gr-doa: Direction Finding in GNU-Radio

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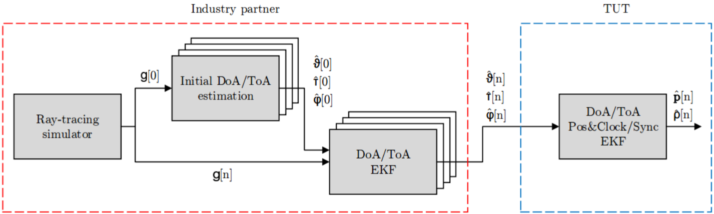
Outline

- Project Background
- MUSIC
- Hardware options
  - USRP-N210
  - X300/X310
  - FMComms5
- Antenna Calibration
- Test and Results
- EADF Feasibility
- Test and Results

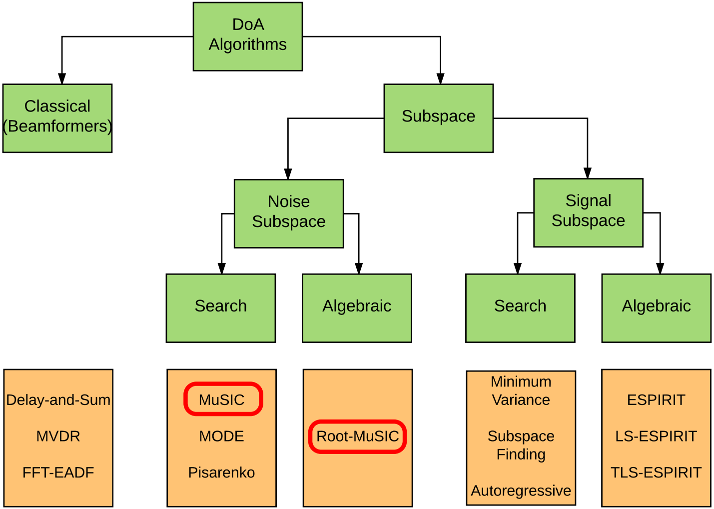


TAMPERE UNIVERSITY OF TECHNOLOGY

Collaboration Outline

- Phase 1: Baseline DoA SDR implementation and analysis (gr-doa)
- Phase 2: Link based DoA with TUT DoA modeling specifics (EADF)

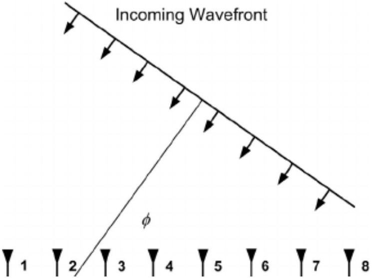
Algorithms in gr-doa



Phased Array Direction Finding Basics

Basics:

- Signal is planar (far field)
- Antenna elements have a fixed and known phase
- Antenna positions are known
- Signal has limited correlation between elements



ULA: Phased Array Model

Element positioning in reference to array center:

$$p_{z_n} = 0, \;\; p_{y_n} = 0, \;\; p_{x_n} = \left(n - \frac{N-1}{2}\right) d, \quad n = 0, 1, \ldots, N-1,$$

Received signal cascaded delays:

$$u_z = \sin(\theta)\cos(\phi), \; u_y = \sin(\theta)\sin(\phi), \; u_x = \cos(\theta),$$

$$\mathbf{u} := [u_z \;\; u_y \;\; u_x]^T$$

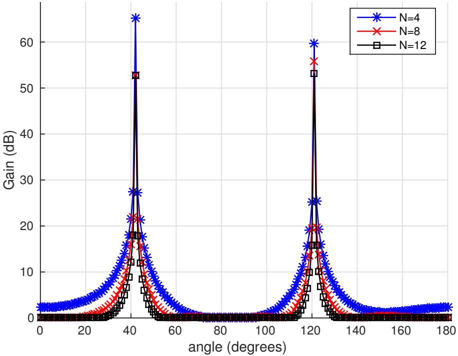
$$\mathbf{k}(\theta, \phi) = -\frac{2\pi}{\lambda}\mathbf{u} = -\frac{2\pi}{\lambda}\left[\sin(\theta)\cos(\phi) \quad \sin(\theta)\sin(\phi) \quad \cos(\theta)\right]^T.$$

