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Collaborative and Responsive Sensors for Low-cost Spectrum Sensing and Geolocation

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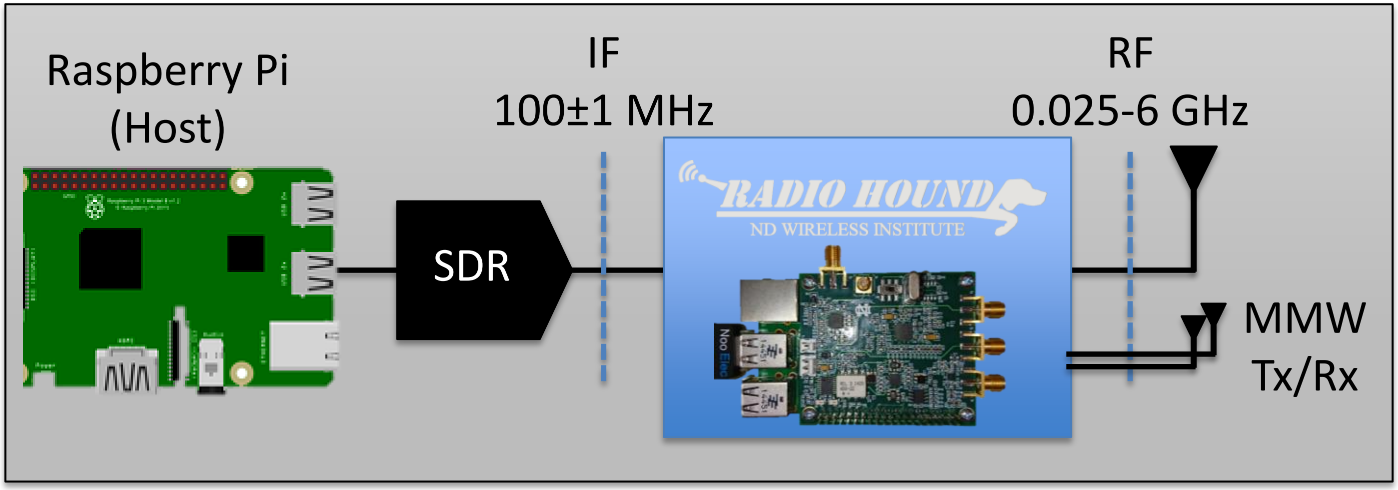
RadioHound Vision: A Sensor on Every Phone



Mobile Phone Accessory

https://www.motorola.com/us/moto-mods

- **Vision:** Become the Waze (real-time traffic) of spectrum usage
- **Approach:** Put a spectrum sensor on every phone and report data to central database
- **Method:** Leverage processing and backhaul of phones and augment with wideband (25 MHz-6 GHz) sensor (e.g., MotoMod)
- **Sensor:** Low-cost ($20) software defined radio and custom (RFIC-based) RF front-end ($20) covering 25 MHz to 6 GHz
- **Prototype platform:** Raspberry Pi as proxy for Mobile phone

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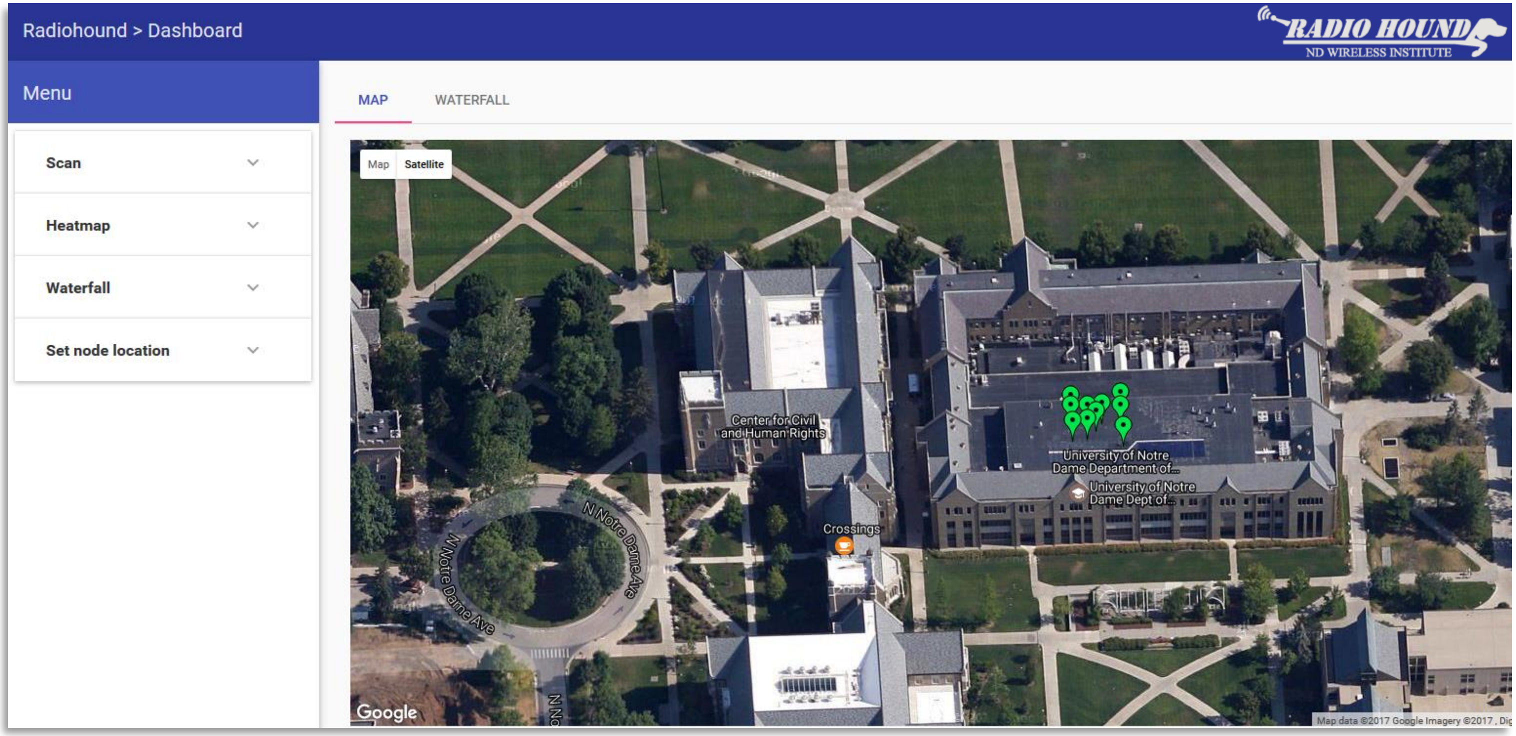
Web-based Graphical User Interface



