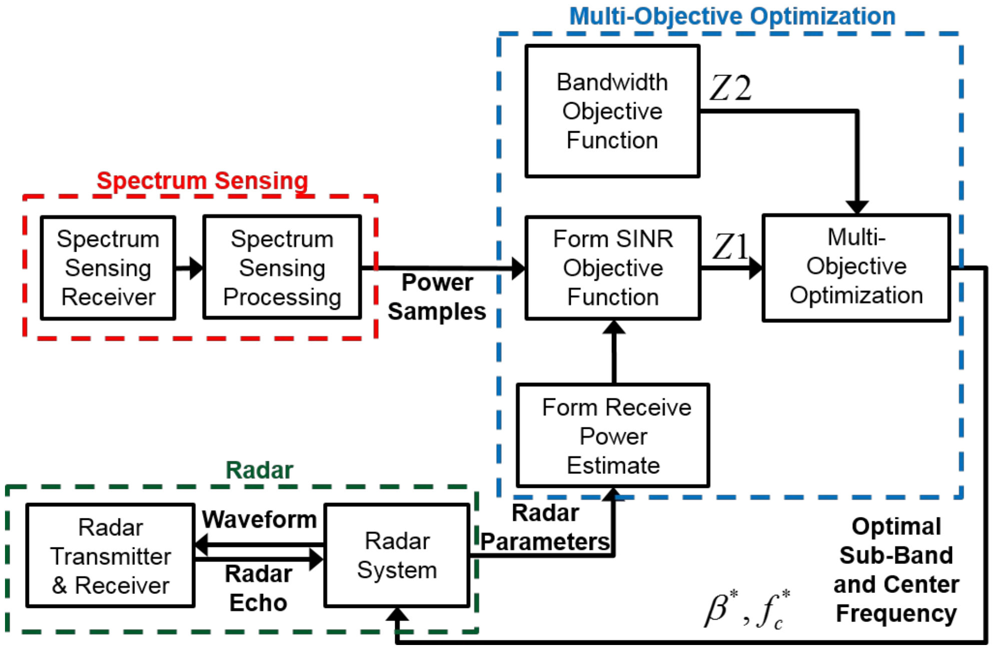
Timing

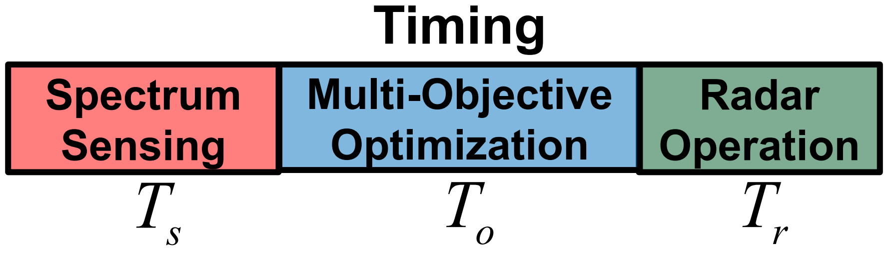
Spectrum Sensing	Multi-Objective Optimization	Radar Operation
T_s	T_o	T_r

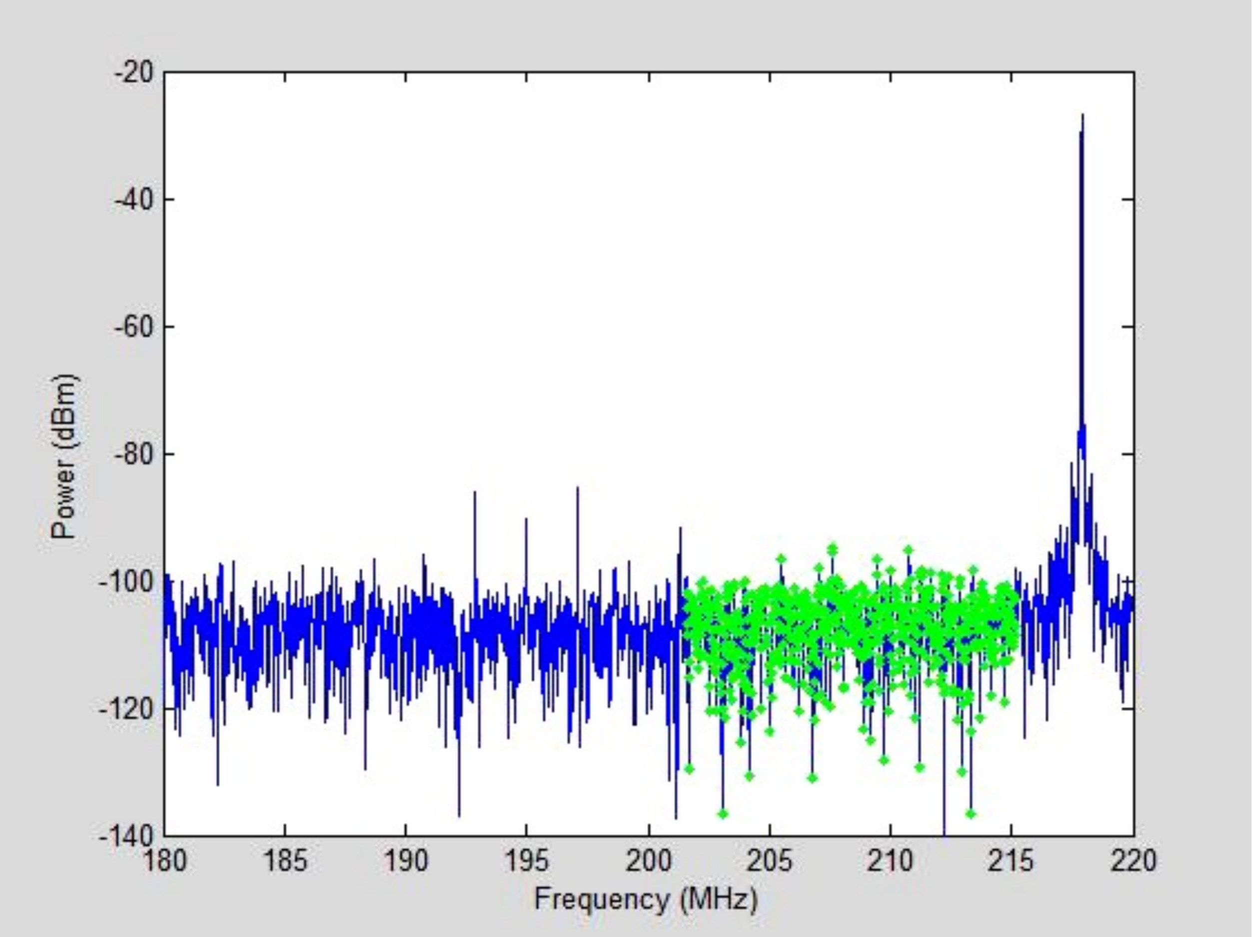
- **Divide the bandwidth into several sub-bands (or channels), where each sub-band has an undefined size & location**
- **Choose the optimal sub-band that maximizes the bandwidth and SINR trade-off for radar.**
- **Reduces the radar spectral footprint while maximizing performance.**

A.F. Martone, K.D. Sherbondy, K.I. Ranney, T.V. Dogaru, "Passive Sensing for Adaptable Radar Bandwidth," in *Proc. of the IEEE Int. Radar Conf.*, Arlington, VA, May, 2015.