Array manifold vector:

$$\mathbf{v}(\mathbf{k}) = \left[e^{-j\mathbf{k}^T p_0} \quad e^{-j\mathbf{k}^T p_1} \ldots \quad e^{-j\mathbf{k}^T p_{N-1}}\right]^T$$

DoA Baseline: MUSIC

MUSIC: Multiple Signal Classification



R. Schmidt, "Multiple emitter location and signal parameter estimation," in IEEE Transactions on Antennas and Propagation, vol. 34, no. 3, pp. 276-280, Mar 1986.

Received signal model:

$$\mathbf{x}(t) = \sum_{d=1}^{D} u_d(t)\mathbf{v}(\mathbf{k}_d) + \mathbf{n}(t)$$

MUSIC subspace principles:

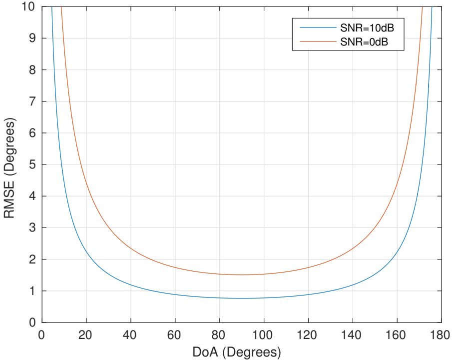
$$\mathbf{R}_{xx} = E\left[\mathbf{x}\,\mathbf{x}^H\right] = \mathbf{V}\,\mathbf{R}_{uu}\,\mathbf{V}^H + I\sigma^2$$

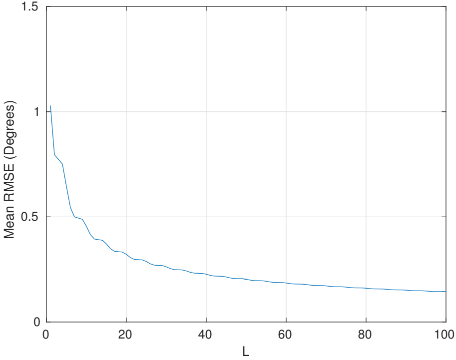
$$\mathbf{U}_N \in \mathbb{C}^{(N-D)xN},\ \mathbf{U}_S \in \mathbb{C}^{DxN}$$

$$\mathbf{v}^H(\mathbf{k}_d)\mathbf{U}_N = 0$$

$$P_{MUSIC} = \frac{1}{\mathbf{v}^H(\mathbf{k}(\theta,\phi))\mathbf{U}_N\mathbf{U}_N^H\mathbf{v}^H(\mathbf{k}(\theta,\phi))}$$