- All sensor data deposited in central repository
- Web-application controls remote sensors and visualizes results
- Allows the visualization of spectral estimations and waterfalls
- Allows the production of heatmaps

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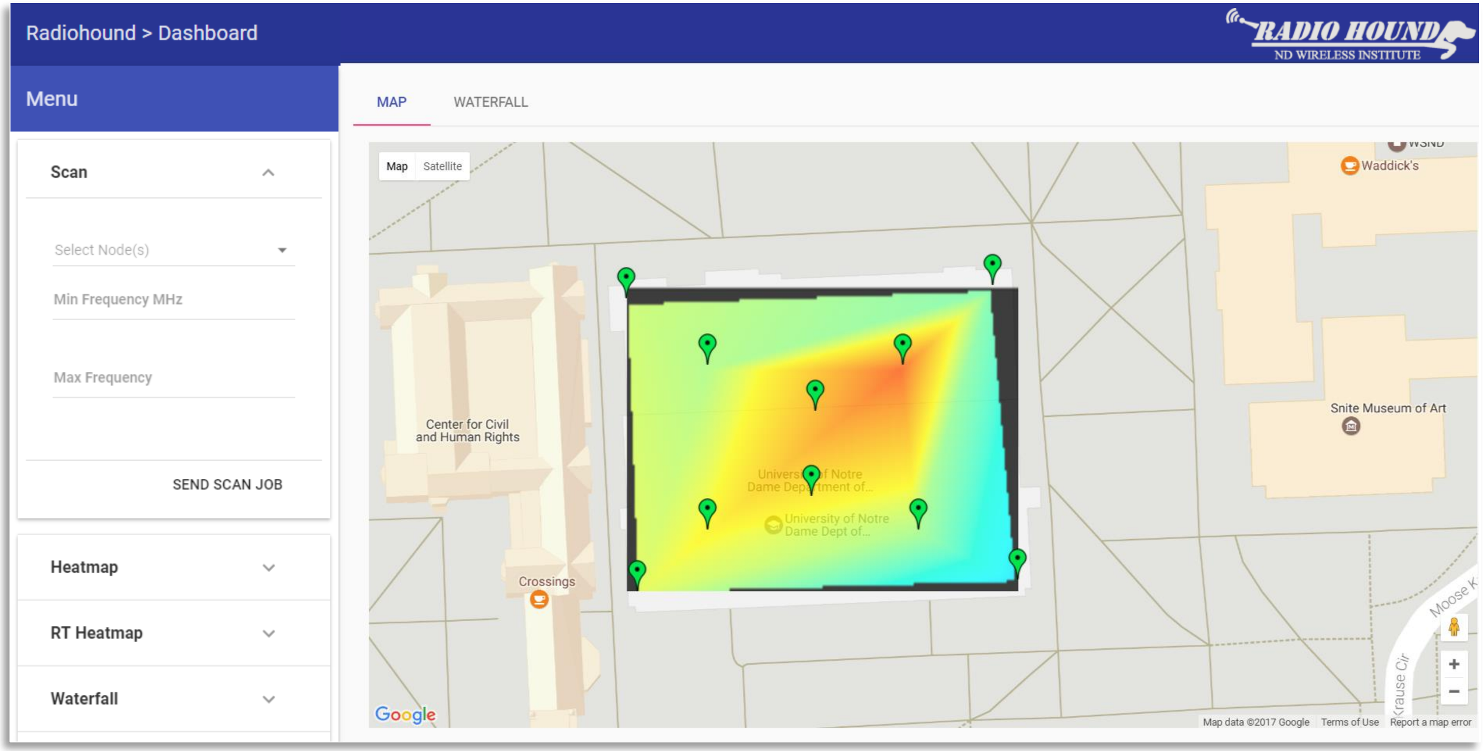

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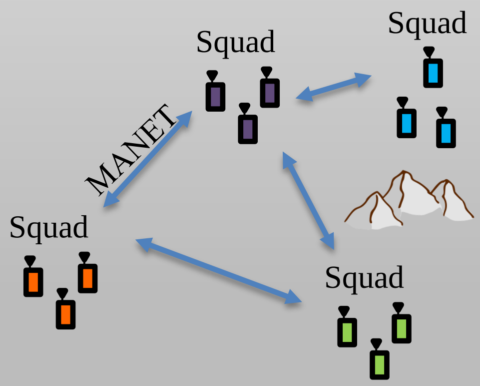
Signal-processing for *Tactical* Distributed Spectrum Sensing

"Scientists cannot produce results useful for warfare without understanding the operational environment"

ARL/ND Vision: Tactical Distributed Sensing



Sensor Package

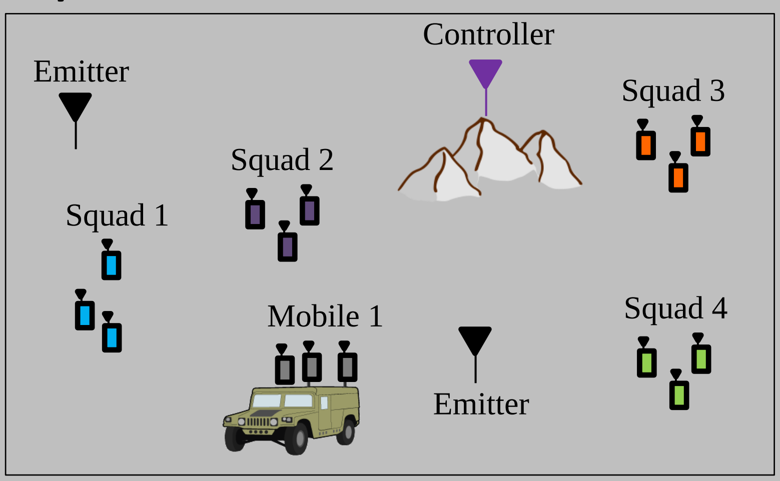
- **Question:** What is "Tactical Distributed Spectrum Sensing"
- It is NOT asymptotic sensor networks ($N_{\text{sensors}} << \infty$)
- It is NOT randomly distributed (clustered)
- It IS congested and contested (not civilian)

