Indian Institute of Information Technology Kottayam

ACOUSTIC SOURCE LOCALIZATION

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OUTLINE

- Introduction
- Objectives and Scope
- Techniques used for Acoustic Source Localization
- Conventional-FFT Algorithm
- MUSIC Algorithm
- Literature survey
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INTRODUCTION [1]

- **Acoustic source localization** is the process of determining the location or direction of origin of a sound in a given environment
- Sound source localization is an important task for a multitude of applications, including **robot audition** and **voice-controlled** smart devices.
- **Direction of arrival** estimates are essential in providing angular positional information for **localization**.

1. K. Rashida, S. Kamal, C. Satheesh Chandran, A. A. Balakrishnan and M. H. Supriya, "Prototype Implementation of Spatial Filtering using Sensor Array," *2019 International Symposium on Ocean Technology (SYMPOL)*

Sensor Characteristics [1]

- Microphone Array Configuration
- Number of Microphones
- Microphone Sensitivity
- Frequency Response
- Directional Characteristics
- Noise Characteristics
- Dynamic Range

1. K. Rashida, S. Kamal, C. Satheesh Chandran, A. A. Balakrishnan and M. H. Supriya, "Prototype Implementation of Spatial Filtering using Sensor Array," *2019 International Symposium on Ocean Technology (SYMPOL)*

Techniques used for ASL [1]

1. Conventional Beamforming:

- Use of an array of **antennas or transducers** to perform signal processing based on the spatial characteristics of a signal.

ADVANTAGES

- **Real time processing**
- **Robust**
- **Interpretability**

DISADVANTAGES

- **Require Prior Information**
- **Limited in Complex Environment**
- **Sensitive to Array Geometry**

1. K. Rashida, S. Kamal, C. Satheesh Chandran, A. A. Balakrishnan and M. H. Supriya, "Prototype Implementation of Spatial Filtering using Sensor Array," *2019 International Symposium on Ocean Technology (SYMPOL)*

Techniques used for ASL[3]

2. AI and ML Techniques

ADVANTAGES

- Adaptability
- Feature Learning
- Flexibility

DISADVANTAGES

- Complexity
- Data Dependency
- Black Box Nature

3. Chung, M.-A.; Chou, H.-C.; Lin, C.-W. Sound Localization Based on Acoustic Source Using Multiple Microphone Array in an Indoor Environment. *Electronics* 2022, *11*, 890.

Conventional Beamforming[1]

- Determine the **location of a source** signal in space

- Characterize the signals from sources, to **distinguish different targets**

- Use the signals captured by the microphone arrays to **automatically obtain the position** and details of the acoustic sources.

1. K. Rashida, S. Kamal, C. Satheesh Chandran, A. A. Balakrishnan and M. H. Supriya, "Prototype Implementation of Spatial Filtering using Sensor Array," *2019 International Symposium on Ocean Technology (SYMPOL)*

Beamforming Algorithms[1]

1. **Delay and Sum Algorithm**

- Signals are **delayed** and **summed** coming from different microphones
- By adjusting delays we can focus on different directions to enhance signals arriving from **specific directions**

1. K. Rashida, S. Kamal, C. Satheesh Chandran, A. A. Balakrishnan and M. H. Supriya, "Prototype Implementation of Spatial Filtering using Sensor Array," *2019 International Symposium on Ocean Technology (SYMPOL)*

Beamforming Algorithms[2]

2. Multiple Signal Classification(MUSIC)

- **Objective:** Identify and locate **multiple** sound sources in a **noisy environment**.
- **Process: Separates** sounds picked up by microphones and analyzes **unique arrival patterns**.
- **Identification:** Matches patterns to **determine** the **direction** and **location** of each sound source

2.Desai, *et al* A Review on Sound Source Localization Systems (July 22, 2021).

Beamforming Algorithms[4]

3. Minimum Variance Distortionless Response(MVDR)

- **Purpose:** Focus on a desired sound source while minimizing **background** noise.
- **Method:** Calculates the direction that minimizes overall noise while keeping the desired signal clear.
- **Adaptability:** Adjusts continuously to changes in the environment to maintain clarity.

4.Jekateryńczuk, G.; Piotrowski, Z. A Survey of Sound Source Localization and Detection Methods and Their Applications. *Sensors* **2024**, *24*, 68.

Objectives

- To perform **Acoustic Source Localization** using **Signal Processing** techniques in indoor environment
- To implement **Conventional-FFT** Algorithm
- To implement **MUSIC Algorithm**

Scope

- Implementation of different **Algorithms** for Acoustic Source Localization
- Implement better **Algorithms** for Acoustic Source Localization
- Improve Acoustic Source Localization using **AI/ML** techniques

Conventional FFT-Algorithm[1]

In this section, I tried to implement the **Conventional FFT-based** method.
The reason I implement this method is:

1. Conventional FFT-based method is a quite **typical approach** in DOA estimation, it has specific advantages as well as disadvantages.