Spectrum Sensing Multi-Objective Optimization (SS-MO)





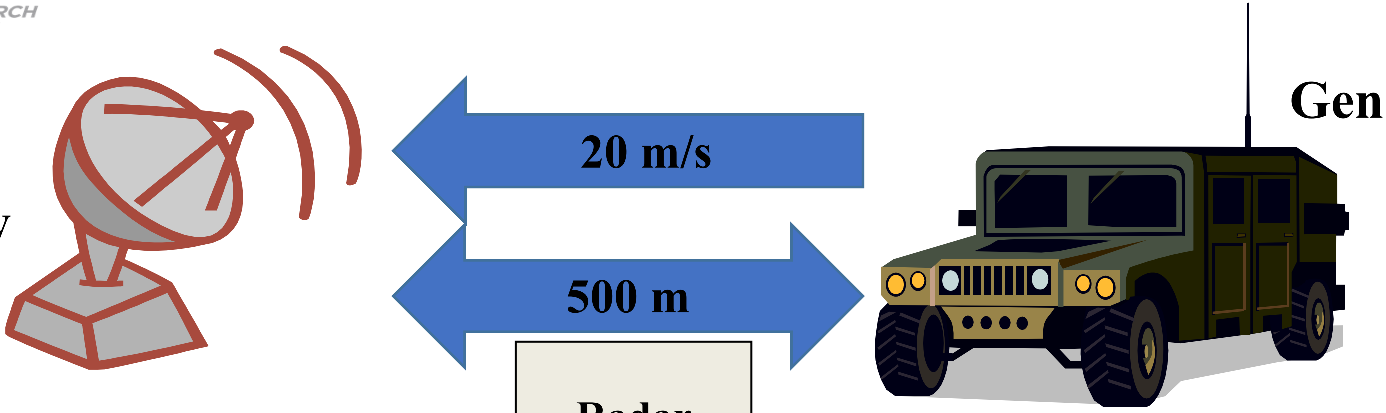


- **Divide the bandwidth into several sub-bands (or channels), where each sub-band has an undefined size & location**
- **Choose the optimal sub-band that maximizes the bandwidth and SINR trade-off for radar.**
- **Reduces the radar spectral footprint while maximizing performance.**

A.F. Martone, K.D. Sherbondy, K.I. Ranney, T.V. Dogaru, "Passive Sensing for Adaptable Radar Bandwidth," in *Proc. of the IEEE Int. Radar Conf.*, Arlington, VA, May, 2015.

DEVCOM
ARMY RESEARCH
LABORATORY

Dual Role Sharing: SS-MO Simulation with Moving Target



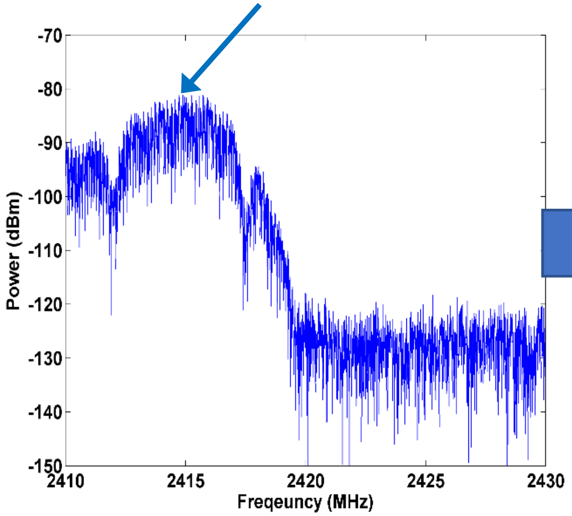
Notional
Stationary
Radar

Generic moving
target

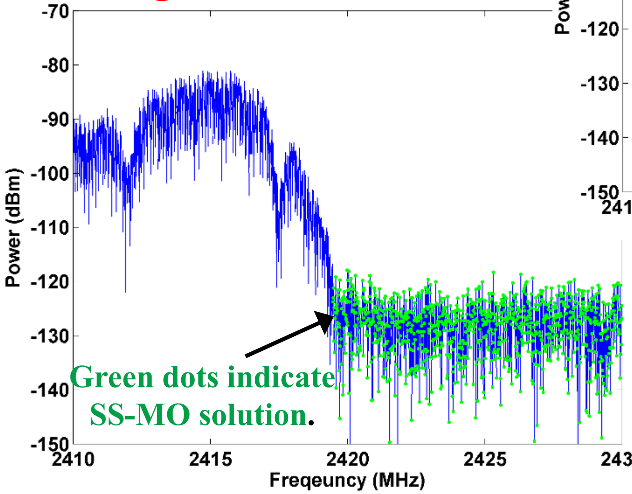
Radar
Model

Spectrum Sensing
Multi-Objective
Optimization

802.11b WLAN Radio:
BLUE SPECTRUM

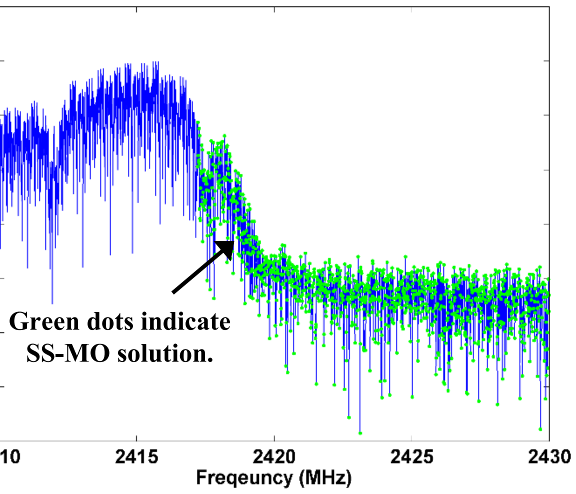


Target Distance 500 m



Green dots indicate
SS-MO solution.

Target Distance 140 m



Green dots indicate
SS-MO solution.

The radar trades off SINR for bandwidth as target distance decreases

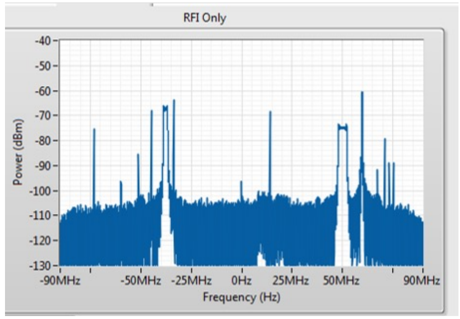
This example considers the radar as the primary system that will share the spectrum if possible but control the spectrum if needed!

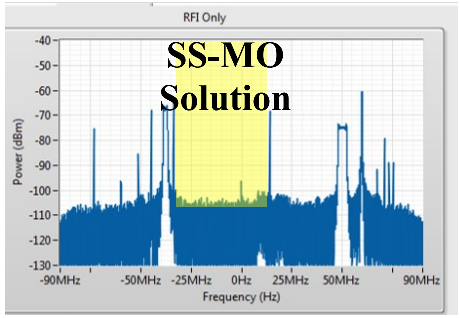
A.F. Martone, et. al., "Early target detection for adaptable MTI radar," *IET Radar, Sonar, and Navigation*, Vol. 11, no. 10, July, 2017.