Motivation: *Can we take advantage of the clustered nature of tactical sensing?*

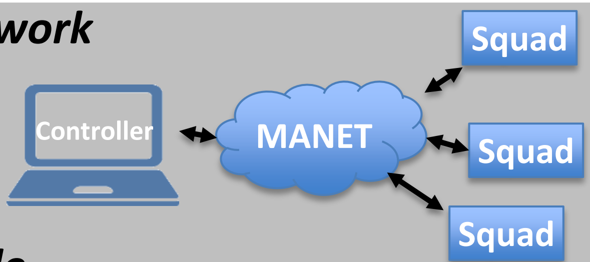
Tactical Distributed Spectrum Sensing

- What if every soldier at the tactical edge had a spectrum sensor?
- What **should** you do with these low-capability sensors?
  - Original vision was **pervasive** crowd-sourced spectrum usage mapping
  - Tactical: **clustered** sensors, high **dynamic range** environment

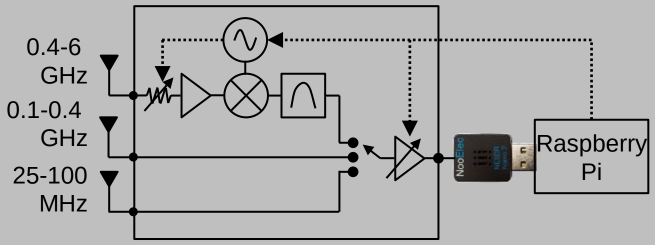
Representative scenario

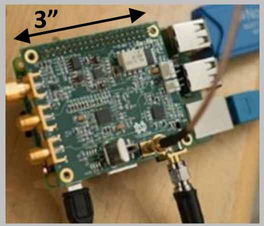


Sensor network



Sensor node

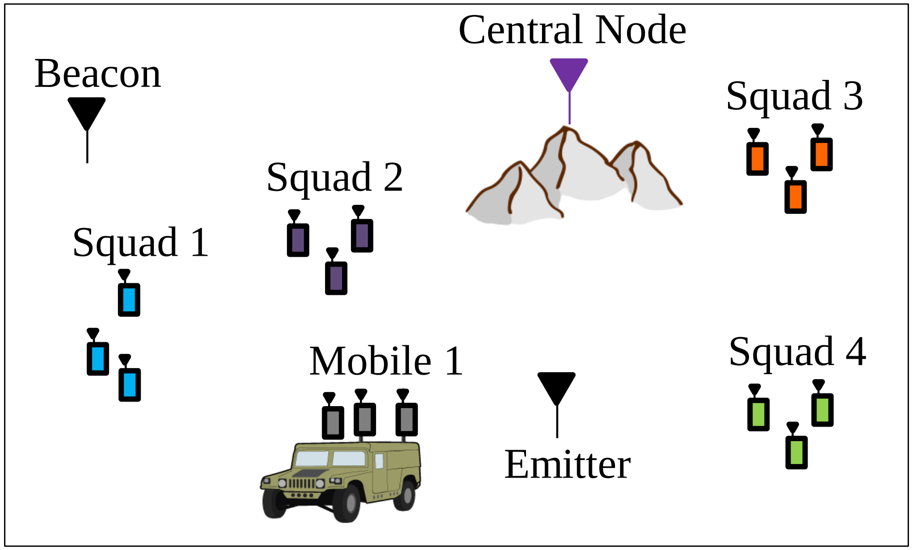




Custom RF Raspberry Pi stack

Clustered measurement constraints

- Several sensors within a squad observe the same signal of interest
- Each sensor contributes its own uncorrelated noise
- Reasonable bandwidth exists within a squad* but bandwidth may be limited between squads



* Sufficient to share IQ samples

"Should be able to combine sensor data"

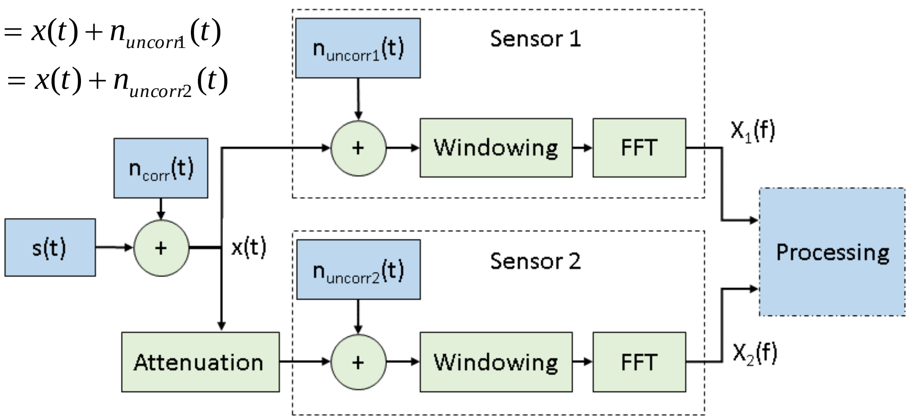
- **Requirements:**
  - Generate a power spectrum
  - No a priori knowledge of emitters necessary
  - Should extract information from a saturated receiver and maintain low-noise performance
  - Does not require precise time-sync (~100μsec) or phase reference
  - Isolates high data rates within squad performing data reduction for data moving between squads