2.It provides the basic concept of how **DOA estimation** works.

3.Additionally, **conventional FFT** method is relatively **easier to understand and coding in program.**

1. K. Rashida, S. Kamal, C. Satheesh Chandran, A. A. Balakrishnan and M. H. Supriya, "Prototype Implementation of Spatial Filtering using Sensor Array," *2019 International Symposium on Ocean Technology (SYMPOL)*

Conventional FFT-Algorithm[1]

4.By implementing this method, I could have a better understanding of **DOA estimation**.

5. Finishing implement conventional FFT-based method could give me a result which is useful when I implement the **proposed algorithm later on**.

6.The result could be seen as reference when I compare the performance between **conventional FFT** and **proposed method**.

1. K. Rashida, S. Kamal, C. Satheesh Chandran, A. A. Balakrishnan and M. H. Supriya, "Prototype Implementation of Spatial Filtering using Sensor Array," *2019 International Symposium on Ocean Technology (SYMPOL)*

Conventional-FFT Algorithm(Implementation)

- **Setting up parameters:**

lamda: Wavelength of the signal.
d: Inter-element spacing of the array (half of the wavelength for a ULA).
N: Number of elements in the array.
M: Number of sources (set to 1 for a single source scenario).
rad: Conversion factor from degrees to radians.
theta_1: Desired DOA of the source in degrees.
phi_1: Angle in radians corresponding to theta_1**.**
SNR: Signal-to-Noise Ratio in dB.

- **Signal generation:**

s_1: The signal received at each antenna element due to the source. It's a complex exponential signal with phase shifts corresponding to the angle of arrival.

Conventional-FFT Algorithm(Implementation)

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Adding noise:

- Gaussian noise with a given **SNR** level is added to the **received signal x.**
- **X is the FFT** of the **received signal x**.
- **Y represents the power spectrum** obtained by squaring the magnitude of the FFT result.

DOA estimation:

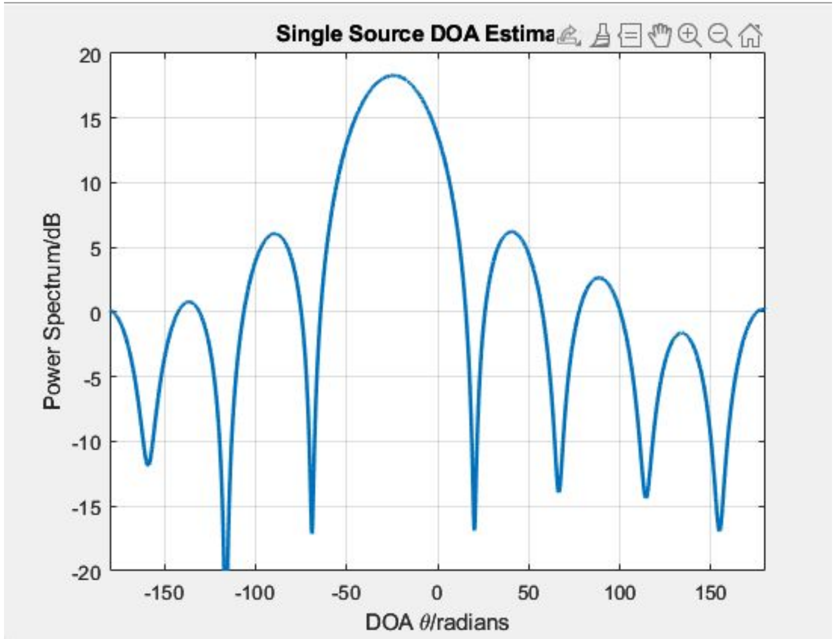
- **phi_axis and theta_axis** represent the angular range over which the DOA will be estimated.
- The peak of the **power spectrum indicates the estimated DOA**.
- **phi_0 and theta_0** represent the **estimated DOA** in radians and degrees, respectively.