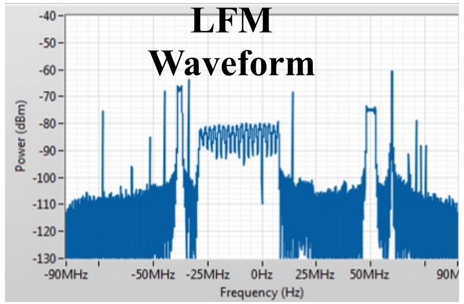
SS-MO Software Defined Radar (SDRadar) Implementation: *From Theory to Practice* (ARL, KU, PSU)

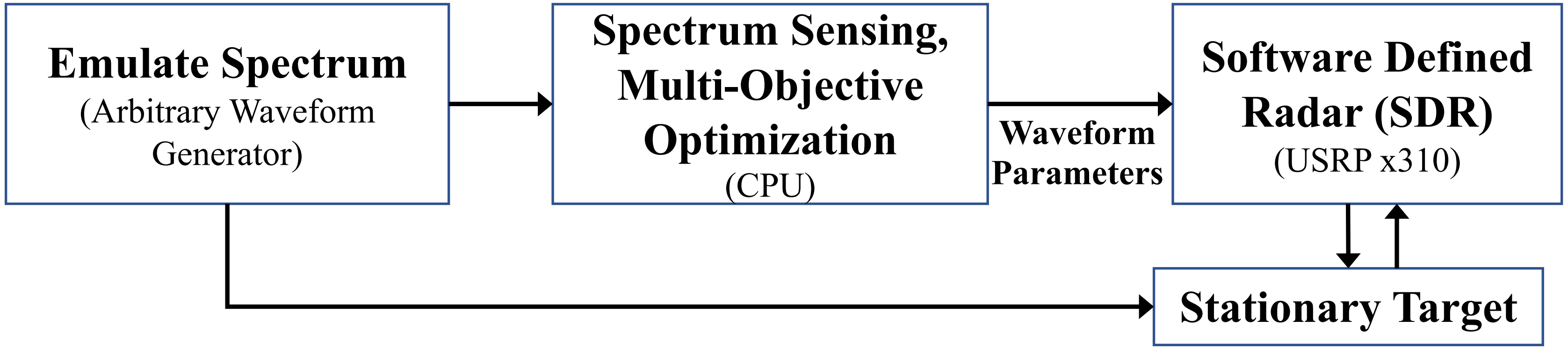
USRP X310 software defined radio (SDR) and host computer

- Economical, well supported platform for RF system development









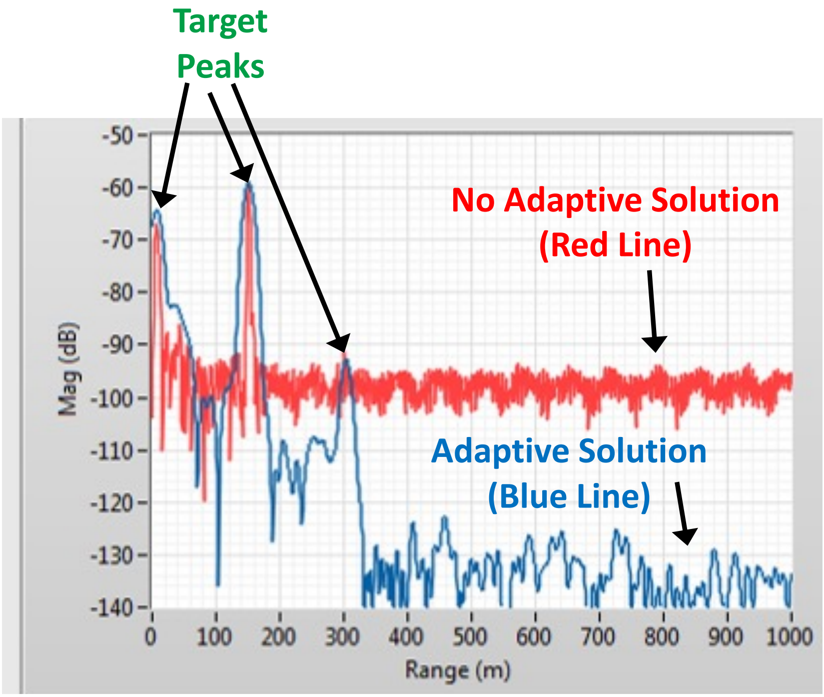
Emulate Spectrum
(Arbitrary Waveform Generator)

Spectrum Sensing, Multi-Objective Optimization
(CPU)

Waveform Parameters

Software Defined Radar (SDR)
(USRP x310)

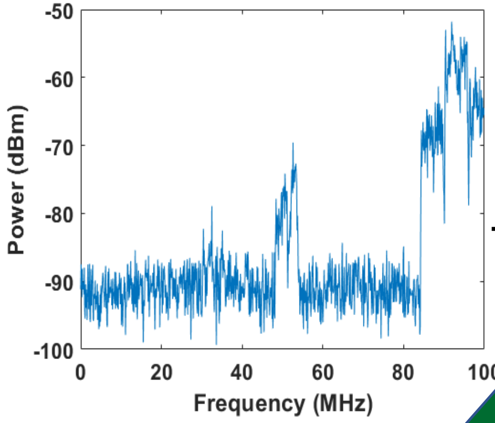
Stationary Target



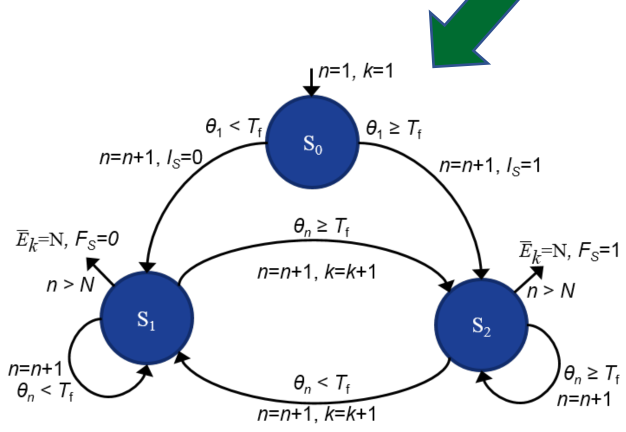
Range Profile

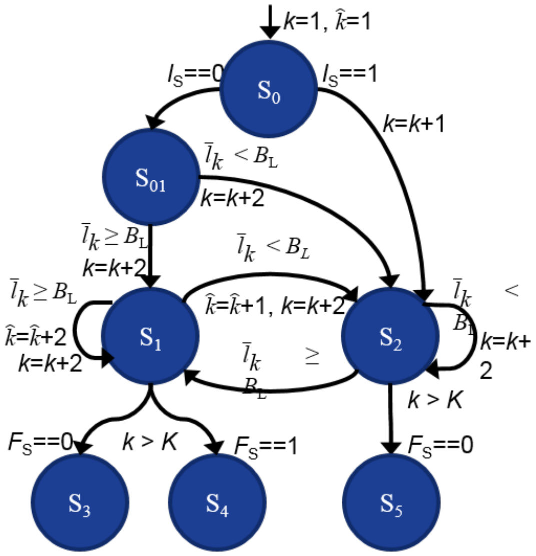
B.H. Kirk, J.W. Owen, R.M. Narayanan, S.D. Blunt, A.F. Martone, K.D. Sherbondy, "Cognitive software defined radar: waveform design for clutter and interference suppression," Radar Sensor Technology XXI, International Society for Optics and Photonics, vol. 10188, Anaheim, CA, pp. 446-461.