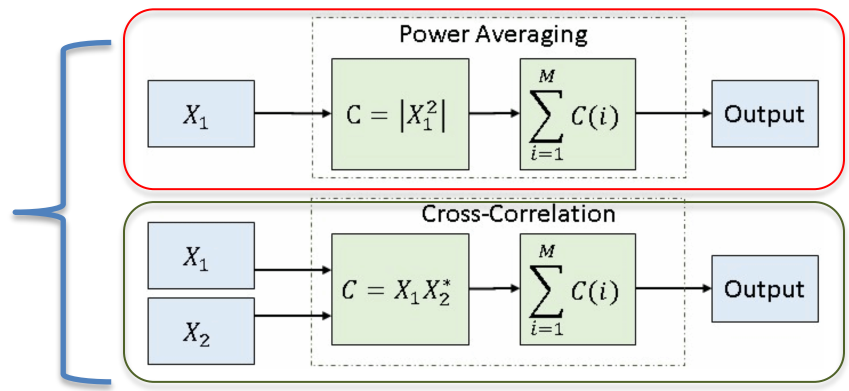
Method	Pros	Cons
Coherent-averaged FFTs	- Noise floor reduces -10dB/decade	Without time-sync and determinism, signals attenuated
Power-averaged FFTs	- Simple - Good initial response (prior to averaging) - Does not require precise time-sync	Noise floor constant (variance of noise is reduced)
Auto-correlation	- Simple - Does not require precise time-sync	Noise floor constant (variance of noise is reduced)
Cross-correlation	- Noise floor reduces -5dB/decade - Can aggregate >2 sensors to increase or signal quality	Requires two independent sensors

Cross-correlation Receiver

- Model: Each sensor in the pair computes a Fourier transform, *X(f)*, of a time signal, $x(t)=s(t)+n_{corr}(t)+n_{uncorr}(t)$
- *Power average:* average *M* power spectra from single sensor, $|X_1{}^2|$
- *Cross-correlation:* average *M* cross-power spectra, $X_1X_2{}^*$
- Metric: compare Spur-free dynamic range, $SFDR={}^2/_3(IIP3-P_{noise})$

$$x_1(t) = x(t) + n_{uncorr1}(t)$$
$$x_2(t) = x(t) + n_{uncorr2}(t)$$

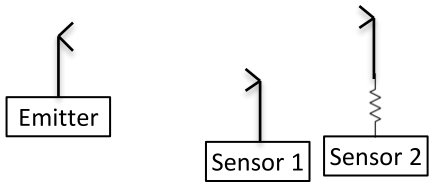




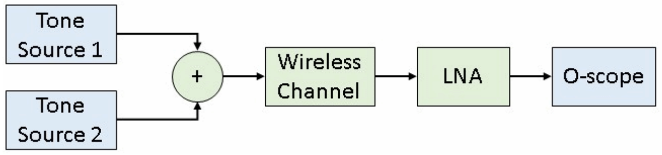
$$E[x_1 \bullet (x_2)^*]$$
$$E[(x+n_{uncorr1})(x+n_{uncorr2})^*]$$
$$E[|x|^2]+E[x^* n_{uncorr1}]+E[xn^*_{uncorr2}]+E[n_{uncorr1}n^*_{uncorr2}]$$
0 0 0
$$E[|x|^2]=E[|s|^2]+E[|n_{corr}|^2]$$

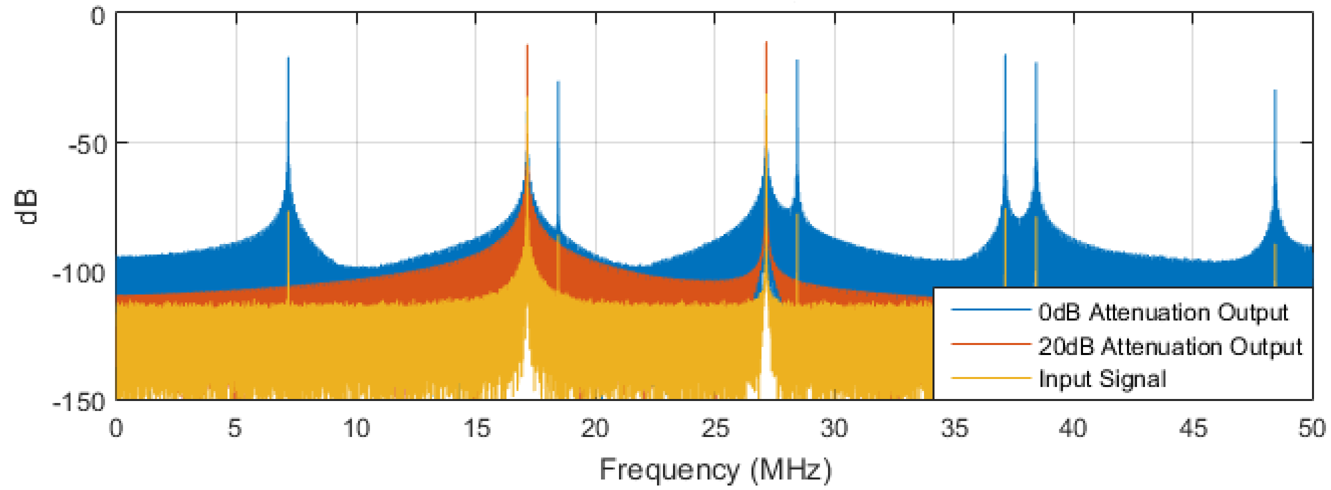
Compare power averaging and cross-correlation over *M* averages

Simulation Environment



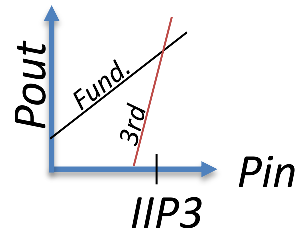
- **Test signal:**
  - -10 dBm sinusoid at 27.174487 MHz and
  - -10 dBm sinusoid at 17.146236 MHz with 50 percent random amplitude modulation
- **Model:**
  - Channel: "coarse time-sync", delayed $\leq T_{samp}/2$
  - Non-linearity (LNA): $v_{out}=v_{in}-(^8/_3)v_{in}^3$

