Demonstration of Real-time Cognitive Radar using Spectrally-Notched Random FM Waveforms

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Motivation

- The RF spectrum is becoming sparser due to the acceleration of 4G/5G, spectrum sell-off, and the Internet of Things:

  → <u>A paradigm shift is needed for future radar systems</u>

  1) Cognitive radar has recently been implemented on low-cost alternative software-defined radios (SDRs) to enable spectrum sharing capabilities *using standard chirp radar waveforms* [1]
  2) Notched Random FM (RFM) waveforms have been demonstrated to realize **<u>improved bandwidth utilization via non-repeating waveforms</u>** [2], though they were not previously capable of being generated in real-time.
  3) Here, notched RFM waveforms are generated in real-time and integrated into an SDR-based cognitive radar system [1] to dynamically react to interference **<u>(~ 5 ms reaction time)</u>**

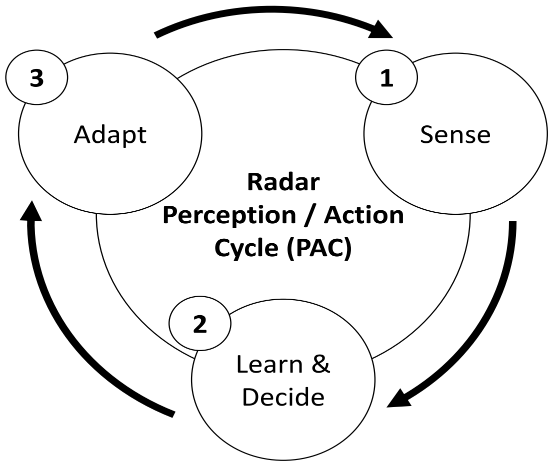
- The efficacy of this approach is demonstrated experimentally in loopback.

[1] B.H. Kirk, R.M. Narayanan, K.A. Gallagher, A.F. Martone, K.D. Sherbondy, "Avoidance of time-varying radio frequency interference with software-defined cognitive radar," *IEEE Trans. Aerospace & Electronic Systems*, vol. 55, no. 3, pp. 1090-1107, June 2019.

[2] B. Ravenscroft, J.W. Owen, J. Jakabosky, S.D. Blunt, A.F. Martone, K.D. Sherbondy, “Experimental demonstration and analysis of cognitive spectrum sensing and notching for radar,” *IET Radar, Sonar & Navigation*, vol. 12, no. 12, pp. 1466-1475, Dec. 2018.

Cognitive Radar 101

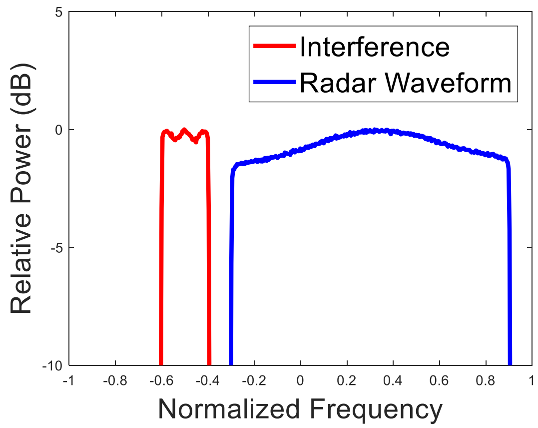
While many forms of cognitive radar exist, here cognition is applied to the non-cooperative spectrum sharing problem



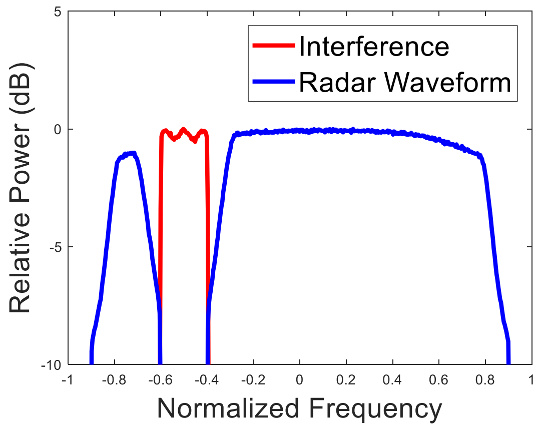
1) Sense the spectrum environment
2) Ascertain where interference is located
3) Generate physically realizable waveforms to mitigate mutual interference

The approaches under consideration are:

"sense & avoid": change the spectral location and extent of the radar bandwidth based on interference sensed in the environment



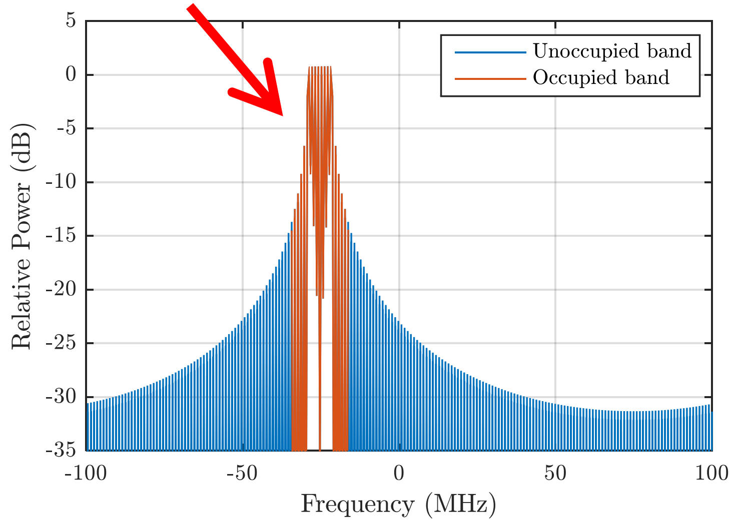
"sense & notch": places notches in the radar spectrum based on interference sensed in the environment

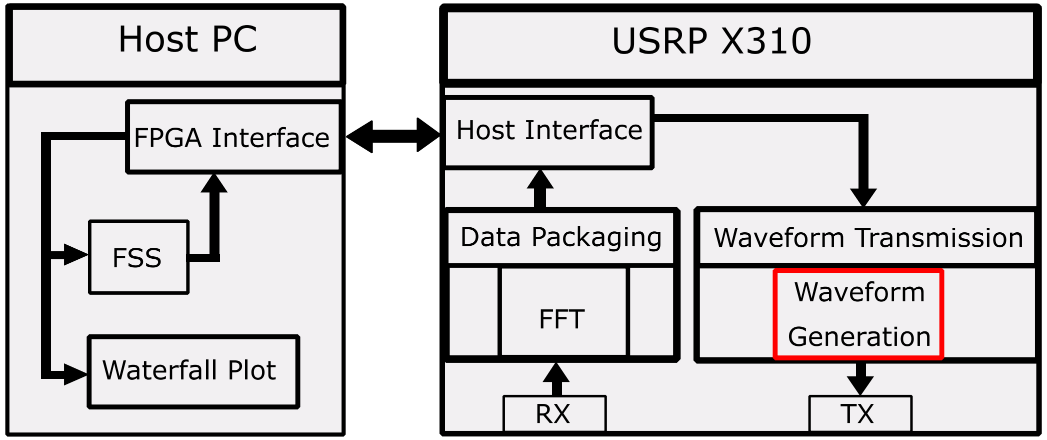


1) Fast Spectrum Sensing (FSS) + Sense-and-Avoid (SAA) Chirp Waveforms

- FSS performs rapid band-aggregation & decision making to monitor locations of significant RF interferers and select usable subbands
- In collaboration with Penn State & ARL, a version of FSS has been implemented on the SDR [3]
- Linearly frequency modulated (LFM) chirp waveforms could be generated via direct digital synthesis (DDS) to avoid interferers in real-time [1]