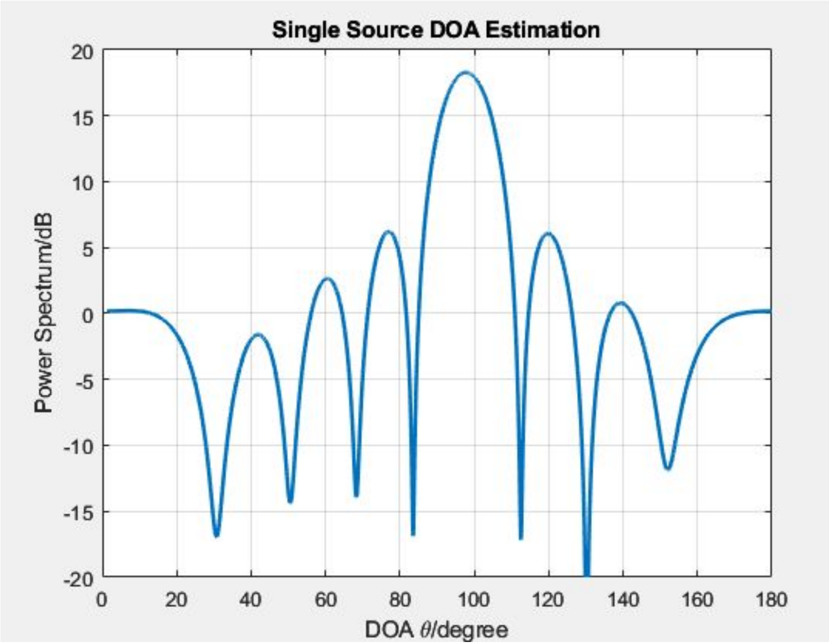
- **Plotting:**

  Figure 1 plots the power spectrum against the angular range in **degrees.**
  Figure 2 plots the power spectrum against the angular range in **radians.**

Conventional-FFT Algorithm(Results)

Results for single source detection





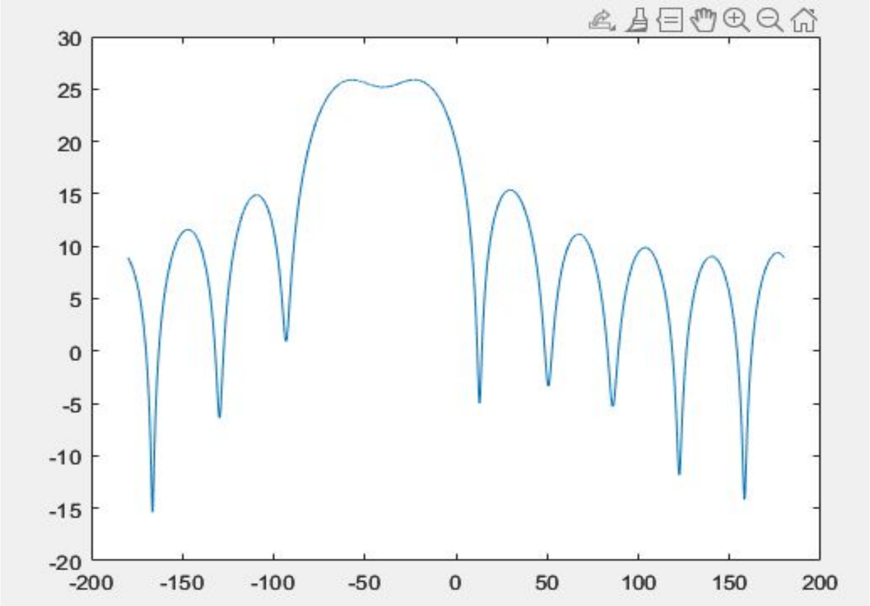
Once found the peak value in the spectrum, the corresponding peak is the estimated direction of arrival(DOA).

Conventional-FFT Algorithm

- The calculation is based on $\boldsymbol{M}$ **= 8 antenna arrays** and the signal to noise ratio $\boldsymbol{SNR}$ **= 20** $\boldsymbol{dB}$.
- It is worth pointed out that with the **increasing of SNR**, the deviation would drop accordingly.
- But it is not practical for the real case, because the SNR is determined by the environment and **could not been changed by human being**.

Conventional-FFT Algorithm(Results)

Results for multiple source detection



Two sources conventional FFT method with close direction angle

Conventional-FFT Algorithm

- It could be seen from the spectrum that the two peak values are **merged together** and it is hard to find the **two peak values** already.
- With further reducing the direction difference, the final spectrum would fall into only **one peak**, which means totally fail to estimate the correct **DOA of source signals.**
- The difference of direction angle between the two source signals is set to **16.5°**, which is less than **π/M = 18°**.

Conventional-FFT Algorithm[1]

- **Brief Conclusion**

1. From the **conventional FFT-based** method implementation, it can be shown that this method is more **effective for the single source case**, which would provide an **unbiased estimation.**

2. But at the cost of high computational cost. For **multiple source case**, it suffers the problem of **significant spectral leakage** which could cause **biased estimation.**

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MUSIC Algorithm[11]

- **Music algorithm** is a popular method which belonging to **spatial spectrum estimation.**

- MUSIC algorithm aims to **decompose** the **eigenvectors** of the **covariance matrix of the array signal**, and get the related **signal subspace** and **noise subspace**, which are **orthogonal**.