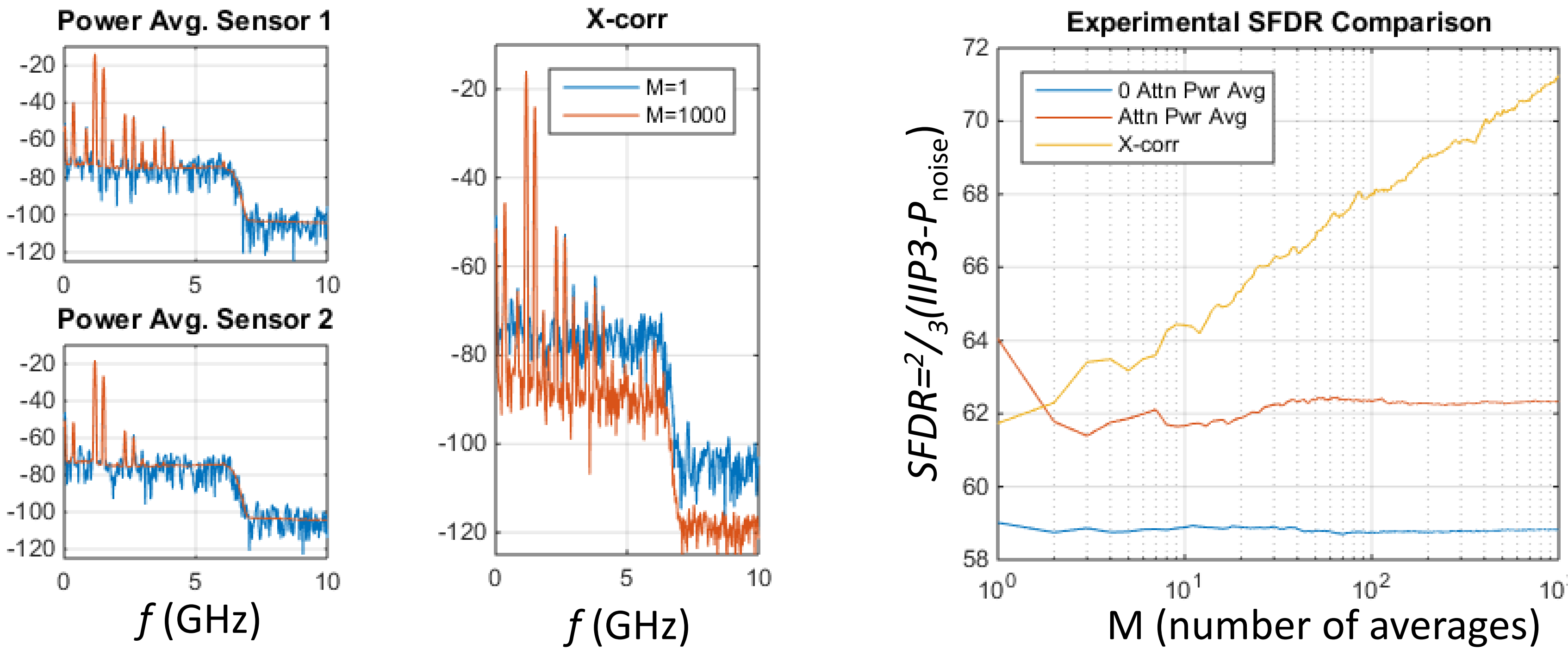




Measured Spectra and SFDR

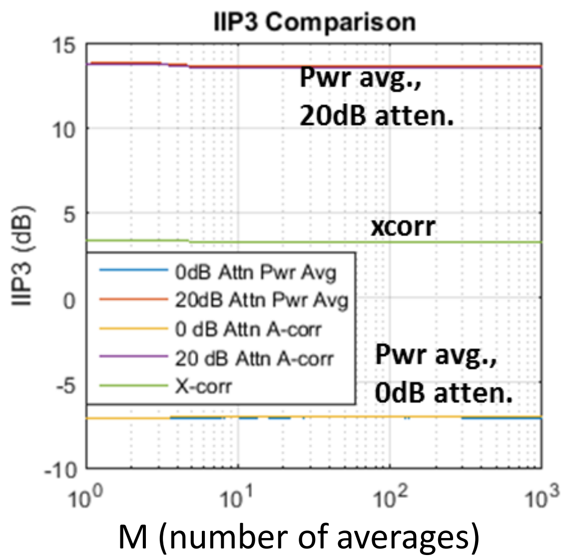
- Two sensors, one un-attenuated, the other with 5 dB attenuation
- Spectra computed for $N_{FFT}=1000$ and compare $M=1, 1000$
- Power-averaged plots use data from sensor 1 or 2, independently
- Spur-free dynamic range, $SFDR={}^2/_3(IIP3-P_{\text{noise}})$