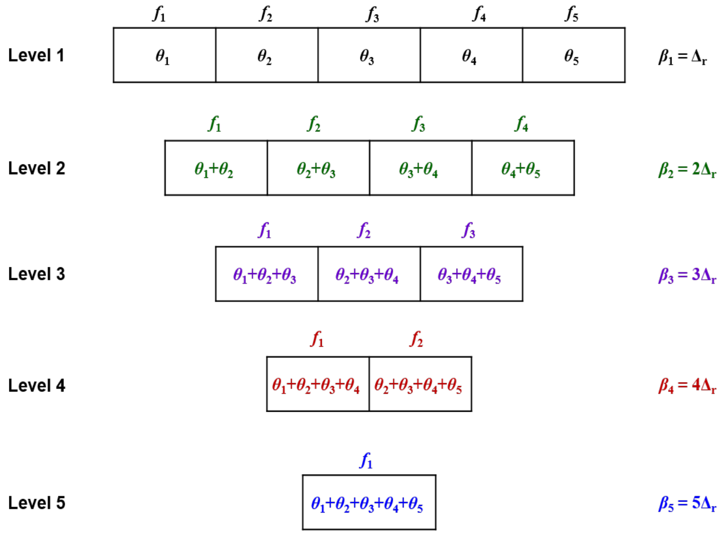
Fast Spectrum Sensing (FSS) Algorithm



Identify Sub-bands → **Merge Sub-bands** → **Multi-Objective Optimization**





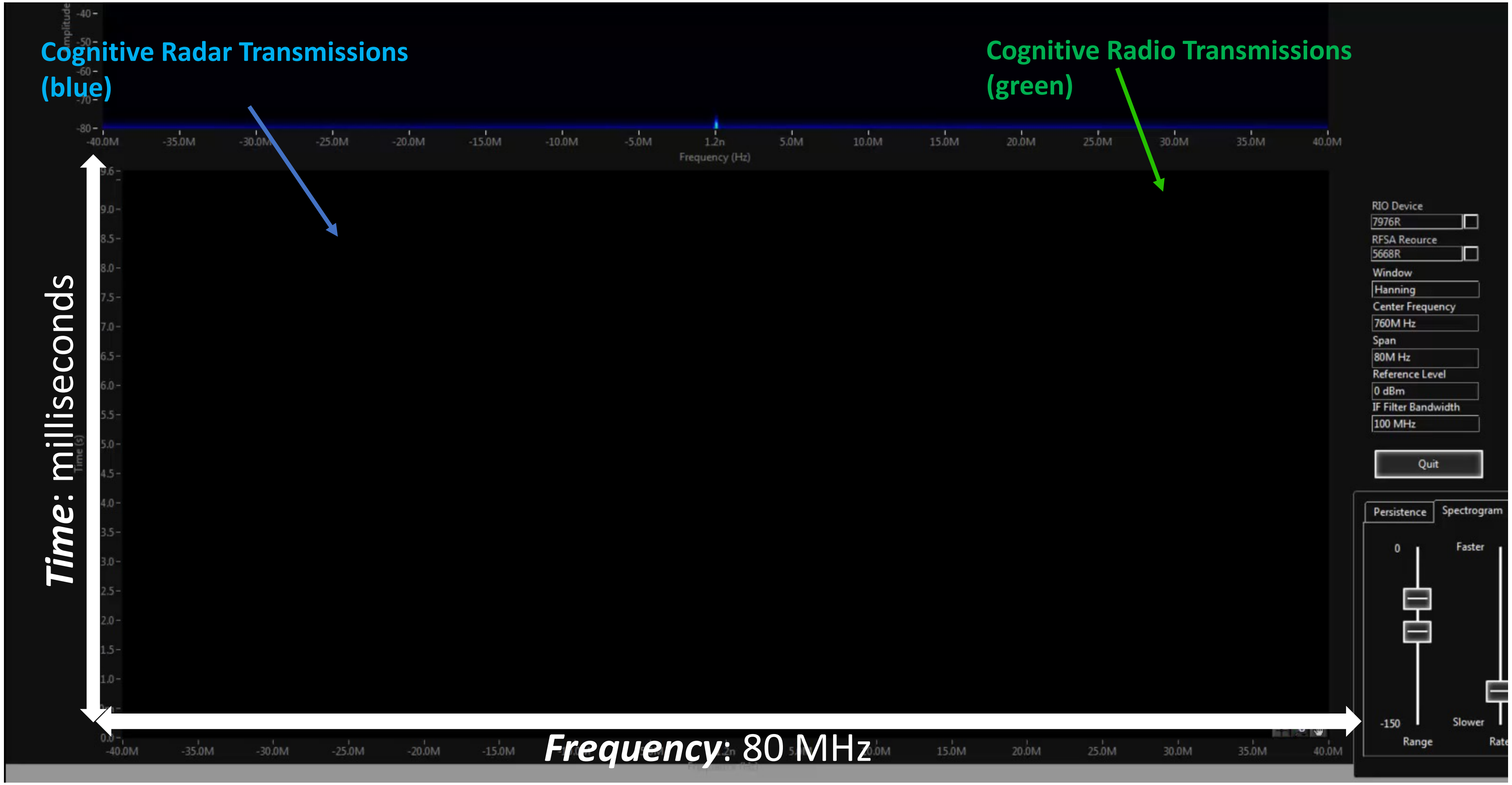


Level 1	f_1 θ_1	f_2 θ_2	f_3 θ_3	f_4 θ_4	f_5 θ_5	$\beta_1 = \Delta_r$
Level 2	f_1 $\theta_1+\theta_2$	f_2 $\theta_2+\theta_3$	f_3 $\theta_3+\theta_4$	f_4 $\theta_4+\theta_5$		$\beta_2 = 2\Delta_r$
Level 3	f_1 $\theta_1+\theta_2+\theta_3$	f_2 $\theta_2+\theta_3+\theta_4$	f_3 $\theta_3+\theta_4+\theta_5$			$\beta_3 = 3\Delta_r$
Level 4	f_1 $\theta_1+\theta_2+\theta_3+\theta_4$	f_2 $\theta_2+\theta_3+\theta_4+\theta_5$				$\beta_4 = 4\Delta_r$
Level 5	f_1 $\theta_1+\theta_2+\theta_3+\theta_4+\theta_5$					$\beta_5 = 5\Delta_r$

The FSS is an algorithm to develop quick spectral situational awareness and refine information.