- Base on this **orthogonal characteristic**, the **spectrum function** could be constructed, and the **DOA of the signal** could be got by searching the peak **value in the spectrum**.

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

There are many advantages of MUSIC algorithm:

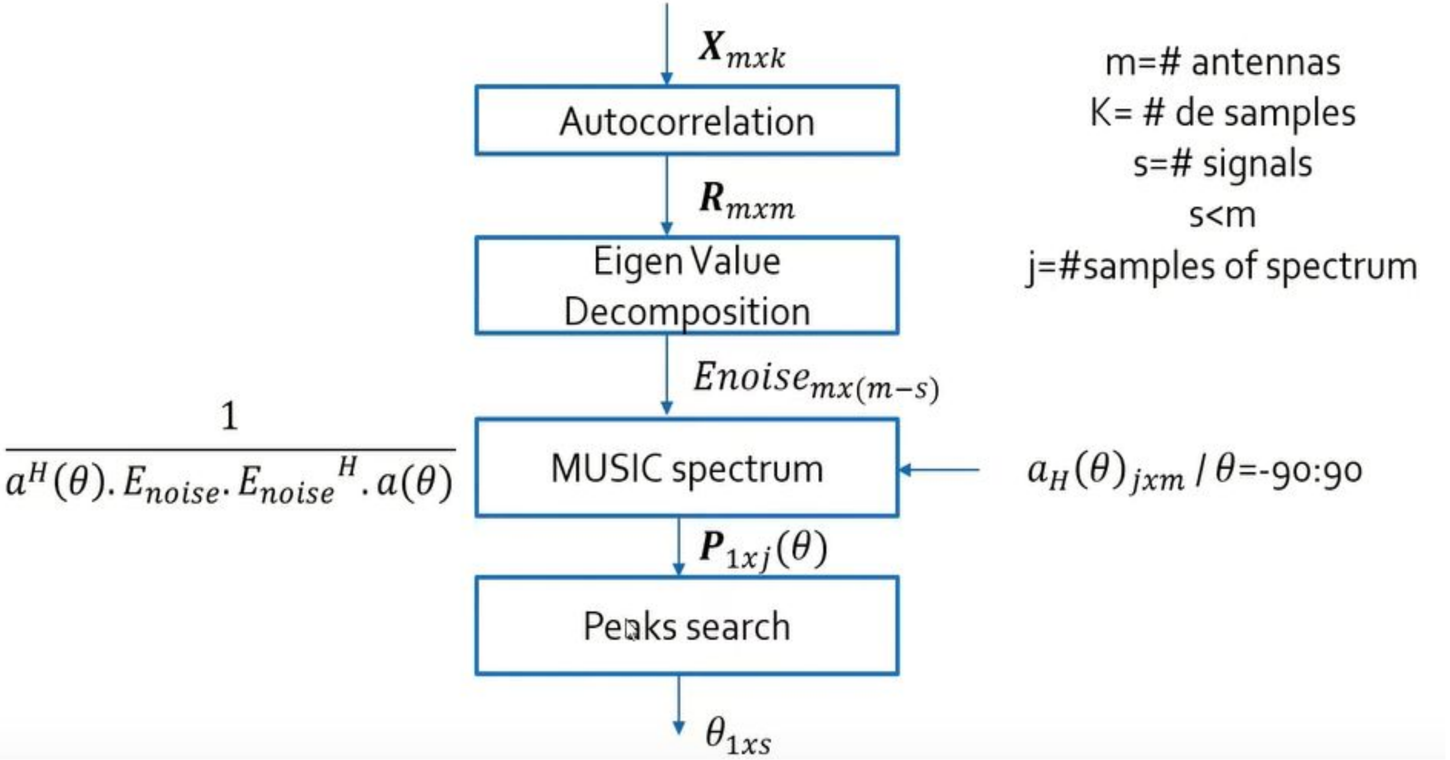
(1) It has the ability to detect the DOA of **multiple signals** at the same time.

(2) High **accuracy and resolution**.

(3) When using high speed processing technology, it is possible to process the signal in **real time**.

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]



A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

1.Setup:

- Assume we have an array of **M sensors (antennas)** with known positions.
- Received signals at each sensor are combined to form a **data matrix X**.
- Consider the scenario with a **microphone array** and a **far-field** sound source.