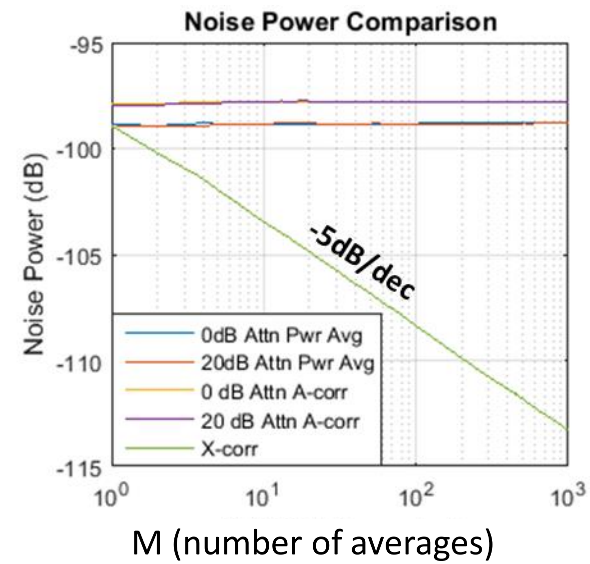


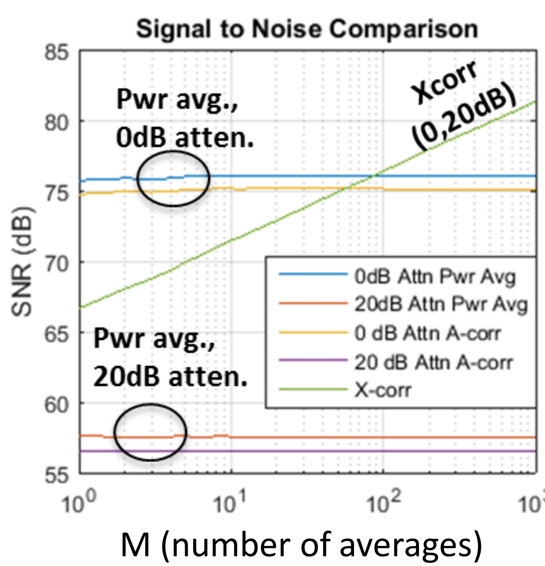


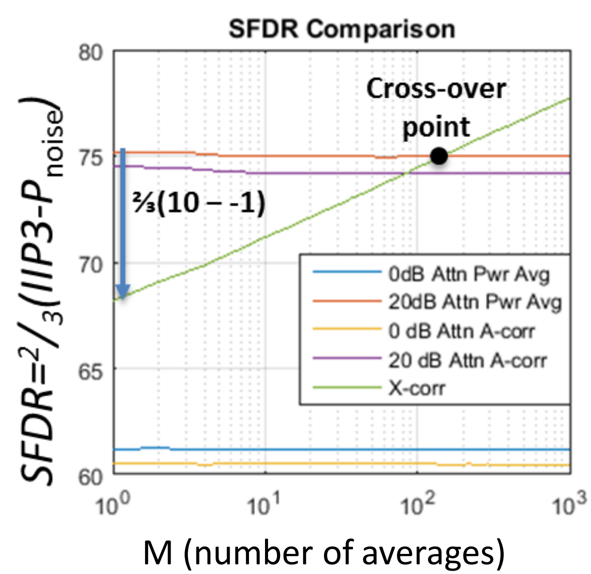
Trends: Power-avg. FFTs vs. Cross-correlation

- Sensor 1 has no atten. and sensor 2 has 20 dB atten.
- Linearity:
  - Averaging does not effect IIP3, regardless of algorithms
  - Cross-correlation is average of two sensors
- Noise:
  - Power averaged sensors maintain same noise power over averaging
  - Cross-correlation sensors start at same noise power but exhibit 5dB/decade reduction in noise power
- SFDR:
  - xcorr SFDR at M=1 is (2/3)*(10dB – -1dB)=7.3dB lower than power averaged
  - **After ~2 decades (*M=250*), cross-correlation SFDR is equal to power averaged**



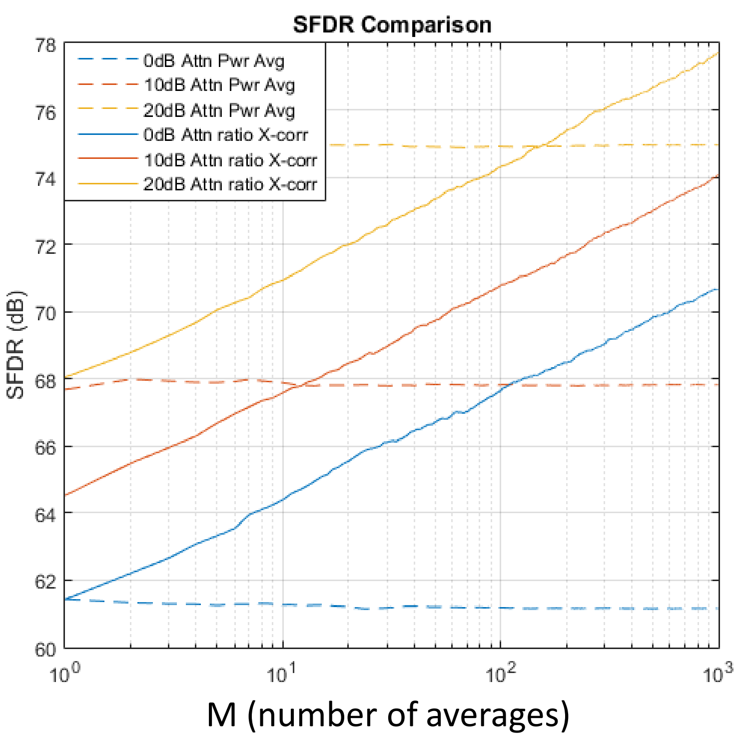


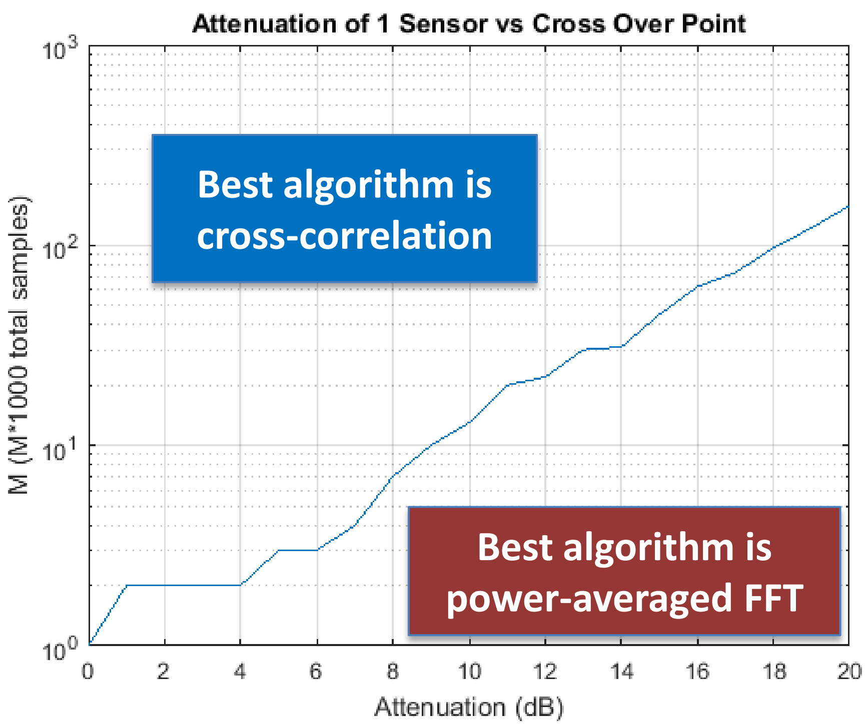




Best Processing Algorithm

- The cross-over point where cross-correlation outperforms power-averaged FFTs is a function of attenuation
- Roughly 10dB/decade trend