Identified RF interferer





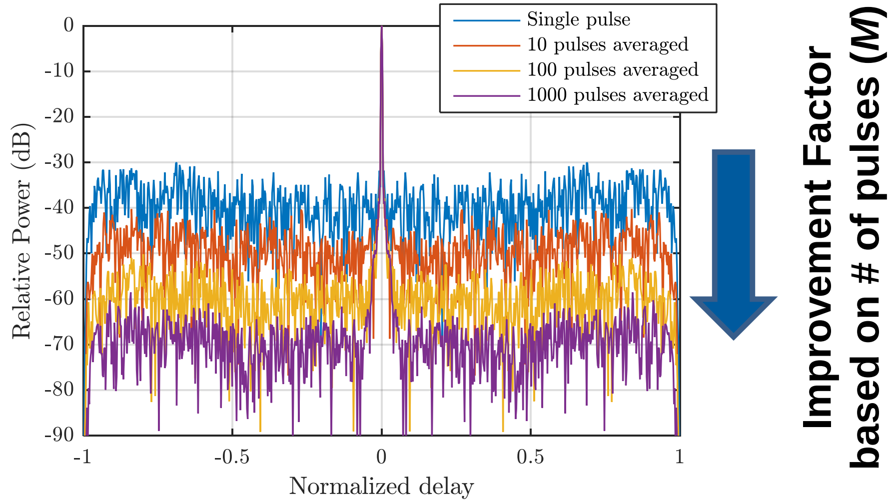
[1] B.H. Kirk, R.M. Narayanan, K.A. Gallagher, A.F. Martone, K.D. Sherbondy, "Avoidance of time-varying radio frequency interference with software-defined cognitive radar," *IEEE Trans. Aerospace & Electronic Systems*, vol. 55, no. 3, pp. 1090-1107, June 2019.

[3] A. Martone, K. Ranney, K. Sherbondy, K. Gallagher, S. Blunt, "Spectrum allocation for non-cooperative radar coexistence," *IEEE Trans. Aerospace & Electronic Systems*, vol. 54, no. 1, pp. 90-105, Feb. 2018.

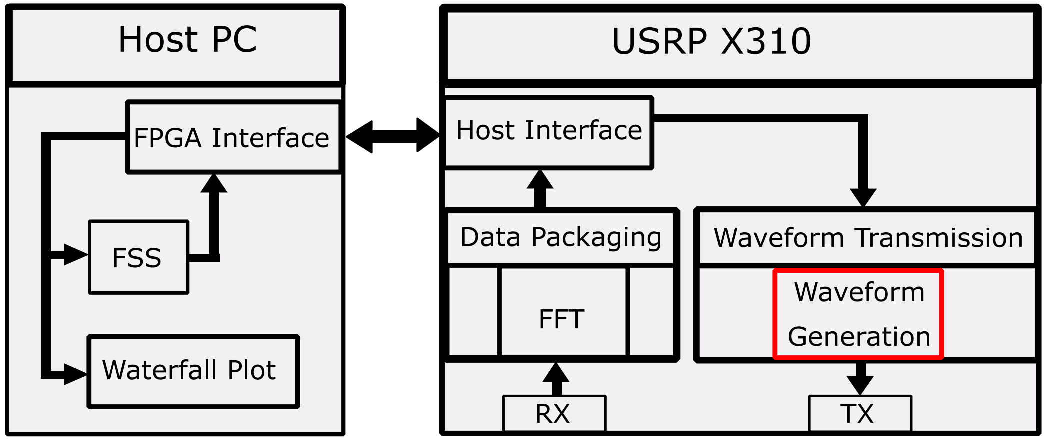
Foundations

2) Generate non-repeating notched FM waveforms

- Various new methods have recently been experimentally demonstrated to realize forms of non-repeating random FM waveforms [4]
- Approaches developed to place in-band spectral notches with better than 50 dB depth, while preserving the waveform's transmitter-amenable FM structure [4]
- Original efforts focused on notching using high-fidelity (i.e. expensive) arbitrary waveform generation (AWG) capability [5]



Sidelobes of random waveforms combine incoherently (but the mainlobes combine coherently!)



[4] S.D. Blunt, J.K. Jakabosky, C.A. Mohr, P.M. McCormick, J.W. Owen, B. Ravenscroft, C. Sahin, G.D. Zook, C.C. Jones, J.G. Metcalf, T. Higgins, "Principles & applications of random FM radar waveform design," to appear in *IEEE Aerospace & Electronic Systems Magazine*.

[5] C.A. Mohr, S.D. Blunt, "Analytical spectrum representation for physical waveform optimization requiring extreme fidelity," *IEEE Radar Conf.*, Boston, MA, Apr. 2019.

2) Generate non-repeating notched FM waveforms

- Was experimentally demonstrated [2], albeit not yet at real-time, that notched, random FM waveforms could be physically realized using the FSS [3]
- When RFI changes dynamically during the radar's CPI, **sense-and-notch (SAN)** must likewise perform at the PRF rate of the radar
- Thus **dynamic waveform generation is required**
- Leveraging SAA deployment [1], the SAN framework is implemented on the FPGA of an Ettus x310 SDR for real-time operation

[1] B.H. Kirk, R.M. Narayanan, K.A. Gallagher, A.F. Martone, K.D. Sherbondy, "Avoidance of time-varying radio frequency interference with software-defined cognitive radar," *IEEE Trans. Aerospace & Electronic Systems*, vol. 55, no. 3, pp. 1090-1107, June 2019.

[2] B. Ravenscroft, J.W. Owen, J. Jakabosky, S.D. Blunt, A.F. Martone, K.D. Sherbondy, "Experimental demonstration and analysis of cognitive spectrum sensing and notching for radar," *IET Radar, Sonar & Navigation*, vol. 12, no. 12, pp. 1466-1475, Dec. 2018.

[3] A. Martone, K. Ranney, K. Sherbondy, K. Gallagher, S. Blunt, "Spectrum allocation for non-cooperative radar coexistence," *IEEE Trans. Aerospace & Electronic Systems*, vol. 54, no. 1, pp. 90-105, Feb. 2018.