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

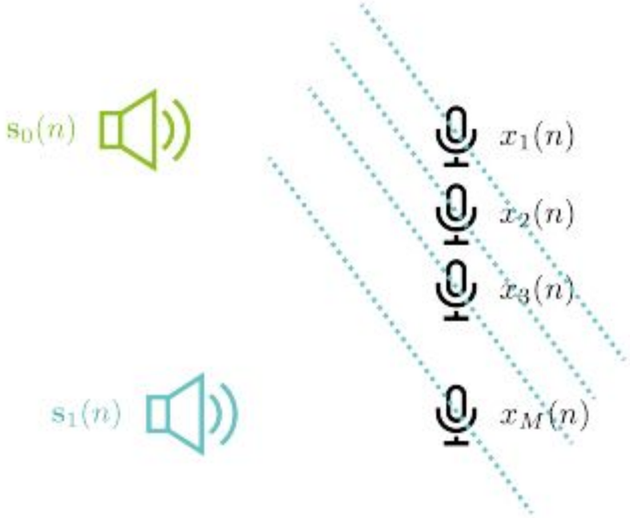
The sound source signals arrive with delays expressed in a steering vector **a0 .**

$$\mathbf{x}(n) = s_0(n) \cdot \mathbf{a}_0$$

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

The sound source signals arrive with delays expressed in a steering vector **a0 , a1 .**

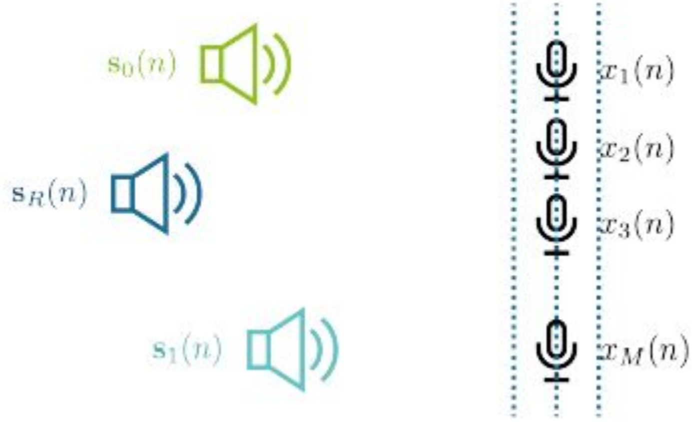


$$\mathbf{x}(n) = s_0(n) \cdot \mathbf{a}_0 + s_1(n) \cdot \mathbf{a}_1$$

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

The sound source signals arrive with delays expressed in a steering vector a0 , **a1 , ··· , a*R*.**



$$\mathbf{x}(n) = s_0(n) \cdot \mathbf{a}_0 + s_1(n) \cdot \mathbf{a}_1 + \cdots + s_R(n) \cdot \mathbf{a}_R$$

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

2.Compute the Covariance Matrix:

- Compute the sample covariance matrix R based on the **received data X**.
- The **covariance matrix** R is calculated as:

$$R = E[XX^H]$$

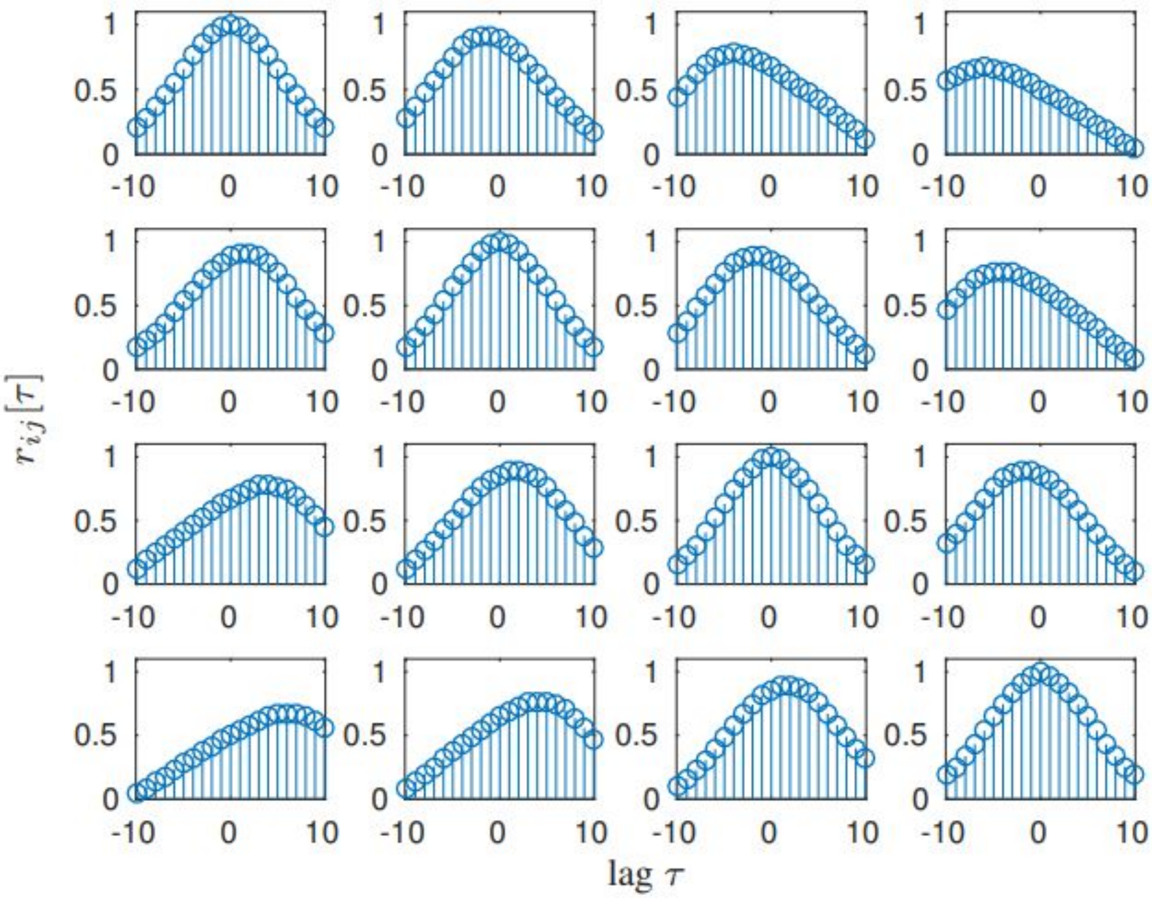
- where,

  $X = S\alpha + N$

- $R = E[(S\alpha+N)(S\alpha+N)H]$

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]



SPACE-TIME COVARIANCE MATRIX EXAMPLE

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

3.Eigenvalue Decomposition:

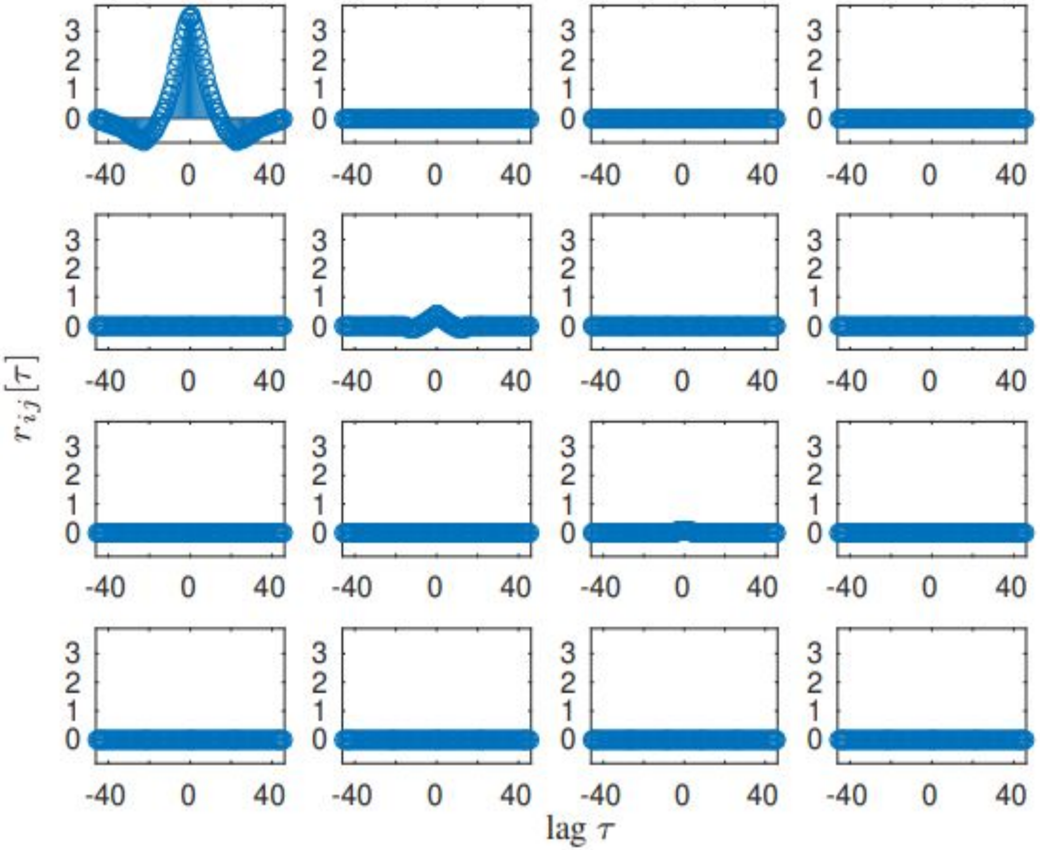
- Perform **eigenvalue decomposition (EVD)** on the covariance matrix R.
- Obtain the **eigenvectors** and **eigenvalues** of R

$$Rv_i = \lambda_i v_i$$

Where **vi** are eigenvectors and λi are corresponding eigenvalues

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]