A. F. Martone, K. I. Ranney, K. Sherbondy, K. A. Gallagher and S. D. Blunt, "Spectrum Allocation for Noncooperative Radar Coexistence," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 54, no. 1, pp. 90-105, Feb. 2018

Real Time SDRadar (with FSS) and Cognitive Radio Demonstration (ARL, Virginia Tech, PSU, KU)



Cognitive Radar Transmissions (blue)

Cognitive Radio Transmissions (green)

Time: milliseconds

Frequency: 80 MHz

RIO Device: 7976R

RFSA Reource: 5668R

Window: Hanning

Center Frequency: 760M Hz

Span: 80M Hz

Reference Level: 0 dBm

IF Filter Bandwidth: 100 MHz

Cognitive Radar *"Reaction"*

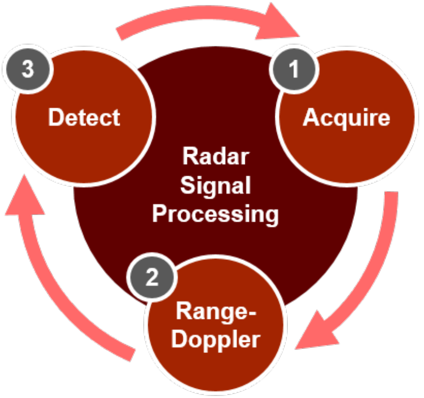
The radar Perception-Action Cycle (PAC) is *significantly faster* compared to the radio, thus:

Coexistence Established!

Is 3.4ms fast enough to establish coexistence with other communication systems?

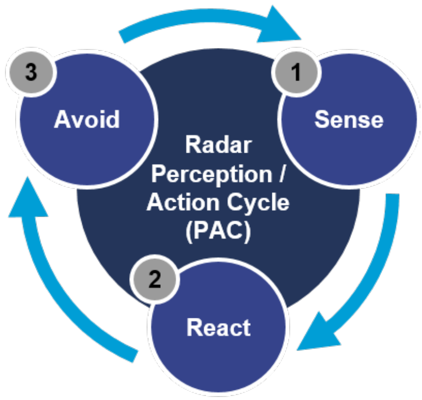
- **Interface Software Defined Radar and Radio**
- **Radar – Ettus x310, 80MHz Bandwidth, 3.4ms adaptation**
- **Radio – Ettus n210, 1 base station and 1 mobile, 1MHz bandwidth, 500ms adaptation**
- **Uplink from mobile to base station is potentially interrupted by radar**
- **Downlink is out of band**

FSS Implementation for Improved Coexistence

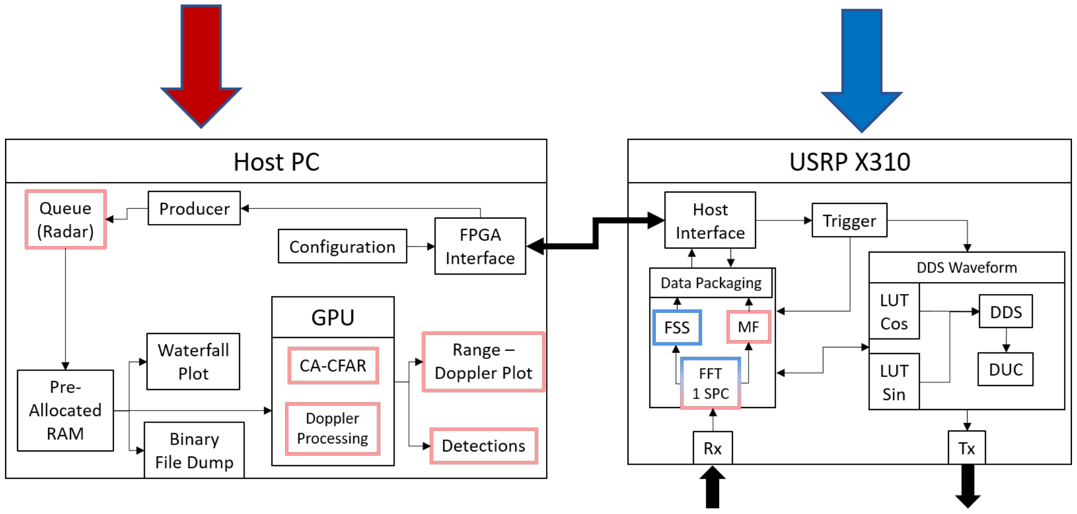


Radar:
- Matched filter
- Doppler processing
- CFAR

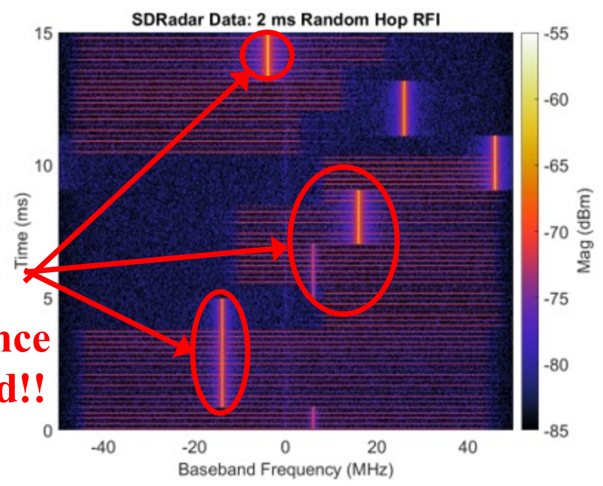
System Resources:
- **Host PC:**
  - CPU
  - GPU
  - RAM
  - VRAM
- **FPGA (SDR):**
  - BRAM
  - DSP 48
  - Slices



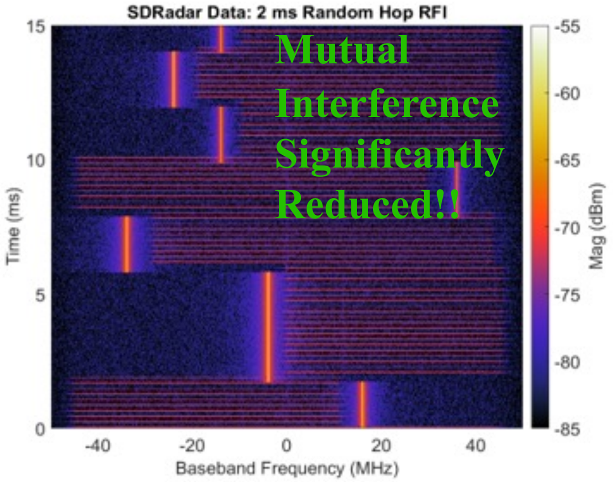
Spectrum Sharing:
- RF sensing
- React (FSS)
- Adapt waveform



Mutual Interference Generated!!

