Digital Beamforming and Direction of Arrival Project

An Introduction to Digital Beamforming and Ideas for a Thesis

M. Shaham[1]

[1]Electrical Engineering Department
Cal Poly San Luis Obispo

EE 563 Graduate Seminar

Table of Contents

Table of Contents

Digital Beamforming Basics (1)

- Digital Beamforming (DBF) is used for directional signal transmission (TX) and reception (RX)
- Amplitude and Phase Variation applied at baseband to digital signal
- Antenna outputs are accessible samples
- A special form of precoding where the array weights need to be determined using a choice of algorithm [1]

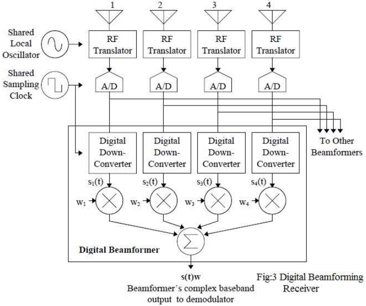

Figure: Digital Beamformer

Beamforming Types Pros and Cons

- Digital:
  + Wideband operations and ability to create nulls
  - Multiple DAC/ADC & computationally intensive
- Analog: Complex weight applied at RF
  + Fairly simple to implement (one ADC/DAC)
  - Single Frequency Design
- Hybrid: Subarrays, precoded streams sent to each array then analog phase shifts [1]
  + intermediate complexity
  - multiple RF chains required

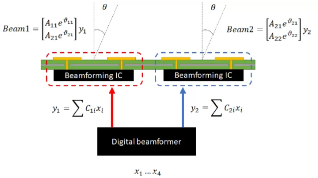

Figure: Hybrid Beamformer

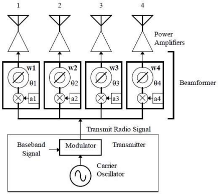

Figure: Analog Beamformer [2]

DBF Basics (2)

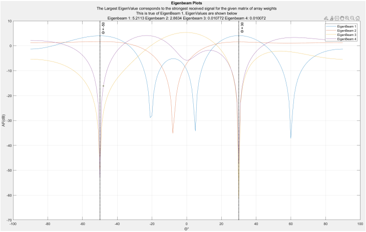

Figure: Eigenbeam Plots Example (known signal directions)

- Array Manifold Vector
  $v_k = [e^{j*p_{z_n}*sin(\theta_m)}]^T$
  $p_{z_n} = (n - \frac{N-1}{2}) * k * d$
  $x(t) = s(t) + n(t)$
  $y(t) = \sum_{k=1}^{N} w_k x_k(t)$
- Correlation Matrices and Eigenbeam Creation $R_{xx} = E\{x(t) * x(t)^H\} = Rss + Rnn$
- Differentiating Signal from Interferer / Noise

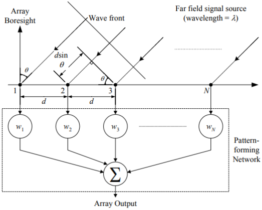

Figure: Array Manifold Vector Visualization[3]

EigenValue Decomposition

- The eigenvector decomposition is taken from the correlation matrix
- Number of eigenvalues correspond to N in the square matrix (N = array size)

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1k} \\ a_{21} & a_{22} & \cdots & a_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ a_{k1} & a_{k2} & \cdots & a_{kk} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} = \lambda \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix},$$

$$\begin{bmatrix} a_{11}-\lambda & a_{12} & \cdots & a_{1k} \\ a_{21} & a_{22}-\lambda & \cdots & a_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ a_{k1} & a_{k2} & \cdots & a_{kk}-\lambda \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}.$$

$$(\mathsf{A} - \lambda\, \mathsf{I})\, \mathbf{X} = \mathbf{0},$$

$$\det(\mathsf{A} - \lambda\, \mathsf{I}) = 0.$$

$$\mathsf{A}\mathbf{x} = \lambda \mathbf{x}$$

x is an eigenvector of A corresponding to eigenvalue, λ.

Figure: Matrix Math to compute eigenvalues and eigenvectors from a system

```
>> eigval

eigval =

   5.2113 - 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i
   0.0000 + 0.0000i   2.8634 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i
   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0108 + 0.0000i   0.0000 + 0.0000i
   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0101 - 0.0000i

>> eigvec

eigvec =

   0.1915 + 0.5872i  -0.0858 - 0.0991i   0.5041 + 0.2496i  -0.3502 - 0.4028i
  -0.2342 - 0.2528i  -0.6360 - 0.2783i   0.4289 + 0.2839i   0.0946 + 0.3546i
  -0.3095 - 0.1418i   0.6962 + 0.0000i   0.5894 + 0.0000i   0.0084 + 0.2281i
   0.6196 + 0.0000i   0.1142 - 0.0557i   0.1800 + 0.1981i   0.7269 + 0.0000i
```

Figure: Eigenvalues and Eigenvectors from Example Above

<u>Eigenvalues & Eigenvectors</u>

$$\boxed{A v = \lambda v}$$

where $A \in \mathbb{R}^{m \times m}$ (Square Matrix)

eigenvectors $\longrightarrow v \in \mathbb{R}^{m \times 1}$ (Column Vector)

eigenvalues $\longrightarrow \lambda \in \mathbb{R}^{m \times m}$ (Diagonal Matrix)