DIAGONALISED MATRIX OF EIGENVALUES

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

4.**Spatial Spectrum Estimation:**

- The spatial spectrum is computed using the **eigenvectors**.
- Compute the spatial spectrum function (also known as the MUSIC spectrum) as:

$$P_{\mathrm{MUSIC}}(\theta) = \frac{1}{|\mathbf{a}^H(\theta)\mathbf{V}_N|^2}$$

- where a(θ) is the **steering vector corresponding to the DOA θ**, and V is the **noise subspace** spanned by the eigenvectors.

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

5.**Peak Detection**

- Identify the peaks in the MUSIC spectrum.
- Peaks in the spectrum correspond to **potential DOAs** of the signals

6.**DOA Estimation:**

- Extract the **DOA estimates** from the identified peaks.
- The **DOA estimates** are the angles corresponding to the peaks in the MUSIC spectrum.

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm[11]

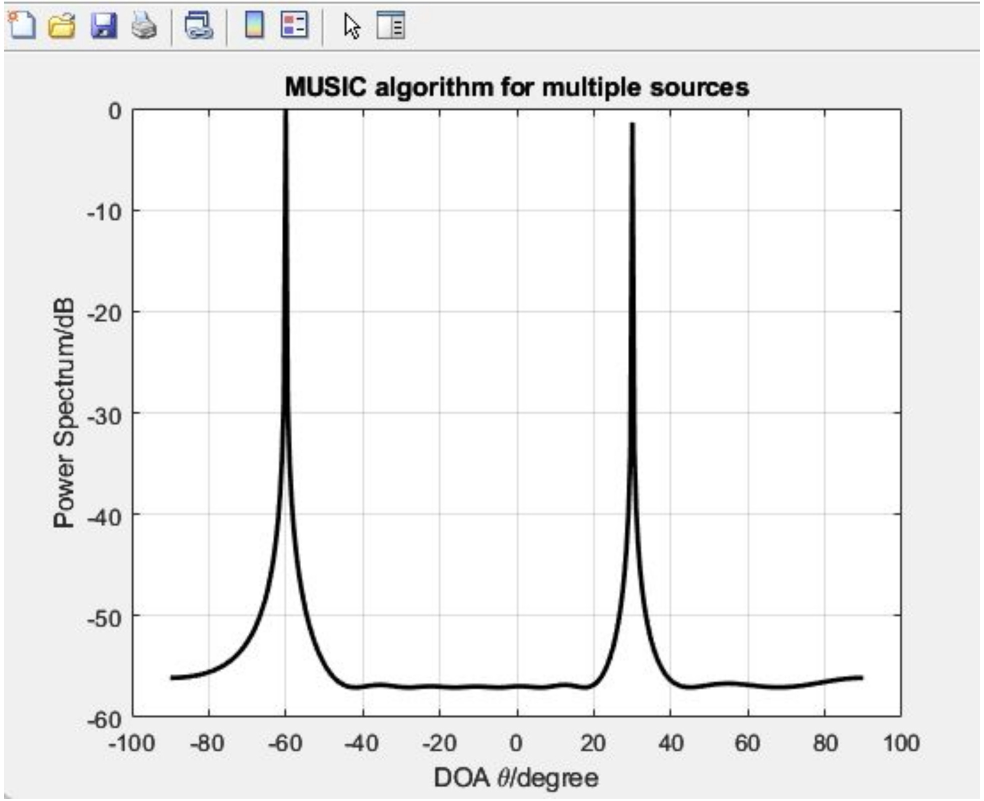
- Overall, the **MUSIC algorithm** exploits the subspace properties of the received signal to **estimate the DOAs**, making it robust and capable of handling **correlated signals** and **noise**.
- It's widely used in various applications, **including radar**, **sonar**, **wireless communication**, and **array processing**

A. O. T. Hogg, V. W. Neo, S. Weiss, C. Evers and P. A. Naylor, "A Polynomial Eigenvalue Decomposition Music Approach for Broadband Sound Source Localization," *2021 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, NY, USA, 2021, pp. 326-330, doi: 10.1109/WASPAA52581.2021.9632789.