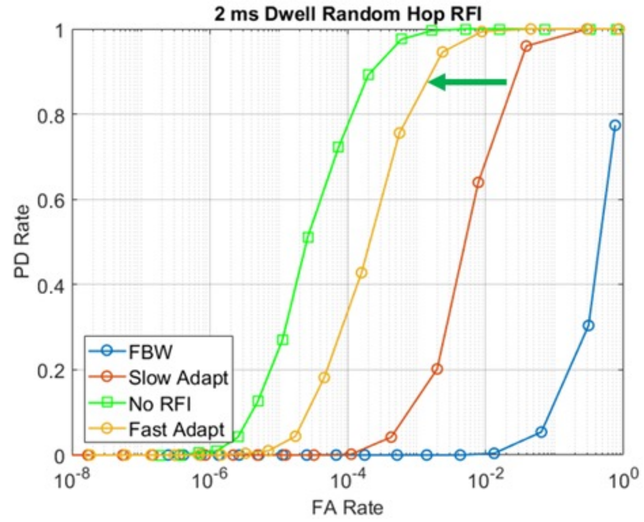


SDRadar: FSS on *Host PC*



Mutual Interference Significantly Reduced!!

SDRadar: FSS on *FPGA*

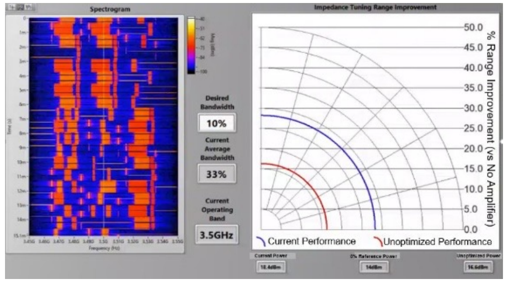


B. H. Kirk, R. M. Narayanan, K. A. Gallagher, A. F. Martone and K. D. Sherbondy, "Avoidance of Time-Varying Radio Frequency Interference With Software-Defined Cognitive Radar," IEEE Transactions on Aerospace and Electronic Systems, vol. 55, no. 3, pp. 1090-1107, June 2019.

Cognitive Radar (CR) Techniques for DSA

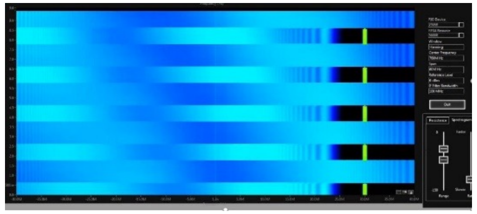
Baylor University
WIRELESS AND MICROWAVE CIRCUITS AND SYSTEMS

CR Tunable Hardware

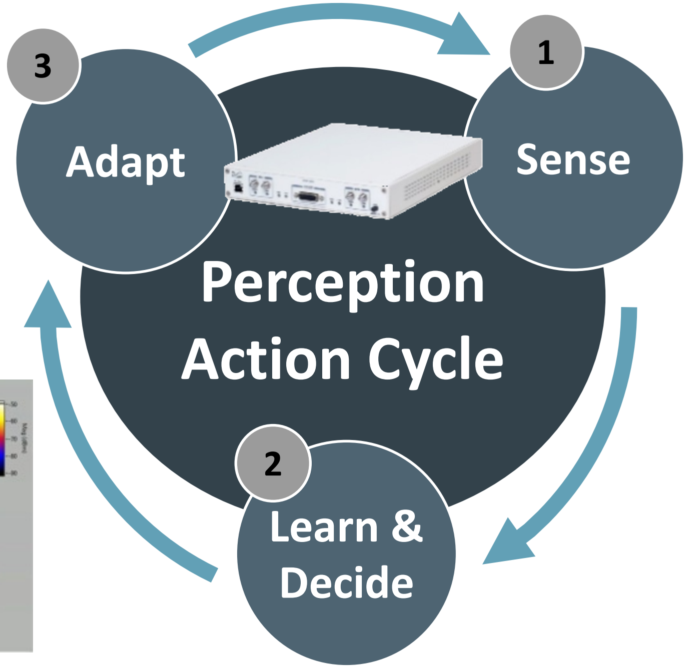


PennState

CR FSS



SDRadar PAC: 164 μs

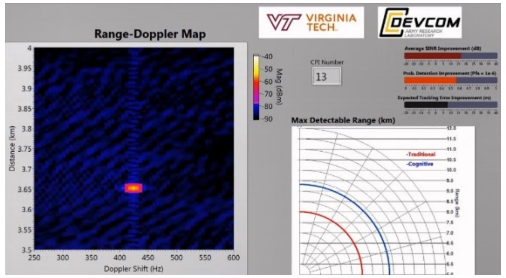


Perception Action Cycle

1 Sense

2 Learn & Decide

3 Adapt



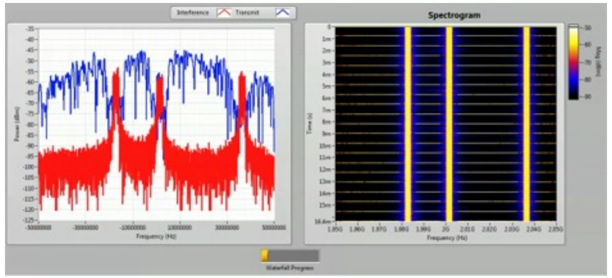
SDRadar PAC: 410 μs

VIRGINIA TECH

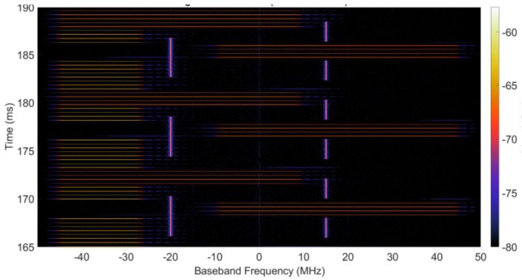
CR Machine Learning

KU RSL

CR Waveform Notching



SDRadar PAC: 451 μs



PennState

CR Channel Prediction

SDRadar PAC: 410 μs

These CR Techniques have *different advantages and disadvantages* for DSA.

A. F. Martone *et al.*, "Closing the Loop on Cognitive Radar for Spectrum Sharing," *IEEE Aerospace and Electronic Systems Magazine*, vol. 36, no. 9, pp. 44-55, Sept. 2021.

Cognitive Gain and Loss

Cognitive techniques can demonstrate significant improvements in performance under correct modelling assumptions

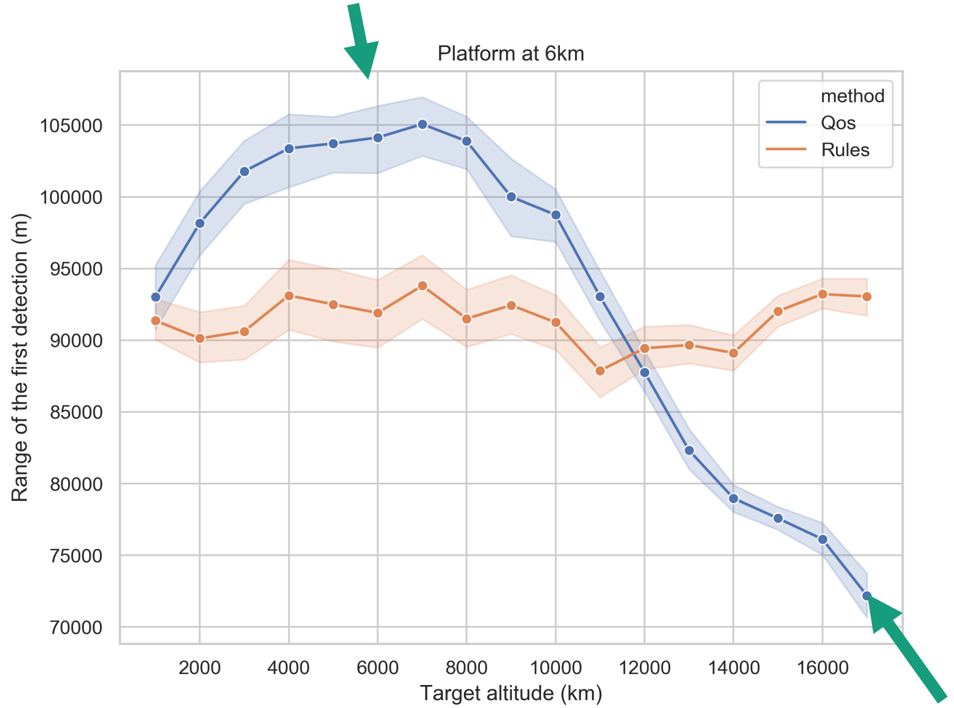
How is radar performance affected by modelling errors?