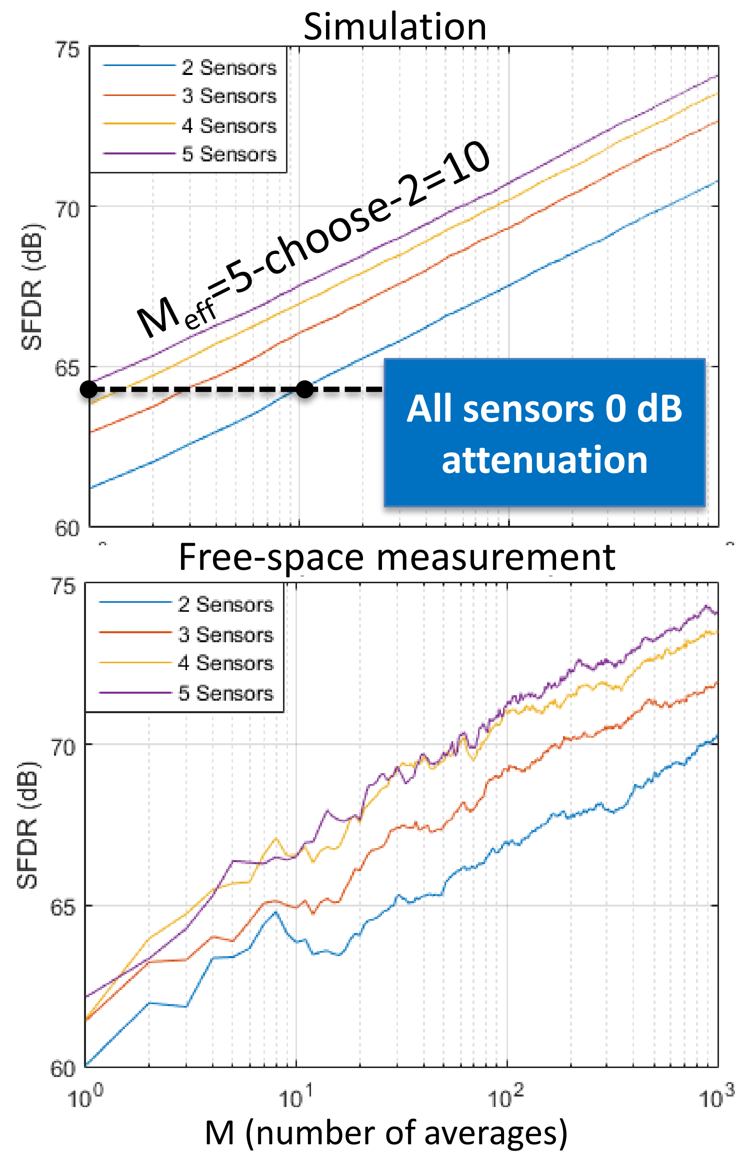




Combining multiple sensors

- Combine multiple sets of sensors, $s=[2,3,4,5]$, with 0 dB attenuation
- Each pair of sensors is cross-correlated (total: s-choose-2)
- Combining sensors is an average with M_{eff} sensors
- $M_{eff} = (s\text{-choose-}2) = (1/2)s^2 - (1/2)s$
- Computational complexity increases with M_{eff}

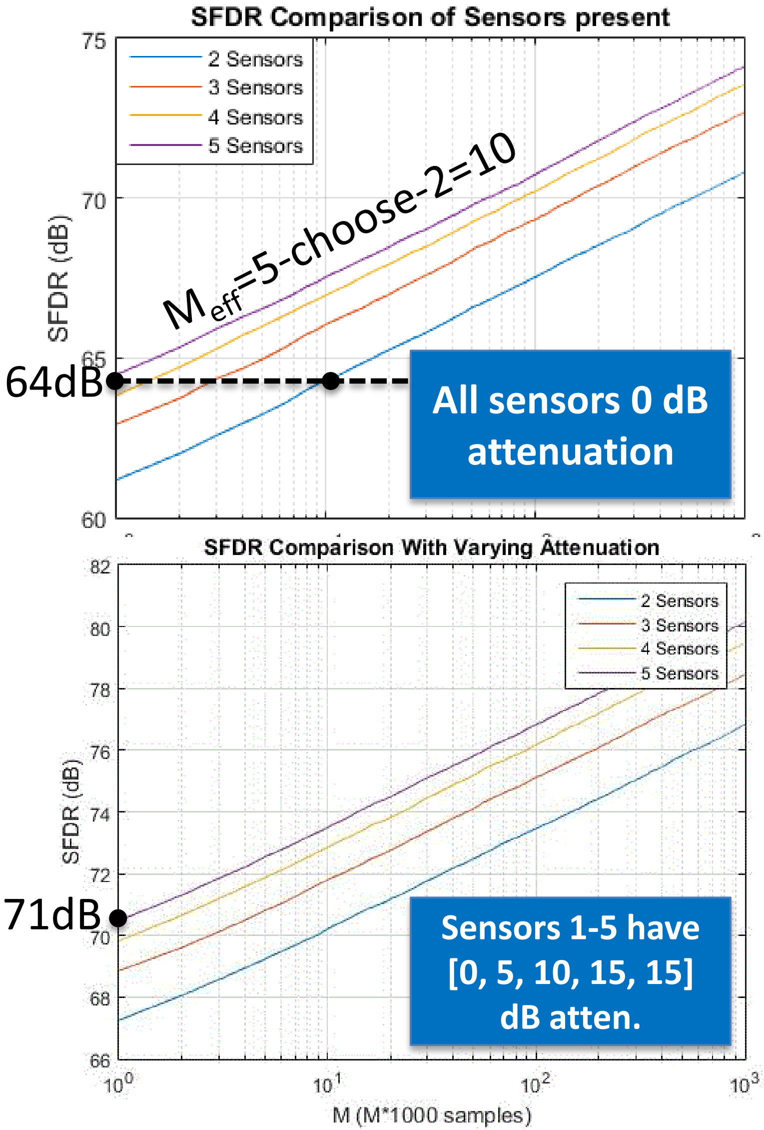
Combining multiple sensors trades computational complexity for scan speed