MUSIC: Estimation Performance



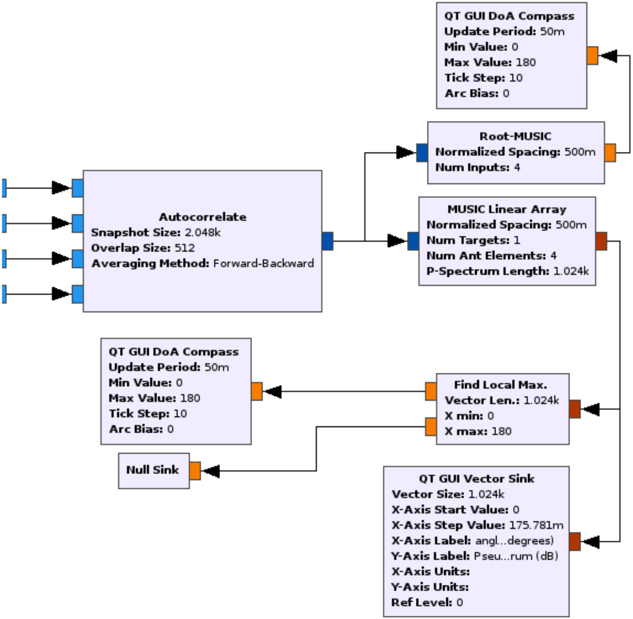


$$var(\theta) \geq \frac{\sigma^2}{2}\left\{\sum_{k=1}^{L} Re\left[u^*(k)\frac{\partial \mathbf{v}^H}{\partial \theta} \cdot \left[\mathbf{I}_N - \mathbf{v}(\mathbf{v}^H\mathbf{v})^{-1}\mathbf{v}^H\right]\frac{\partial \mathbf{v}}{\partial \theta}u(k)\right]\right\}^{-1}$$

$L =$ snapshot length

P. Stoica and A. Nehorai, "MUSIC, maximum likelihood, and Cramer-Rao bound," in IEEE Transactions on Acoustics, Speech, and Signal Processing, vol. 37, no. 5, pp. 720-741, May 1989.

Estimation Blocks

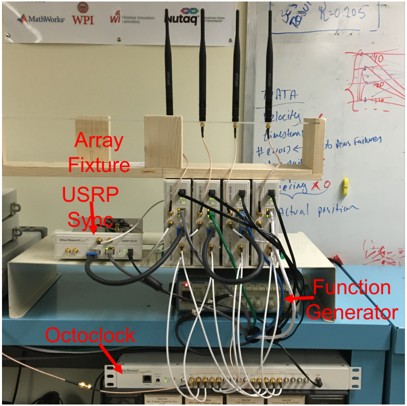


GUI

Real-time visuals

- QT Compass
- Pseudo spectrum (MUSIC block only)

N210 Based Array Construction (First Try)



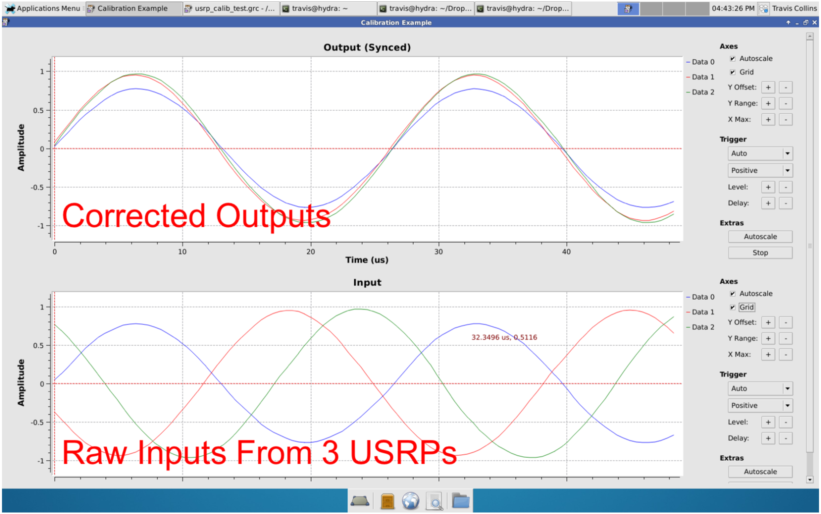
Array Fixture

- $d = \frac{\lambda}{2}$ for $f_c = 2.45$ GHz
- Same length cabling between components

Radios and Software

- Utilizing 4xUSRP N210 radios
- Octoclock provides MB frequency and PPS sampling signals
- Not phased aligned
- GNURadio prototyping platform