Sense-and-Notch Random FM

To that end, the we are leveraging the confluence of:

1. Cognitive spectrum sensing & decision making
2. Diverse, non-repeating waveform capabilities (i.e. waveform agility)
3. COTS SDR hardware for cost-effective scalability

… **to experimentally assess the efficacy of spectrally-notched, random FM waveforms for real-time cognitive operation**

Notched FM Waveform Generation

Rapid & flexible waveform generation is needed to quickly react to dynamic RFI

The notched, random FM waveform generation implemented on the SDR is executed in two stages:

1. Perform K iterations of alternating time-frequency projections to produce q^{th} pseudo-random optimized FM (PRO-FM) waveform [6].
   - The resulting spectrum $|G(f)|$ is Gaussian-shaped with a shallow spectral notches incorporated.
   - Notched PRO-FM provides a good initialization, permitting faster convergence in the next stage.
2. Then apply L iterations of zero-order reconstruction optimization of waveforms (ZOROW) [7] to the q^{th} PRO-FM waveform to significantly deepen the notches.

$$\bar{\mathbf{r}}_q^{(k+1)} = \mathbb{F}^{-1}\left\{\bar{\mathbf{g}} \odot \exp\left(j\angle \mathbb{F}\left\{\bar{\mathbf{s}}_q^{(k)}\right\}\right)\right\}$$

$$\bar{\mathbf{s}}_q^{(k+1)} = \bar{\mathbf{u}} \odot \exp\left(j\angle \bar{\mathbf{r}}_q^{(k+1)}\right)$$

[6] J. Jakabosky, S.D. Blunt, B. Himed, "Spectral-shape optimized FM noise radar for pulse agility," *IEEE Radar Conf.*, Philadelphia, PA, May 2016.

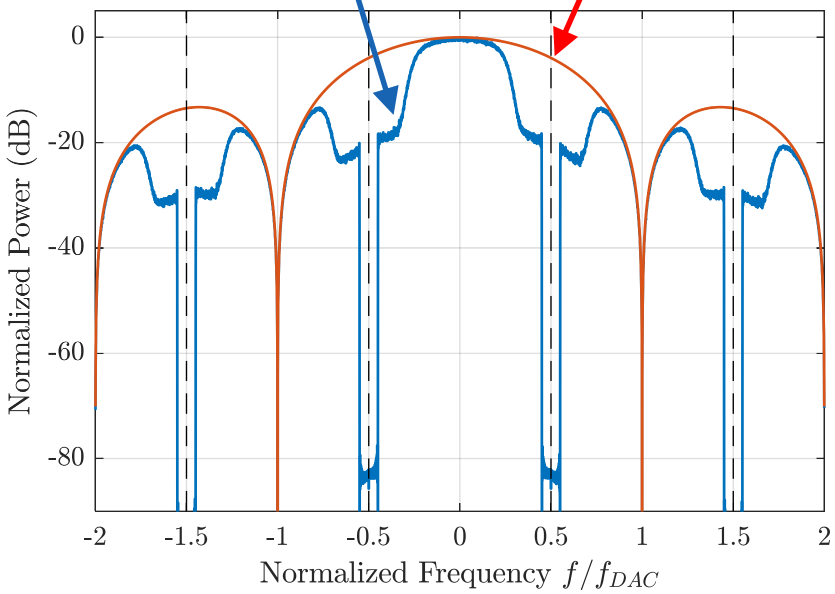
[7] C. Mohr, J.W. Owen, S.D. Blunt, "Zero-order reconstruction optimization of waveforms (ZOROW) for modest DAC-rate systems," *IEEE Intl. Radar Conf.*, Washington, DC, Apr. 2020.

Assess the notch depth achievable in COTS hardware

Zero-order reconstruction optimization of waveforms (ZOROW) deepens waveform spectral notches by using an analytical Fourier representation that accounts for the zero-order hold model of the digital-to-analog converter (DAC) on the SDR [7]

radar waveform spectrum

sinc spectral mask



- The zero-order-hold output of the DAC results in a sinc rolloff of spectral images
- The DAC on the SDR interpolates the input data to push these images higher in frequency
- After the DAC, an analog reconstruction filter attenuates these images

[7] C. Mohr, J.W. Owen, S.D. Blunt, "Zero-order reconstruction optimization of waveforms (ZOROW) for modest DAC-rate systems," *IEEE Intl. Radar Conf.*, Washington, DC, Apr. 2020.

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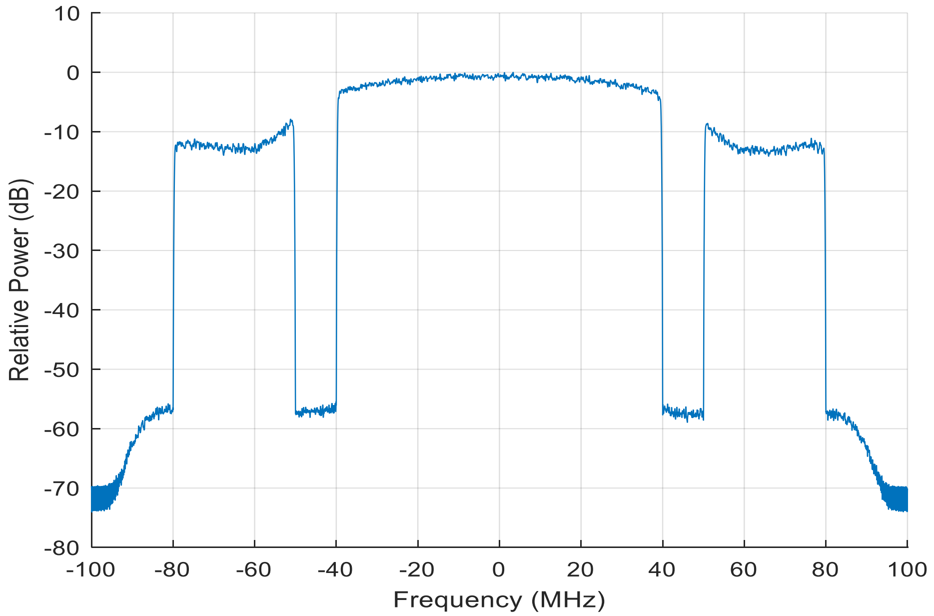
"Transmitted" by SDR (in loopback), received on spectrum analyzer



At least –57 dB notches are achievable!

[7] C. Mohr, J.W. Owen, S.D. Blunt, "Zero-order reconstruction optimization of waveforms (ZOROW) for modest DAC-rate systems," *IEEE Intl. Radar Conf.*, Washington, DC, Apr. 2020.

ZOROW

ZOROW employs the cost function

$$J = \sum_{m} | S_q(f_m;\boldsymbol{\phi}_q) |^2 \qquad \mathbf{s}_q = \exp(j\boldsymbol{\phi}_q) \qquad \boldsymbol{\phi}_q = [\,\phi_{q,1} \;\; \phi_{q,2} \;\; \cdots \;\; \phi_{q,N}\,]^T$$

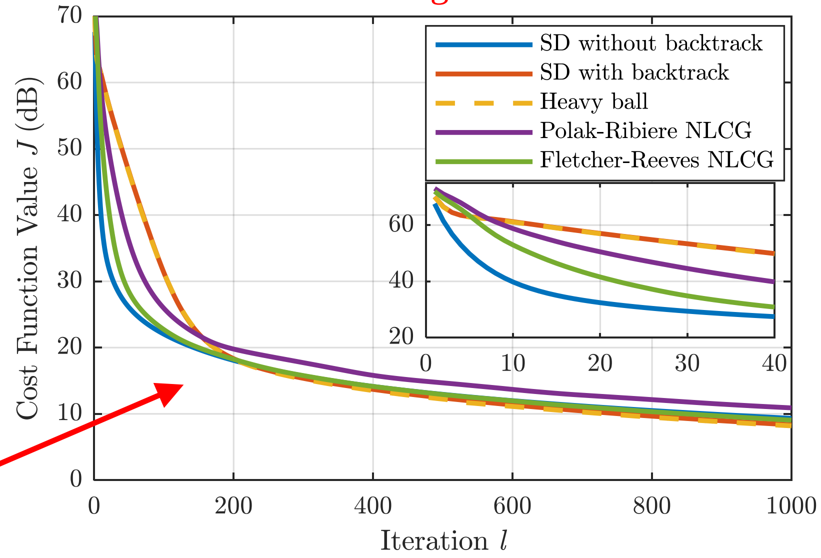
that is summed over frequency interval(s) where notching is required. Gradient-descent optimization of $\boldsymbol{\phi}_q$ performed as [7]