How sensitive is the radar to modelling errors?

Robust Cognitive Radar

- Analysis of radar robustness with cognitive techniques is essential
- Techniques can be used for increasing robustness:
  - Stochastic optimization
    Can directly consider uncertainty in model parameters
  - Robust optimization
    i.e. optimization of worst case performance

Cognitive gain



Cognitive

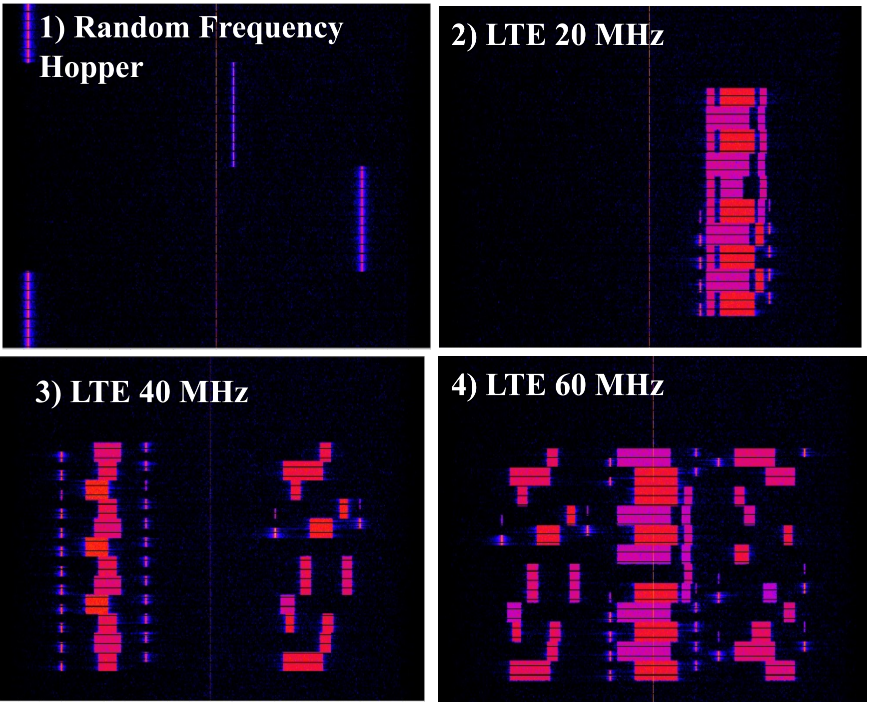
Non-cognitive

Cognitive loss

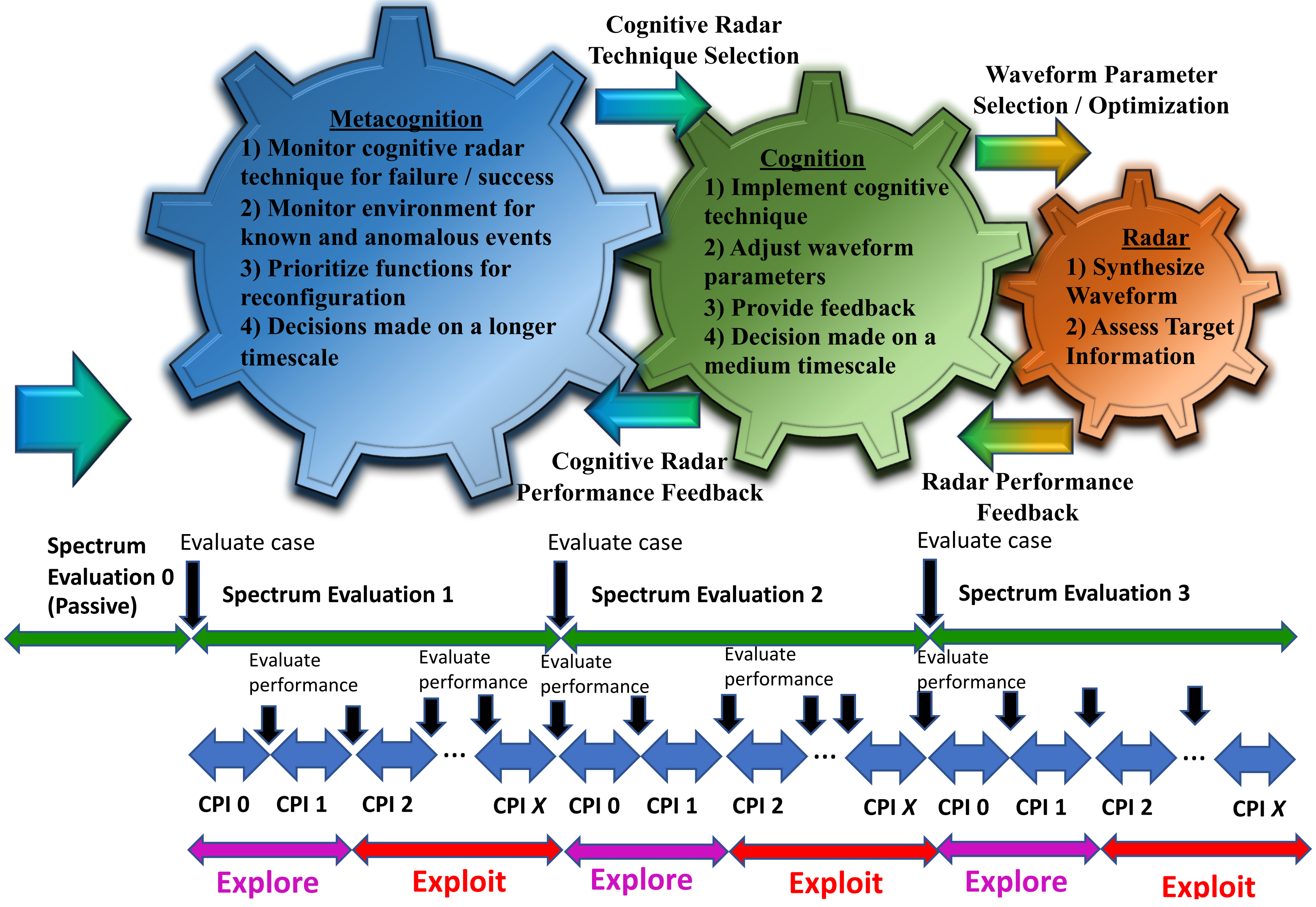
A. F. Martone and A. Charlish, "Cognitive radar for waveform diversity utilization," 2021 IEEE Radar Conference (RadarConf21), 2021, pp. 1-6