Remaining Phase Offset

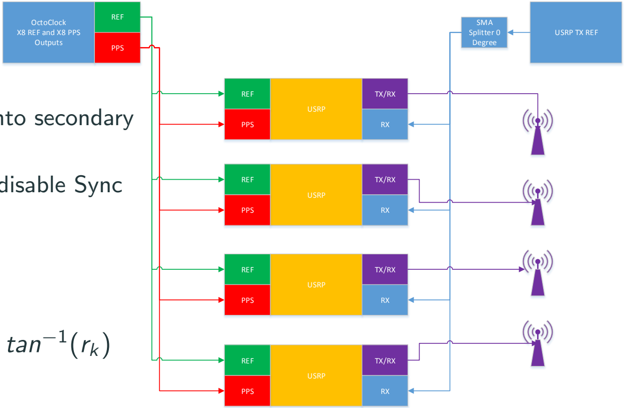


- 10 kHz tone sent into 3xUSRPs through splitter and matched cabling

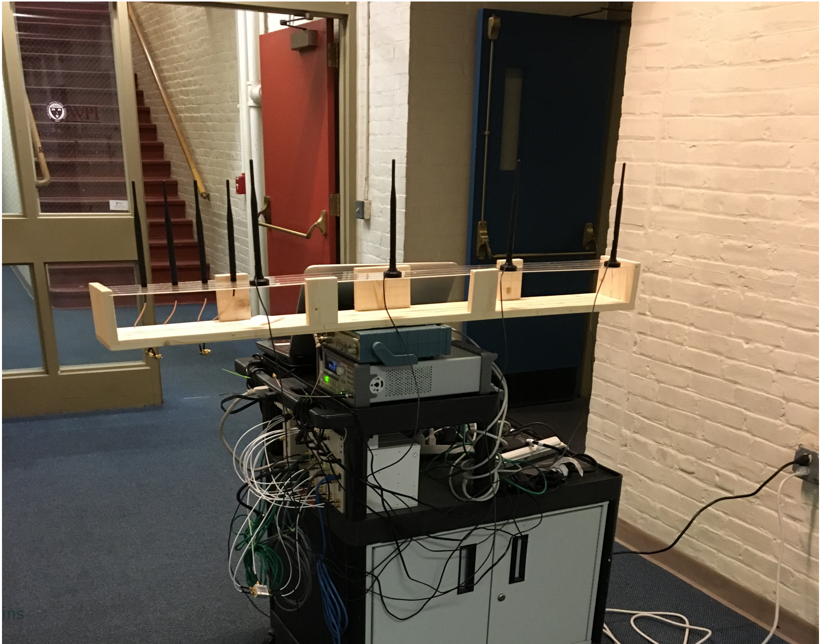
USRP Phase Correction Harness

System Details

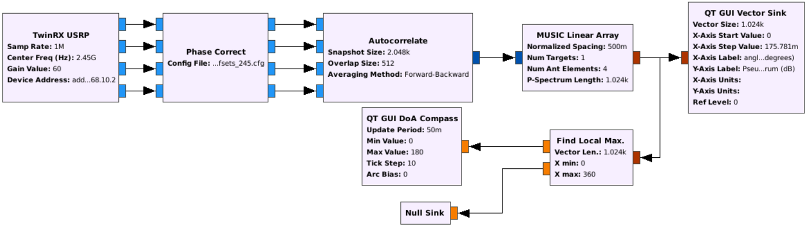
- Two Phase Start:
    1. Transmit tone into secondary port (TX/RX)
    2. Once corrected disable Sync TX
- Can calibrate any daughterboard(s)
- $\Delta\phi_n = tan^{-1}(r_n) - tan^{-1}(r_k)$
- $\hat{r}_n = r_n \, exp(j\Delta\phi_n)$
- Open and closed loop versions