Combining Attenuated Sensors

- Combine multiple sensors with various attenuations to balance linearity and noise
- Still get benefit of M_{eff} sensor combinations
- But, by properly selecting attenuation within the squad SFDR at $M=0$ can be increased
- Here increase is ~7dB and improves at the same slope

Combining multiple sensors and controlling attenuation achieves better initial SFDR



Xcorr Observations

- Depending on attenuation of a front-end, power-averaging may be the best solution for combining multiple spectrum measurements

PROS:

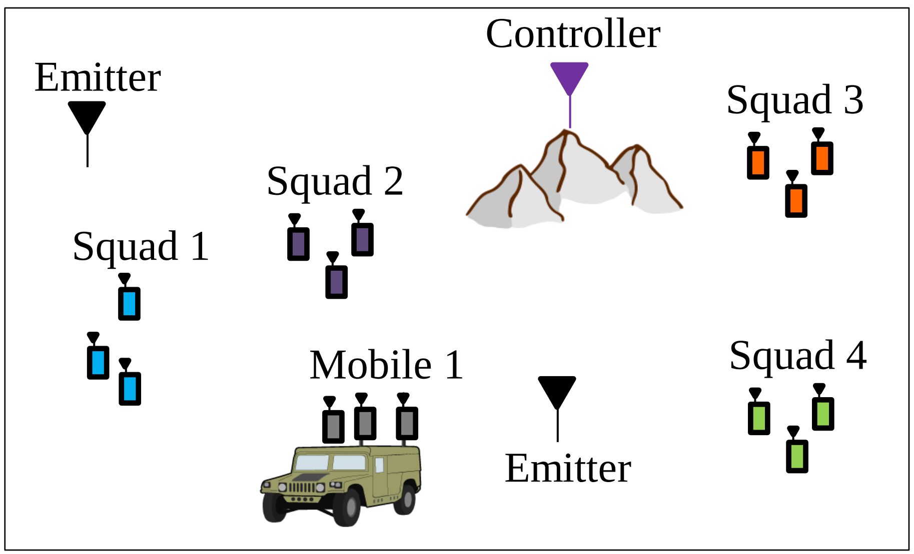
- Cross-correlation is the only approach that offers improvement in noise (and therefore SFDR) so given enough time (averages) it will always be best
- Multiple sensors can be combined (*s*-choose-2) to achieve significantly improved performance even for very few averages and thus provides a means for trading computational complexity for scan speed
- If sensors are equipped with variable attenuators a global controller can optimize performance and speed by combining multiple sensors with various attenuations
- Does not require precise time-sync (~100μsec) or phase reference for power measurements
- Can extract information from a saturated receiver and maintain low-noise performance

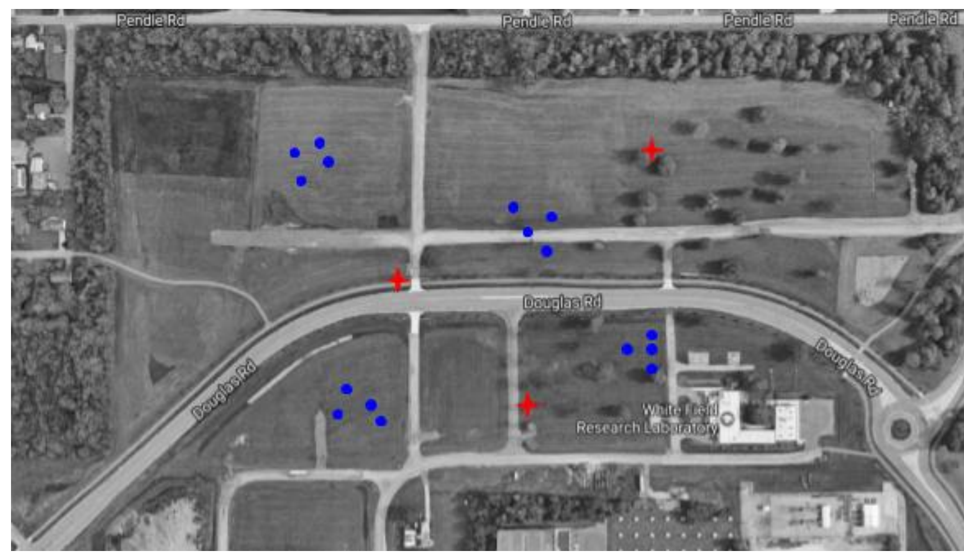
CONS:

- Uses magnitude and phase of data (Not applicable for magnitude only systems)
- Requires >=2 sensors

Field tests June 26

Questions?





Acknowledge: Research was sponsored by the Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-16-2-0140.

Dear Mr. Shaffer…

If you make device, what will you do with it?

Give it to everyone and monitor spectrum everywhere!

What difference will it make (from a military perspective)?

All soldiers will have increased EM situation awareness and, ideally, emitter geolocation

Can we afford it?

Definitely!

Can we exploit the device?

Yes, with intra-squad connectivity on the order of ad-hoc WiFi, and inter-squad connectivity of e.g., 1/10th of that