$$\boldsymbol{\phi}_q^{(\ell+1)} = \boldsymbol{\phi}_q^{(\ell)} + \mu_\ell \, \mathbf{p}_q^{(\ell)} \qquad \mathbf{p}_q^{(\ell)} = \begin{cases} -\mathbf{g}_0 & \text{when } k = 0 \\ -\mathbf{g}_q^{(\ell)} + \beta \mathbf{p}_q^{(\ell-1)} & \text{otherwise} \end{cases}$$

$$\mathbf{g}_q^{(\ell)} = 2\Im\left\{ \tilde{\mathbf{A}}^H (\tilde{\mathbf{s}}_{\mathrm{f},q}^{(\ell)} \odot \tilde{\mathbf{w}}) \odot \mathbf{s}_q^{*(\ell)} \right\}$$

where $0 < \beta < 1$ dictates the type of gradient-descent.

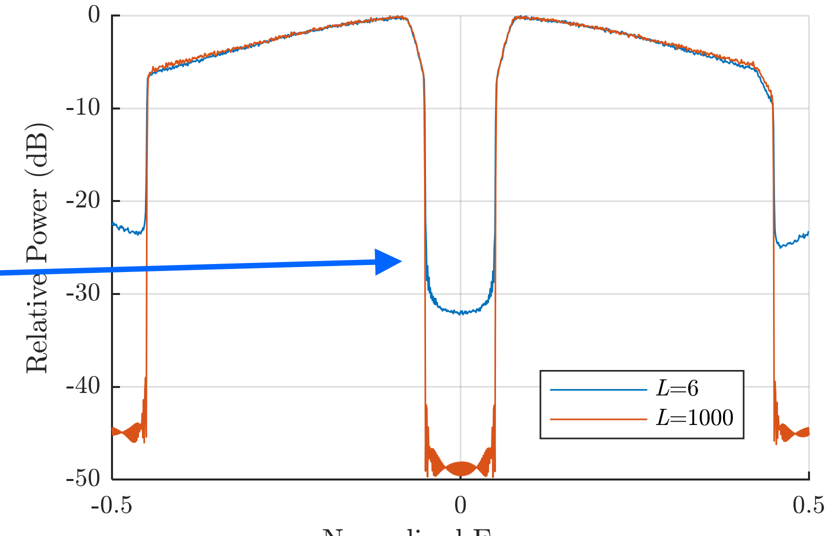
Comparison of ZOROW cost-function minimization for various gradient-descent methods



This gradient can be computed efficiently with FFTs & IFFTs !!!

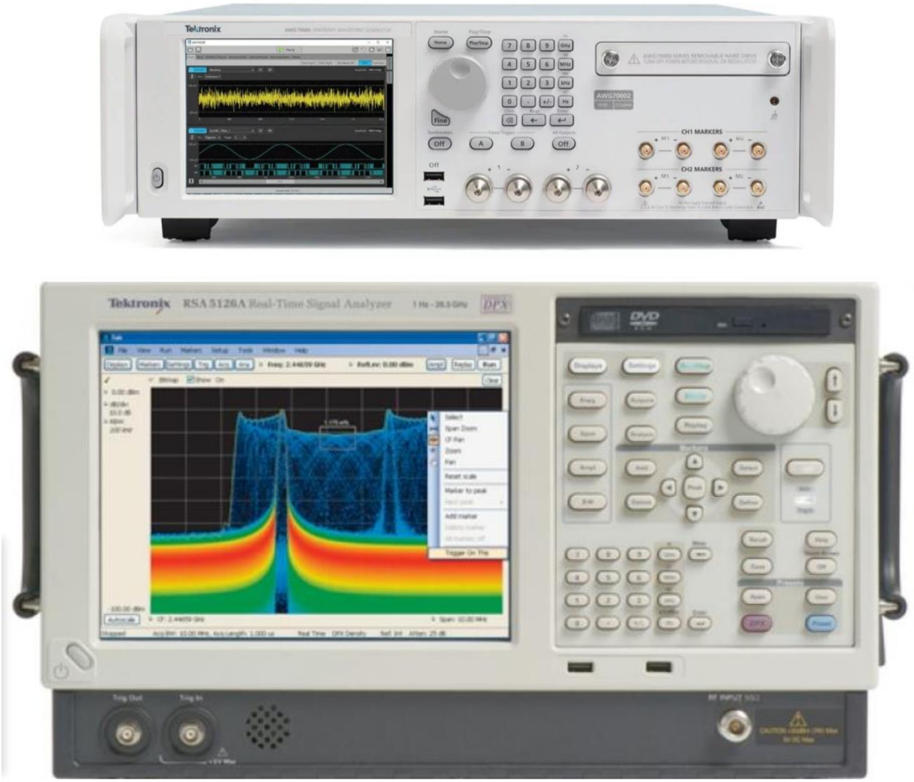
We shall use $L = 6$ iterations of ZOROW for real-time FPGA implementation

RMS power spectra of $Q = 1000$ random FM waveforms



[7] C. Mohr, J.W. Owen, S.D. Blunt, "Zero-order reconstruction optimization of waveforms (ZOROW) for modest DAC-rate systems," *IEEE Intl. Radar Conf.*, Washington, DC, Apr. 2020.

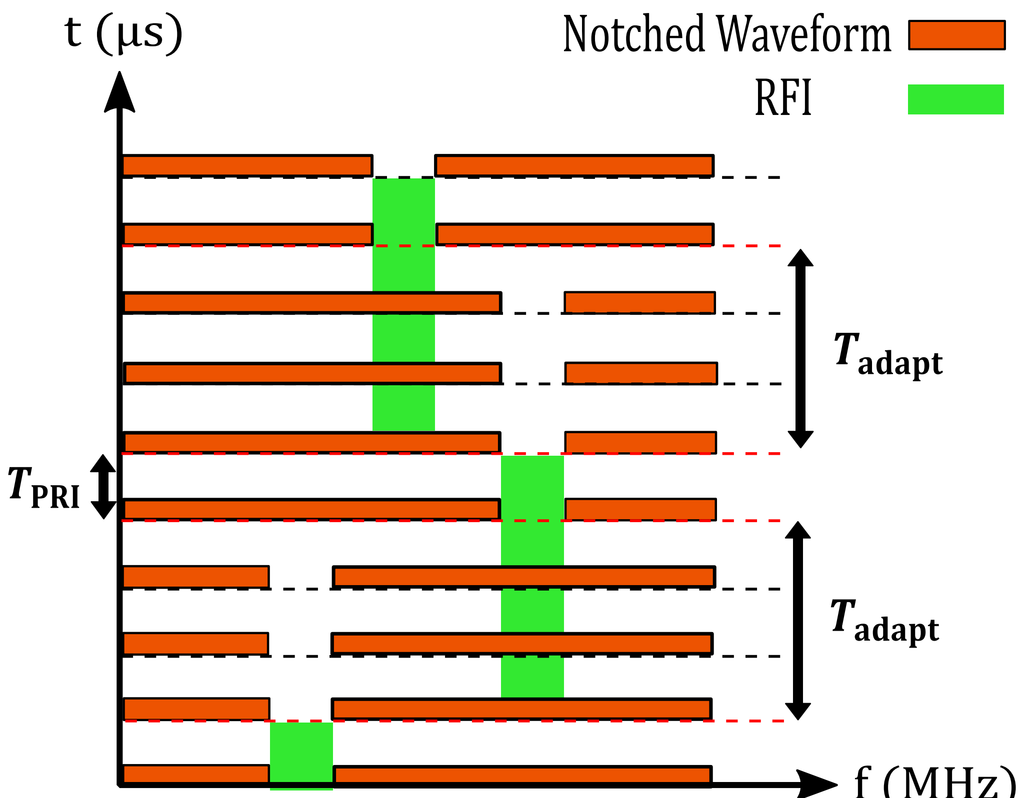
Implementation of Spectrally-Notched, Random FM Waveforms onto the SDR's FPGA
(or mapping high-fidelity to modest-fidelity)