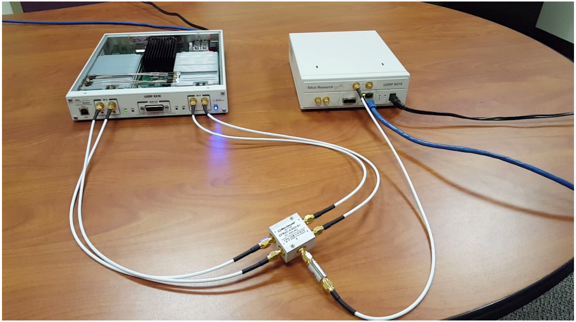
Array Cart



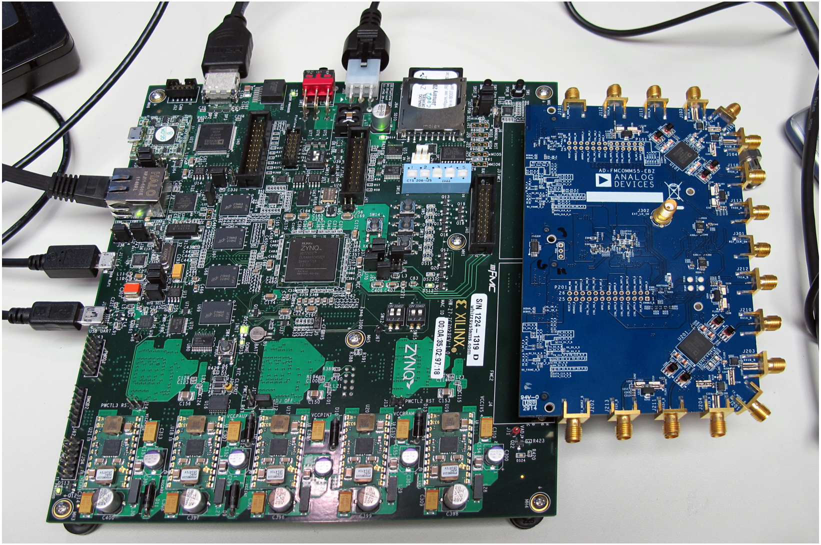
X300/X310 TwinRx Array



- Still needs calibration
- Better phase stability
- Limited to 4-RX
- Easier to carry around!



FMComms5 Array



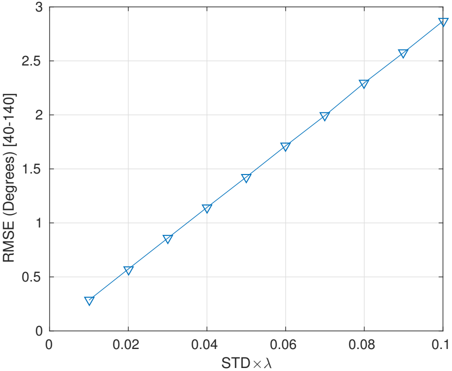
- Self phase calibrating!

DOA: Error Sources

Remaining Possible Sources of Error

- Phase drift between radios over time (Physical)
- Positioning error (Physical)
- Antenna gain and phase missmatches (Physical)
- Reflections in environment (Physical)
- Possible errors in software implementation (Software)

MUSIC: Positioning Error



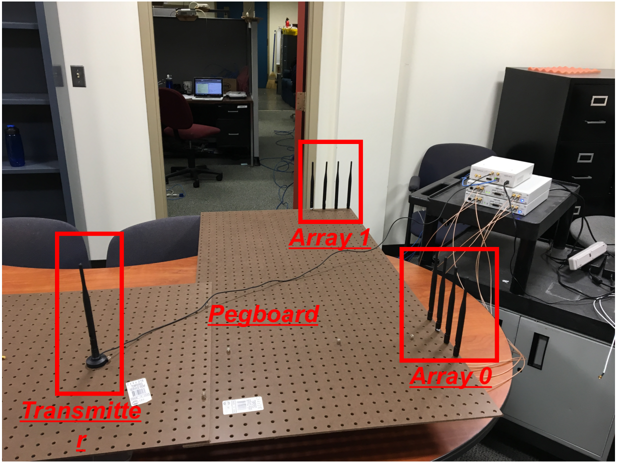
Modified signal model

$$\mathbf{x}(t) = \sum_{d=1}^{D} u_d(t)\hat{\mathbf{v}}(\mathbf{k}_d) + \mathbf{n}(t)$$

Position Error $\mathbf{s}_k = N(0, \sigma^2)$

$$\hat{\mathbf{v}}(\mathbf{k}_d) = \mathbf{v}(\mathbf{k}_d) + \left[\mathbf{s}_1, \mathbf{s}_2, \ldots, \mathbf{s}_D\right]^T$$

MUSIC: Testbed Refinement



Positioning

- Moved to pegboard for precise positioning
- +/-0.125" tolerance $\rightarrow$ 0.028λ (0.7 Degree RMSE)