Figure: The produced eigenvalues are a diagonal matrix

DBF Basics (3)

- Narrow vs Wideband Beamforming
  - Frost Beamformer / LCMV Beamformer
- Array Configurations
- Adaptive Nulling

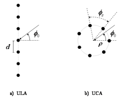

Figure: Showing the basic 2 different antenna configurations [5]

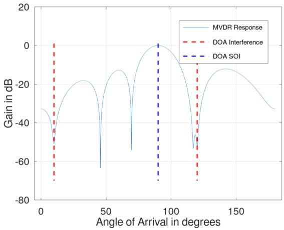

Figure: Preserving the signal of interest while nulling the interference

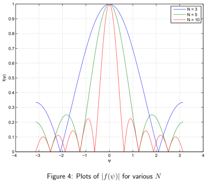

Figure: Comparing the number of antenna elements with radiation pattern [4]

1. Delay and Sum: Signal strength at each arriving angle and find power peaks
2. Root-MUSIC: Finding roots of polynomial - useful for sum or sinusoids in AWGN
3. MUSIC: MUltiple SIgnal Classification where the strength, number, and direction of uncorrelated signals can be determined [8].

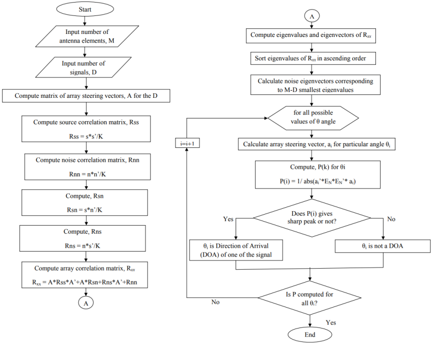

Figure: Flowchart of MUSIC Algorithm from [8]

Direction of Arrival (DoA) Algorithms (2)

1. ESPRIT: Estimation of Signal Parameters via Rotational Invariance Techniques - does not have to go through all steering vectors
2. Capon's Method: Sweeps all theta values - maximum likelihood estimate of signal
3. 2-D DoA: While UCA are inherently, ULA need a second dimension (θ-axis) L-Shaped Array

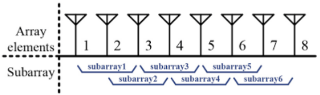

Figure: Antennas being subdivided for ESPRIT

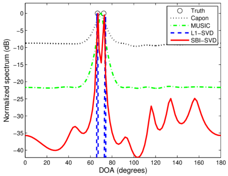

Figure: DoA Comparison of Methods

Table of Contents

Potential Thesis Ideas

Potential Topic 1

Genetic Algorithms / Machine Learning to produce correct antenna positions and optimal weightings

Potential Topic 2

Moving Transmitter and/or receivers and creating optimal element weights from these scenarios

Potential Topic 3

Potentially looking into creating a hardware implementation

Thesis Applications

More thesis potential applications are shown below

Thesis Use Cases

Figure: Knowing Previse Locations of First Responders during emergencies

- Search and Rescue
- First Responders
- Determining Radio Jammer Positions

Figure: Detecting positions of radio jammers to shut down their operations

Table of Contents

Existing Technology

- Kraken SDR: Implementation of DoA
- Starting Point - implement one or two DoA Algorithms on the Kraken SDR in GNU Radaio
- "Misplace" Antenna elements and use GA or NN to perform DoA measurements

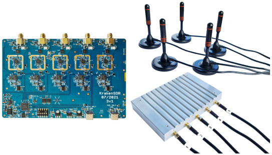

Figure: Internals of Kraken SDR

Figure: Kraken SDR Interface (Algorithm, element spacing, element configuration)

Summary

- Digital Beamform: Each Element samples input data
- Know the null points of the array more accurately
- Less RF design more signal processing
- Can cover a wider band of operation (with narrowband operation required for statistical modeling)

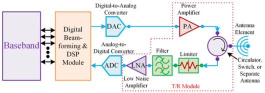

Figure: Digital Beamforming Transceiver Chain

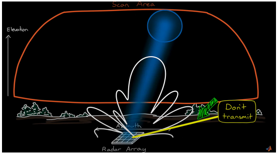

Figure: Example with interferer position kept constant, but tracking main beam for Radar

References

1. https://resources.altium.com/p/what-hybrid-beamforming
2. https://www.rfwireless-world.com/Terminology/Analog-Beamforming-vs-Digital-Beamforming.html
3. "Direction of arrival estimation in wireless mobile communications using minimum variance distortionless response"
4. https://www.waves.utoronto.ca/prof/svhum/ece422/notes/15-arrays2.pdf
5. "Simplified Spatial Correlation Models for Clustered MIMO Channels With Different Array Configurations"
6. https://research.wmz.ninja/articles/2017/03/crbs-in-classical-doa-estimation-problems.html
7. "Adaptive Beamforming With Software-Defined-Radio Arrays"
8. https://commons.und.edu/cgi/viewcontent.cgi?article=2558&context=theses

Thank You!

Questions?