Sense-and-Notch Random FM

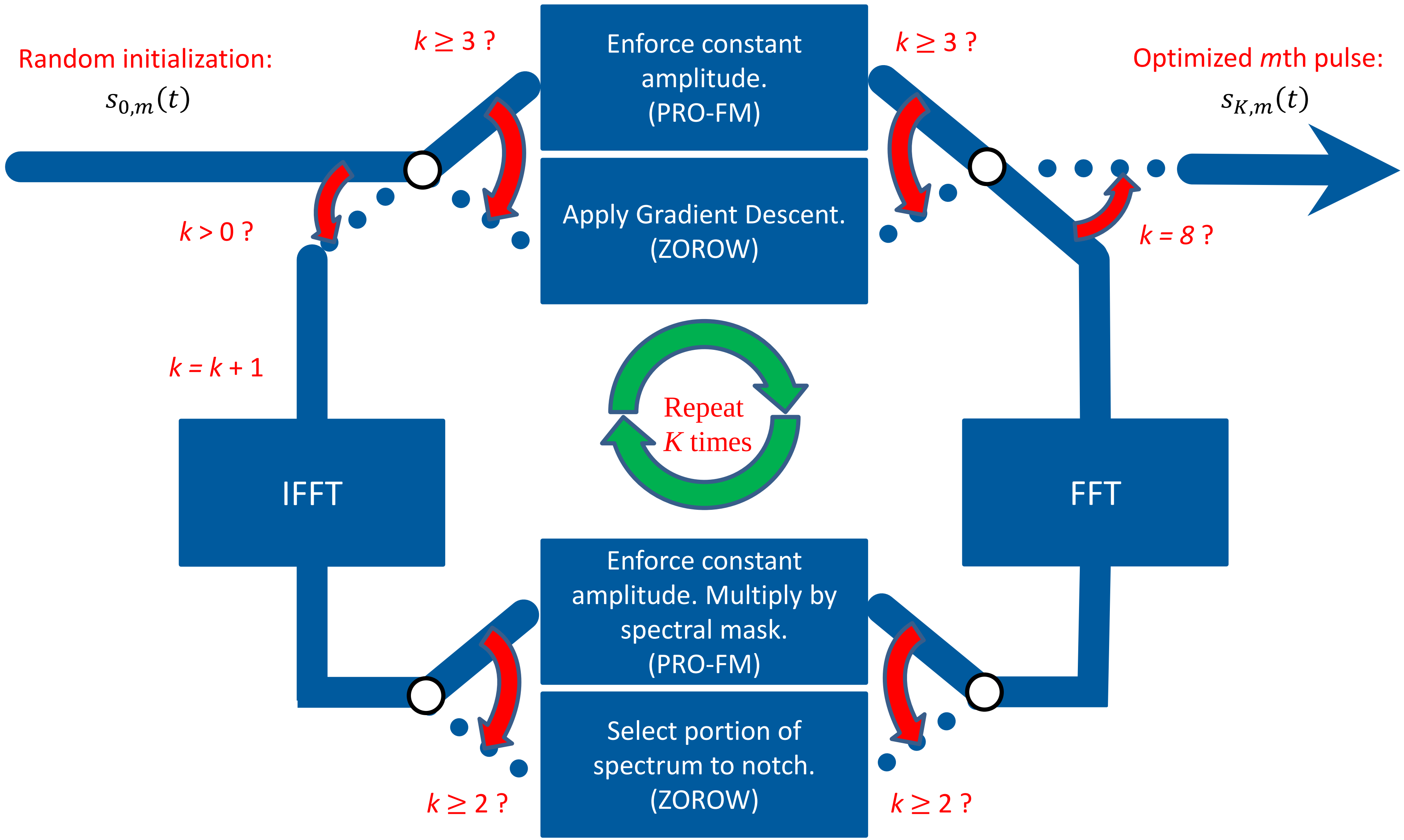
1) Received I/Q samples of the RF spectral environment are streamed to the host computer
2) FSS is applied to identify the spectral locations of RFI
3) RFI spectral locations returned to SDR, where the PRO-FM / ZOROW notched waveform generation is performed.

- Max time T_{PRI} for waveform generation sets the minimum feasible PRI, and thus max PRF for cognitive operation.
- Latency between 1) observance of RFI changes and 2) FSS response with revised notch locations, currently establishes the minimum adaptation interval T_{adapt}
- Consequently, while a new waveform is generated on a per-PRI basis, the notch locations for each waveform are updated by FSS once every R PRIs (depending on PRF)



$T_{\mathrm{adapt}} = 3T_{\mathrm{PRI}}$

Real-Time Notched Random FM Generation



All processing was condensed to FFTs, multiplies, & additions to work on COTS SDR

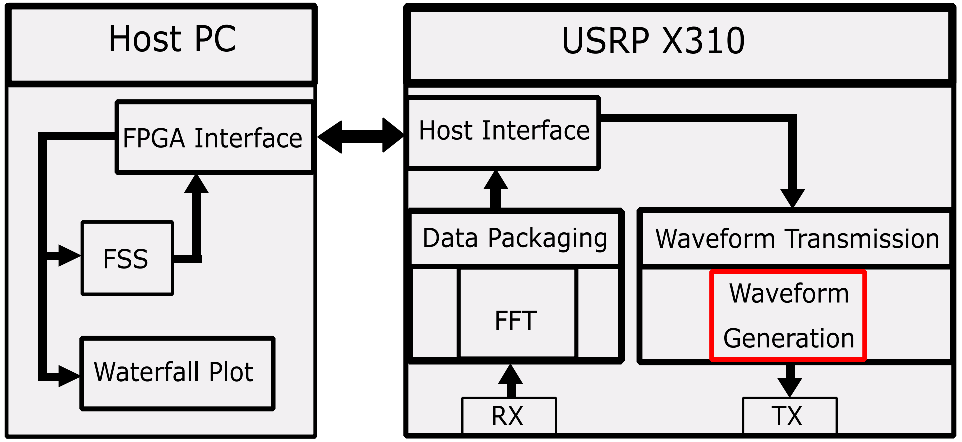
Sense-and-Notch Implementation

The PROFM and ZOROW algorithms are applied sequentially to spectrally shape the radar waveform

Waveforms with sufficient notch depths (~25 dB in this demo) are generated in ~0.5 ms

1) Perform 2 iterations of PRO-FM for initial spectral shaping
   - Only marginal further improvement in spectral shaping after 2 iterations of PRO-FM optimization
2) Then 6 iterations of ZOROW to deepen notches at RFI **and** shape the bandwidth edges to improve spectral containment.
   - Rate of notch depth improvement slows down after ~6 iterations of ZOROW

Greater notch depth could be achieved on the SDR … but doing so would alter the response time trade-space.