MUSIC: Antenna Calibration

- Implemented subspace processing method for antenna calibration
- Only phase mismatches between elements cause estimation error
- Utilize a target placed at a known position

$$\mathbf{R}_{xx} = \Gamma \mathbf{V}\,\mathbf{R}_{uu}\,\mathbf{V}^H \Gamma^H + I\sigma^2.$$

$$\mathbf{C}_{xx,eig} = \mathbf{E}_s \Lambda_s \mathbf{E}_s^H \Gamma^H + I\sigma^2 \mathbf{E}_N \mathbf{E}_N^H,$$

$$\mathbf{E}_s \mathbf{E}_s^H \,\Gamma \mathbf{V} = \Gamma \mathbf{V}.$$

$\mathbf{V}_d$ true response of target at known position

$$diag\{\Gamma\} = \gamma$$

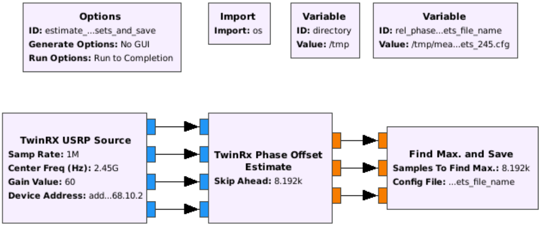
$$\mathbf{E}_s \mathbf{E}_s^H \,\mathbf{V}_d \gamma = \mathbf{V}_d \gamma$$

$$\mathbf{V}_d^H \mathbf{E}_s \mathbf{E}_s^H \,\mathbf{V}_d \gamma = \gamma,$$

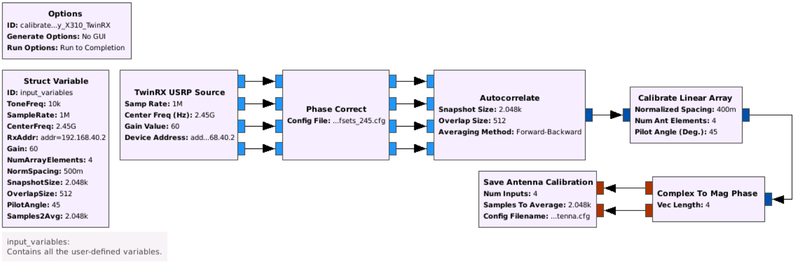
V. C. Soon, L. Tong, Y. F. Huang and R. Liu, "A Subspace Method for Estimating Sensor Gains and Phases," in IEEE Transactions on Signal Processing, vol. 42, no. 4, pp. 973-976, Apr 1994.

Calibration Flowgraphs: Phase and Antennas

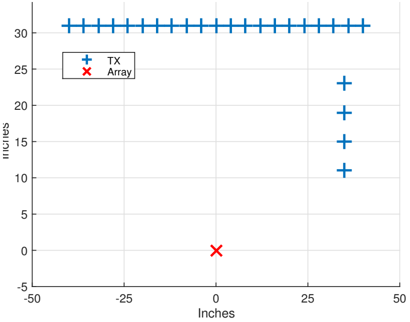
Phase



Antennas

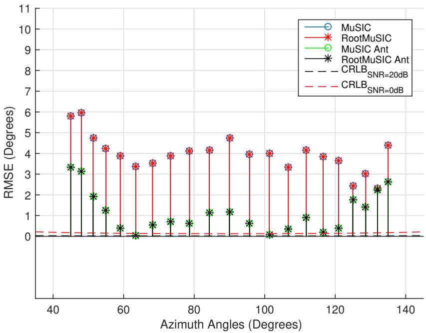


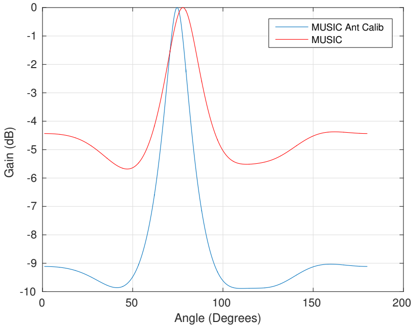
MUSIC: Anechoic Chamber Testing



- Testing in 4x4x4m (W,L,H) room with a single target
- Array positioned away from walls
- X310 dual TwinRX (4 receivers)
- Measurements include MUSIC and Root-MUSIC