DEVCOM ARMY RESEARCH LABORATORY

Metacognitive Radar Model


1) Random Frequency Hopper
2) LTE 20 MHz
3) LTE 40 MHz
4) LTE 60 MHz

Interference Evaluation Cases


Metacognition
1) Monitor cognitive radar technique for failure / success
2) Monitor environment for known and anomalous events
3) Prioritize functions for reconfiguration
4) Decisions made on a longer timescale

Cognitive Radar Technique Selection

Cognition
1) Implement cognitive technique
2) Adjust waveform parameters
3) Provide feedback
4) Decision made on a medium timescale

Waveform Parameter Selection / Optimization

Radar
1) Synthesize Waveform
2) Assess Target Information

Cognitive Radar Performance Feedback

Radar Performance Feedback

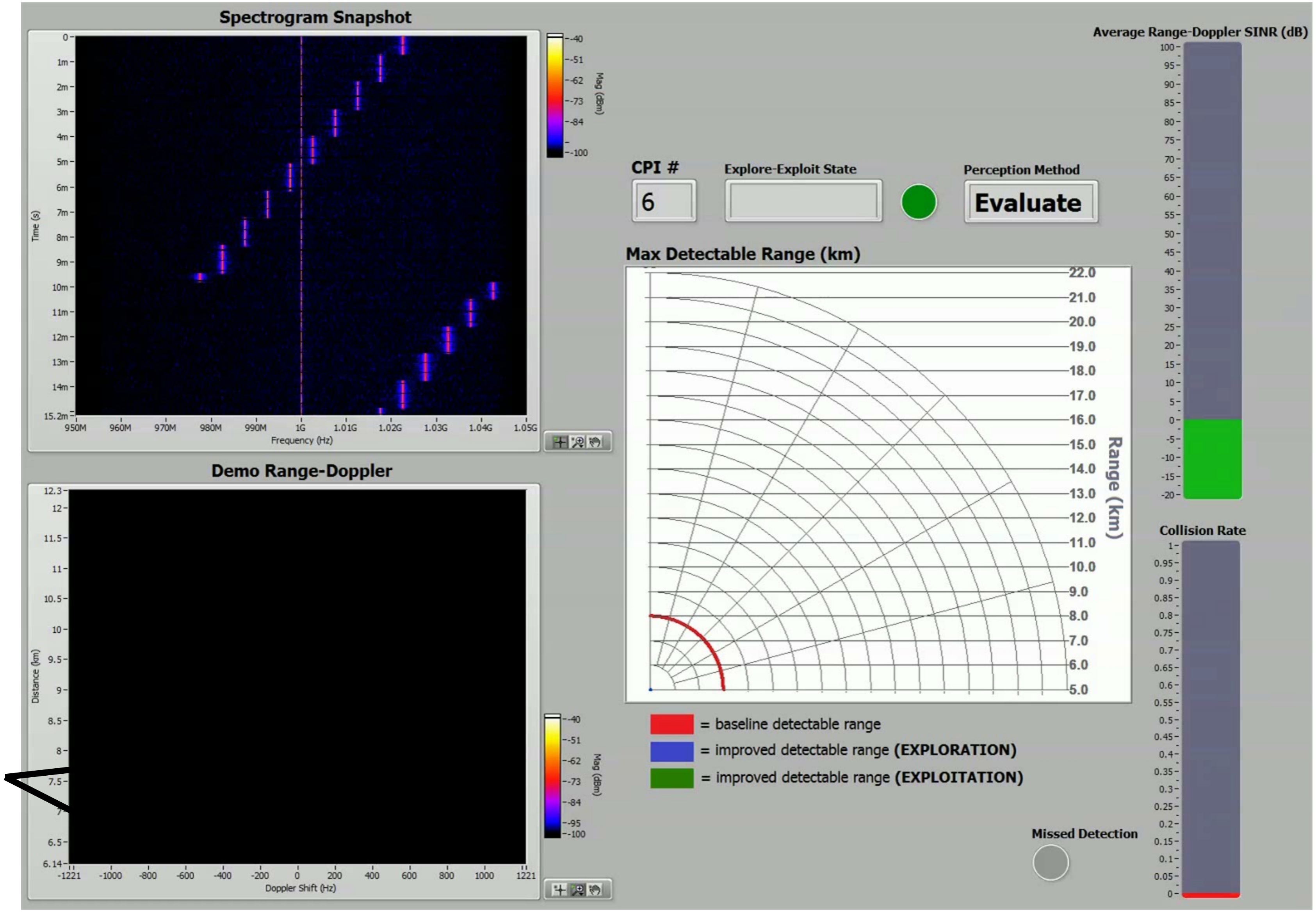
A.F. Martone et al., "Closing the Loop on Cognitive Radar for Spectrum Sharing," IEEE Aerospace and Electronic Systems Magazine, 36(9), pp. 44-55, Sept. 2021.
A. F. Martone et al., "Metacognition for Radar Coexistence," 2020 IEEE International Radar Conference (RADAR), Washington, DC, USA, 2020, pp. 55-60.

Metacognitive Radar Real Time Demonstration on the SDRadar

- **MCR Considers Reaction, Prediction, Learning**

- **Interference Types:**
- **1) Swept Tone, 2) Frequency hopping, 3) 4G LTE 20MHz - 60 MHz LTE**

- **2 Targets**



CPI # 6

Explore-Exploit State

Perception Method Evaluate

🟥 = baseline detectable range

🟦 = improved detectable range (**EXPLORATION**)

🟩 = improved detectable range (**EXPLOITATION**)

Targets

A.F. Martone et al., "Closing the Loop on Cognitive Radar for Spectrum Sharing," IEEE Aerospace and Electronic Systems Magazine, 36(9), pp. 44-55, Sept. 2021.

A Lens on the Future

- **Spectrum sensing for aiding radar presents a form of cognition which is tailored to feedback knowledge of available frequency bands to immediate decisions on radar parameters within the current PAC.**

- **Metacognition provides a high level of flexibility to select strategies of responses according to current needs and the means for radar to adapt in disparate, dynamic spectral environments. It also provides a foundation to *explore multiple PACs that monitor the target scene and spectrum over near, mid, and long term time-lines*.**

- **The next steps should consider radar operation to be a *hybrid active-passive mode,* which is a first step towards distributed multifunction sensor nodes. In this mode, both free and occupied spectrum bands can be used by the radar!**
  - **Signal opportunist in the bands occupied by the primary users and thereby presents itself as a passive sensor.**
  - **On the other hand, for the designated bands, the radar becomes active, using its own transmitter and waveforms.**

- **A multifunctional sensor node should consider *multiple sensing dimensions*: Time, Frequency, Angle, Waveform (code), etc!**

- **A network of nodes will require a higher-level decision process**
  - **How to switch between active-passive modes**