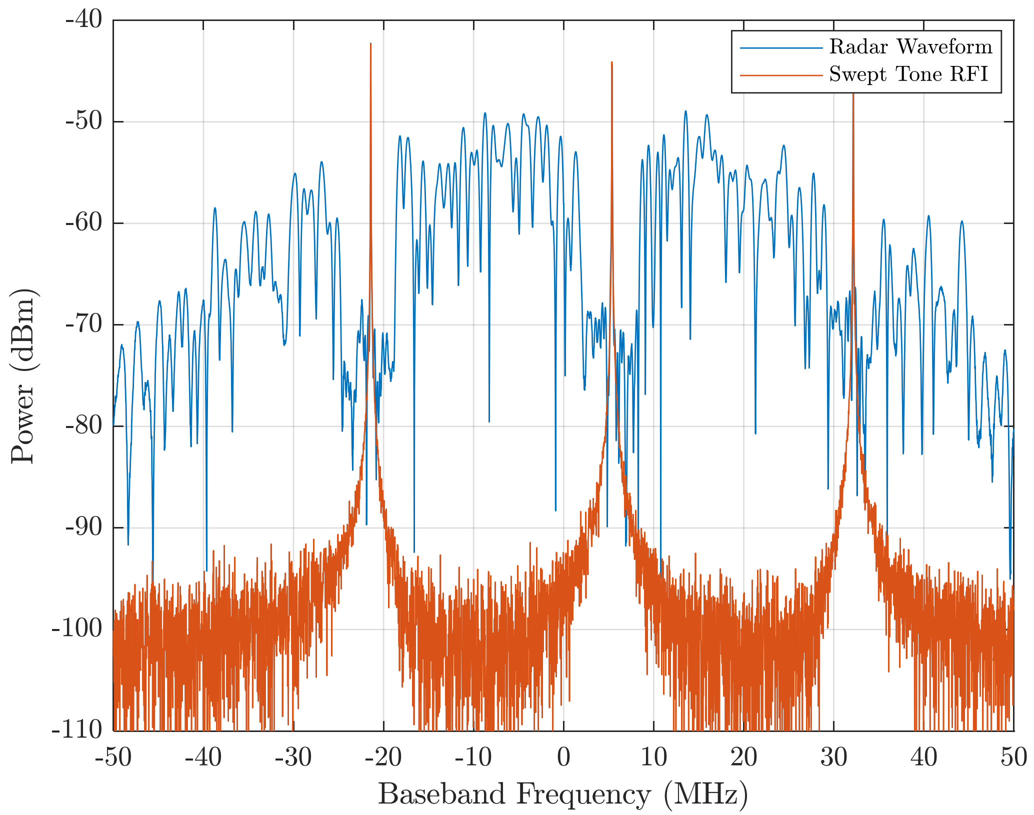
All processing was condensed to FFTs, multiplies, & additions to work on COTS SDR

Experimental Evaluation

- Independent AWG is used to generate **various RFI scenarios** that are combined with the radar emissions in closed loop for cognitive performance testing.
- SDR operates at a center frequency of 2 GHz
- Complex baseband data is collected after receive down-conversion based on a 100 MHz sample clock.
- Pulse duration is 2.56 μs
- PRI is 450.6 μs.

RFI test cases include

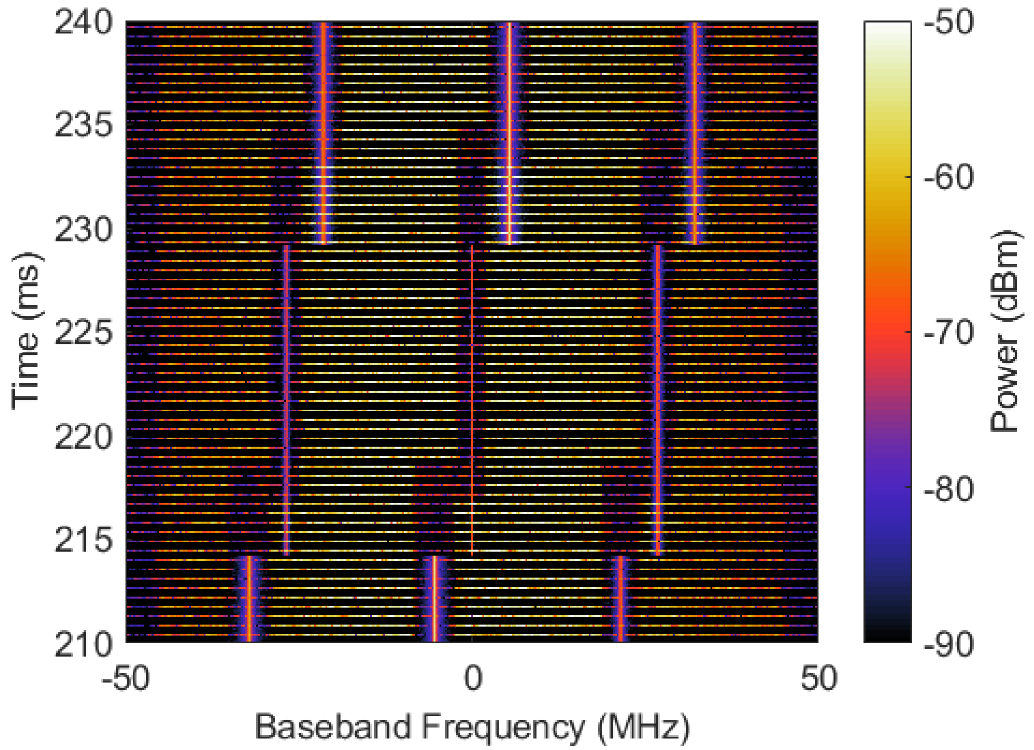
a) 3 swept-frequency tones with 15 ms dwell times
b) 3 swept-frequency tones with 5 ms dwell times
c) 3 independent 5 MHz bands of OFDM subcarriers, randomly hopping with dwell times of 15 ms
d) 1 contiguous 40 MHz band of OFDM subcarriers, randomly hopping with dwell time of 15 ms



Spectrum capture showing 3 tonal interferers (red) and the SAN radar spectrum (blue) with collocated notches.