MUSIC: Chamber Results





- Antenna calibration uses target at known position
- Increase P-Spectrum SNR and DoA estimate

DEMO

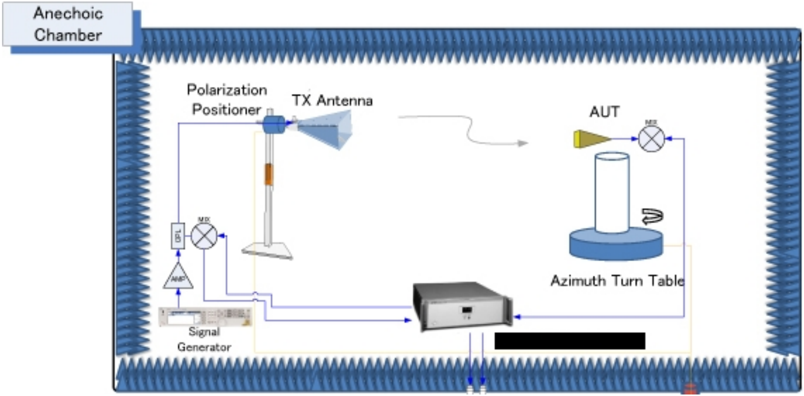
Repository Apps

Hardware Specific `gr-doa/apps`

- `estimate_X310_TwinRX_constant_phase_offsets_and_save.grc`: TwinRX phase correction
- `run_MUSIC_calib_lin_array_X310_TwinRX.grc`: TwinRX antenna calibration
- Run estimation flowgraphs
  - `run_MUSIC_lin_array_X310_TwinRX.grc`: MUSIC
  - `run_RootMUSIC_lin_array_X310_TwinRX.grc`: Root-MUSIC

Octave Simulations and QA `gr-doa/examples`

- Algorithmic examples for MUSIC,Root-MUSIC, and calibrations



Effective Aperture Distribution Function (EADF)

- Alternative and compact representation of antenna angular response
- Applicable to generic array geometrics
- Computationally convenient form (CRLB,DoA)

EADF Antenna Model

Antenna response matrices and EADF representation

$$\mathbf{B}_p = \begin{bmatrix} \mathbf{B} \\ \text{-}\mathbf{B} \end{bmatrix}, \mathbf{G} = FFT_{2D}(\mathbf{B}_p)$$

$\mathbf{G}^{N \times M_A M_E}$, M_A and M_E are the number of azimuth and elevations modes

Mapping vectors are:

$$\mathbf{d}(\theta) = \left[exp(-j\theta(M_A - 1)/2), \ldots, exp(j\theta(M_A - 1)/2)\right]$$

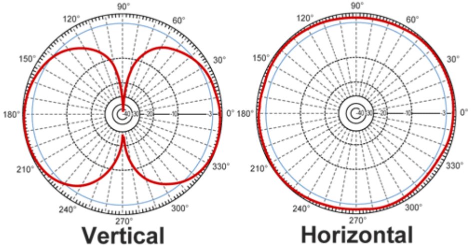
$$\mathbf{d}(\phi) = \left[exp(-j\phi(M_E - 1)/2), \ldots, exp(j\phi(M_E - 1)/2)\right]$$

$$\mathbf{d}(\theta, \phi) = \mathbf{d}(\theta) \otimes \mathbf{d}(\phi)$$

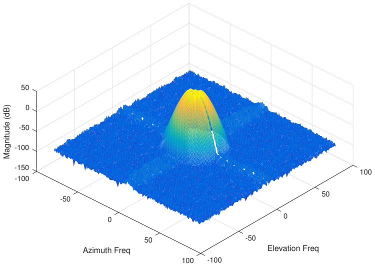
Polarimetric array response:

$$\mathbf{C}(\theta, \phi) = \begin{bmatrix} \mathbf{G}_H \, \mathbf{d}(\theta, \phi) \\ \mathbf{G}_V \, \mathbf{d}(\theta, \phi) \end{bmatrix}$$

A. Schmitz, T. Karolski and L. Kobbelt, "Using spherical harmonics for modeling antenna patterns," 2012 IEEE Radio and Wireless Symposium, Santa Clara, CA, 2012, pp. 155-158.