Case a) 3 swept tones, 15 ms dwell

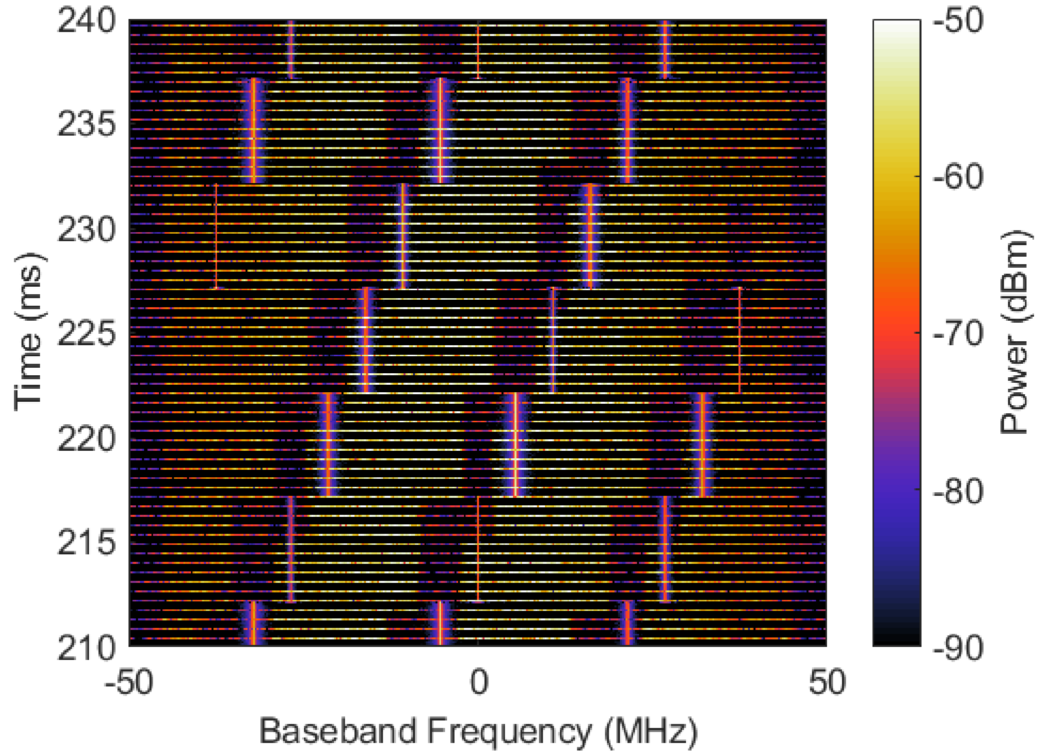
- Waterfall spectrogram (frequency content versus PRI) demonstrates real-time notching performance.
- The ~3 ms adaptation latency translates into a $R = 7$ PRI response delay in changing notch locations
- Since <u>3 ms latency</u> << <u>15 ms RFI dwell</u>, the cognitive radar can respond adequately to form spectral notches of appropriate location & width



Waterfall spectrogram versus PRI time for RFI of **3 stepped tones** (<u>vertical pink bars</u>) and the SAN radar spectrum (<u>horizontal yellow line is each pulse</u>) with notches. **<u>RFI changes every 15 ms.</u>**

Case b) 3 swept tones, 5 ms dwell

- Now the 3 ms latency ≈ 5 ms RFI dwell, so that notch alignment accuracy degrades significantly
- Ongoing work is investigating how to further reduce adaptation latency (e.g. via prediction when RFI exhibits observable patterns [8])

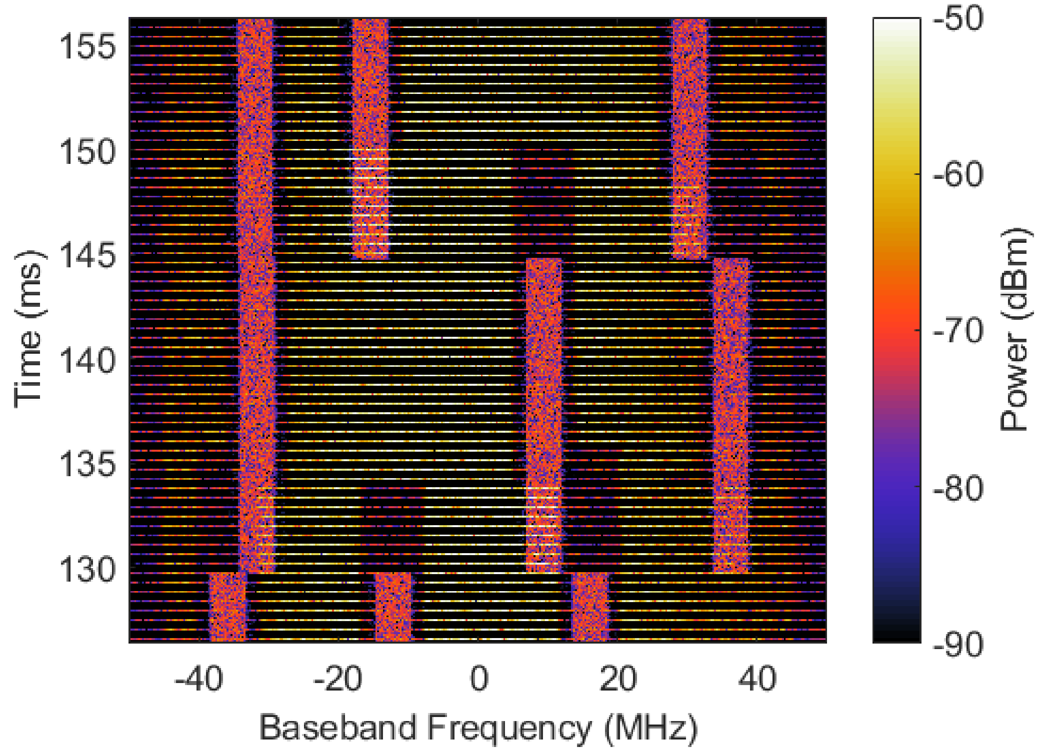


Waterfall spectrogram versus PRI time for RFI of **3 stepped tones** (vertical pink bars) and the SAN radar spectrum (horizontal yellow line is each pulse) with notches. **RFI now changes every 5 ms.**

[8] J. Kovariskiy, J.W. Owen, R.M. Narayanan, S.D. Blunt, A.F. Martone, K.D. Sherbondy, "Spectral prediction and notching of RF emitters for cognitive radar coexistence," *IEEE Intl. Radar Conf.*, Washington, DC, Apr. 2020.

Case c) 3 hopped 5 MHz OFDM, 15 ms dwell

- Notch widths have adjusted to accommodate the 5 MHz OFDM bands that are randomly hopping
- Since 3 ms latency << 15 ms RFI dwell, spectral notching responds adequately
- Random hopping pattern may limit efficacy of prediction
- Cognitive radar and cognitive radio could conceivably reach some state of equilibrium and become static



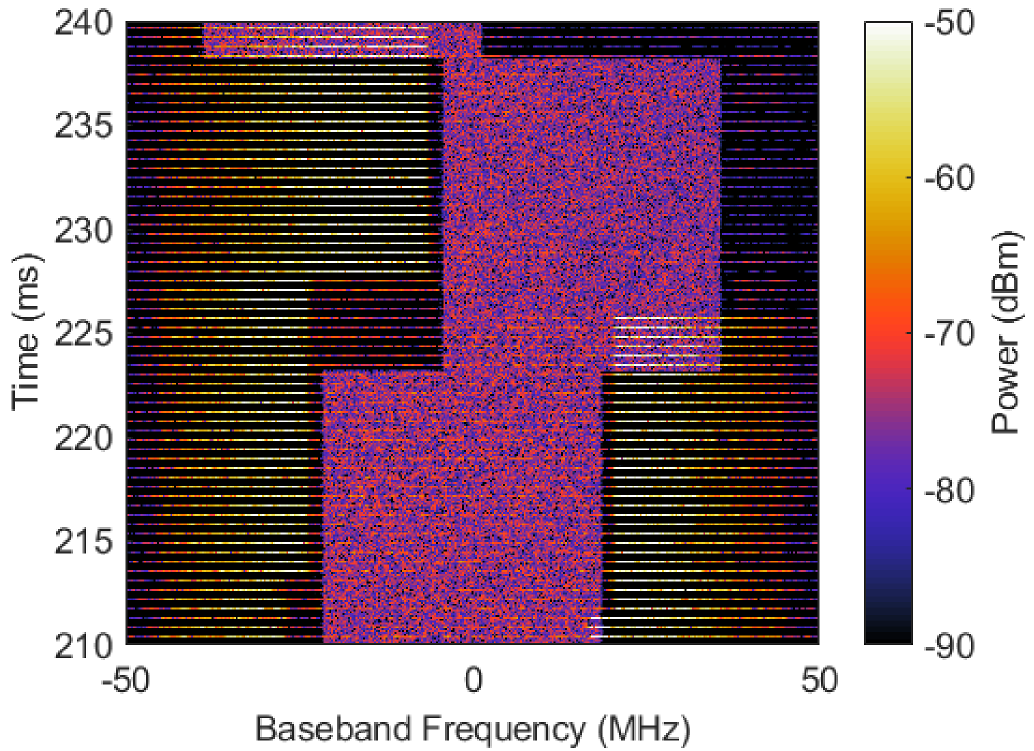
Waterfall spectrogram versus PRI time for RFI of **3 random 5 MHz OFDM bands** (vertical pink bars) and the SAN radar spectrum (horizontal yellow line is each pulse) with notches. **RFI changes every 15 ms.**

Case d) 1 hopped 40 MHz OFDM, 15 ms dwell

- Since <u>3 ms latency</u> << <u>15 ms RFI dwell</u>, spectral notching responds adequately

- However, when RFI bandwidth becomes a significant fraction of the total bandwidth, especially if highly consolidated and “off-center”, then sense-and-avoid (SAA) **[1]** may be better due to lower computational cost

- Determination of SAA vs. SAN, in reactive or predictive manner, is part of ongoing “meta-cognition” work **[9]**



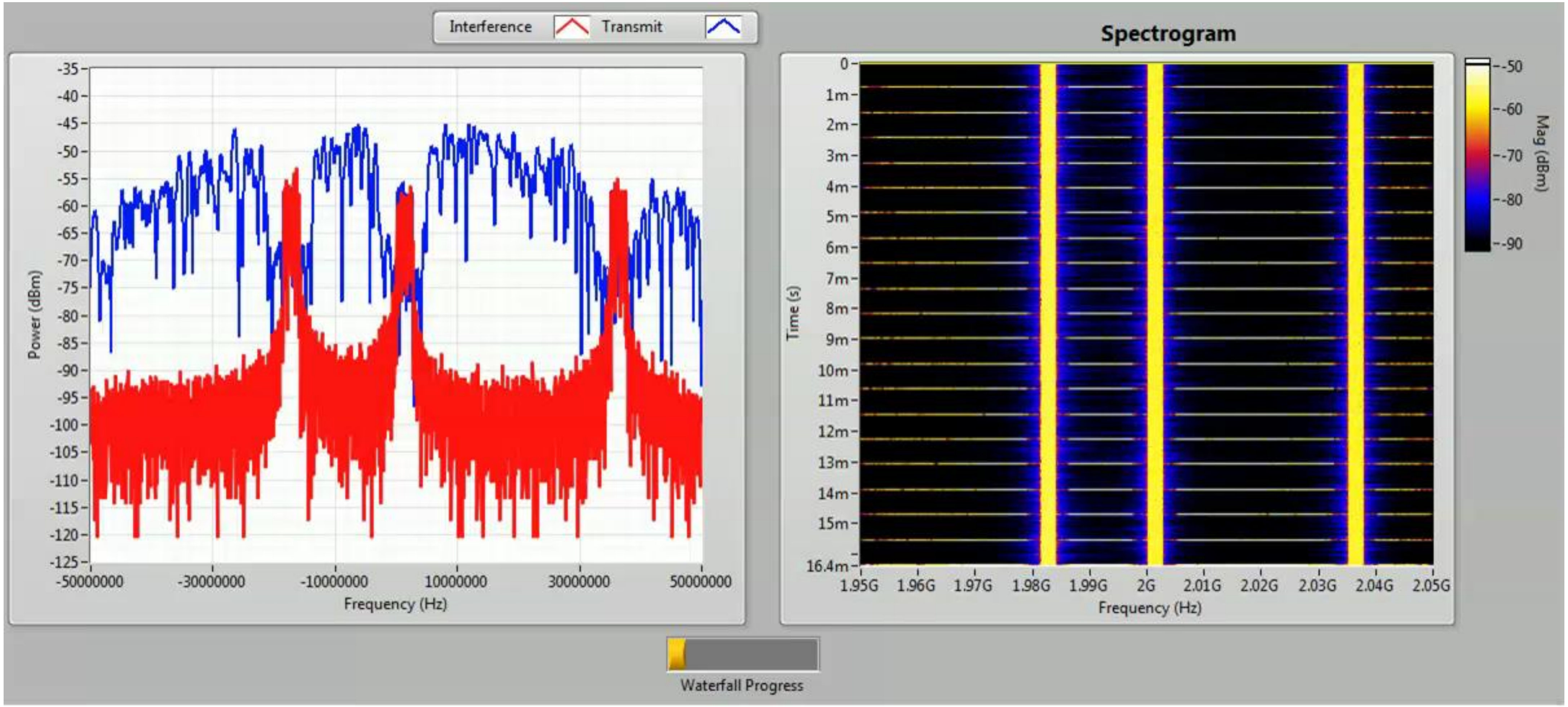
Waterfall spectrogram versus PRI time for RFI of **1 random 40 MHz OFDM band** (<u>vertical pink bars</u>) and the SAN radar spectrum (<u>horizontal yellow line is each pulse</u>) with notches. **<u>RFI changes every 15 ms.</u>**

[1] B.H. Kirk, R.M. Narayanan, K.A. Gallagher, A.F. Martone, K.D. Sherbondy, "Avoidance of time-varying radio frequency interference with software-defined cognitive radar," *IEEE Trans. Aerospace & Electronic Systems*, vol. 55, no. 3, pp. 1090-1107, June 2019.

[9] A.F. Martone, et al, “Metacognition for radar coexistence,” *IEEE Intl. Radar Conf.*, Washington, DC, Apr. 2020.

Demonstration of Real-time Operation

(Video playback is 125× slower than actual operation)



Conclusions

- Spectrally-notched, random FM waveforms can be generated in real-time on COTS hardware to adapt to RFI in a sense-and-notch (SAN) mode
  - ✓ **Capability for spectrum sharing**
  - ✓ **Implementation on COTS hardware enables future upgrades**
  - ✓ **Supports PRFs up to 2.2 kHz**
  - ✓ **Can incorporate multiple spectral notches per waveform at low latency**
  - ✓ **Achieves notch depths of 25 dB relative to peak power (greater depth given greater computational resources or higher latency).**