[LComm Inc.]



EADF Realization

- Monopoles well estimated in azimuth
- Synthetic model as replacement for $\mathbf{B}_p$

EADF-FFT DoA (EFD)

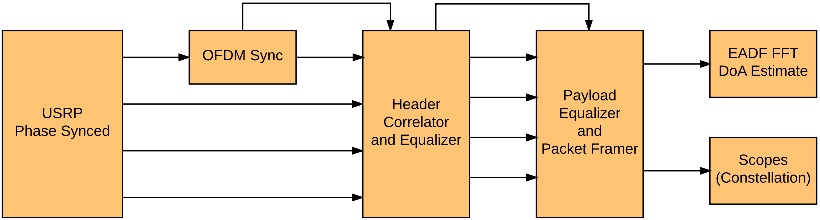
The channel between the transmitting node and receiving array in terms of the polarimetric response is:

$$\mathbf{h} = \mathbf{C}(\theta, \phi)\,\gamma + \mathbf{n}$$

DoA Algorithm

1. Perform channel estimate: $\hat{\mathbf{h}}$
2. Correlate: $\mathbf{A}_H = \hat{\mathbf{h}}\mathbf{G}_H^*$, $\mathbf{A}_V = \hat{\mathbf{h}}\mathbf{G}_V^*$
3. Convert coordinates: $\mathbf{B}_H = |FFT_{3D}(\mathbf{A}_H)|^2$, $\mathbf{B}_V = |FFT_{3D}(\mathbf{A}_V)|^2$
4. Search Max: $\left[\theta, \phi\right]^T = argmax(\mathbf{B}_H + \mathbf{B}_V)$

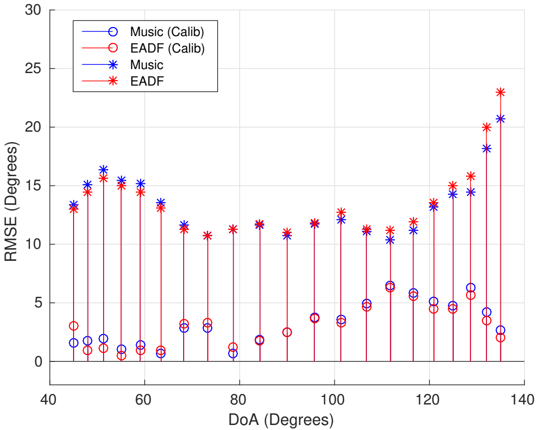
Channel Estimation Platform



OFDM System

- Parameterized system (2 Arrays at 5 MHz each with TUT Config)
- N supported coherent receive channels (4x per radio)
- One directional link
- Successful packets (Header and CRC Check) produce channel estimates
- Verified through simulation and cabling

EFD vs. MUSIC



Results

- Measurements taken in lab environment
- 1000 packets collected minimal variance among measurements
- Adopted correction algorithms from MUSIC implementation

Questions?

Repo: `https://github.com/EttusResearch/gr-doa`

Whitepaper: `https://github.com/EttusResearch/gr-doa/blob/master/docs/whitepaper/doa_whitepaper.pdf`

GitHub: `@tfcollins`

References I

Images

http://www.tut.fi/5G/positioning/

http://www.toyo.co.jp/files/user/img/english/images/Antenna_Receiver.jpg

https://www.ettus.com/content/images/X300_w_twinRX_Large.png

http://blogs-images.forbes.com/scottdavis/files/2016/01/IoT1-1200x900.jpg

Theme

Get the source of this theme and the demo presentation from

`github.com/matze/mtheme`