MUSIC Algorithm (MATLAB Implementation)

```
N=200;%Samples
doa=[30 -60]/180*pi;%Angles At which sources are placed
w=[pi/4 pi/3]';%frequency
M=10;%Array Numbers
lambda=150;%spacing between array elements
d=lambda/2;%array element space
snr=20;%Signal to noise ratio
```

MUSIC Algorithm (MATLAB Implementation)

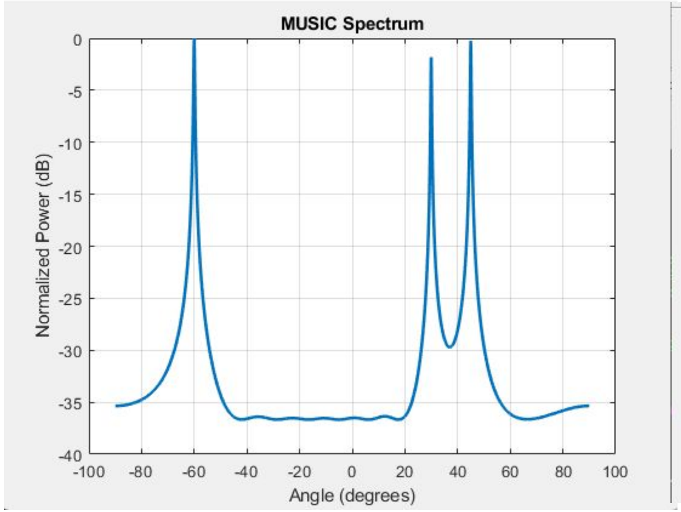


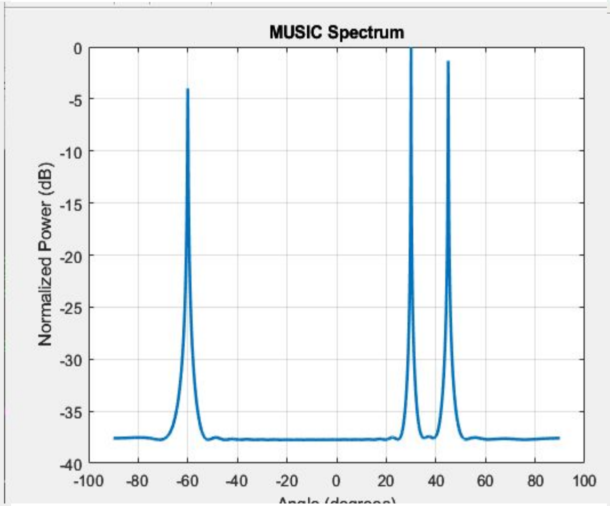
As we can clearly see peaks at **-60 degree** and **30 degree**.

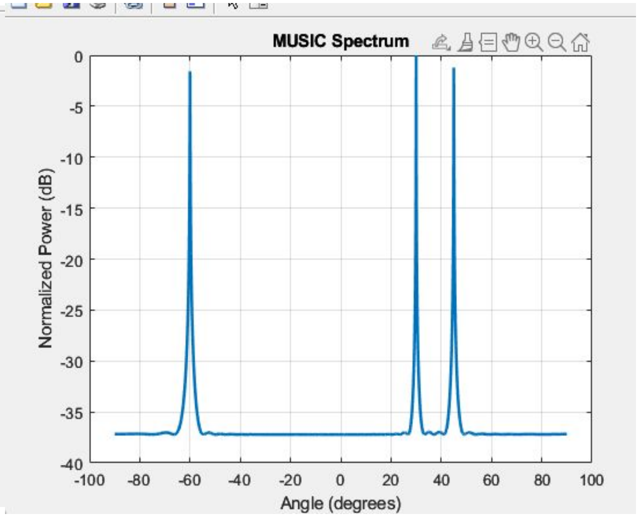
Literature Survey-1

REFERENCE	METHODOLOGY	RESULTS	SCOPE OF IMPROVEMENT
Huang, Liwei & Chen, Huiqin & Chen, Yulin & Xin, Haiyan. (2016). Research of DOA Estimation Based on MUSIC Algorithm. 10.2991/mmebc-16.2016.432.	MUSIC algorithm in **direction of arrival(DOA)** estimation of signals, expounds the principle of this algorithm	Increase of array **element number**, **array element space**, and **signal-to-noise ratio**, MUSIC algorithm for DOA estimation has **higher resolution**	Resolution can be increased in case of high **SNR**

Resolution based on Array Elements (Results)





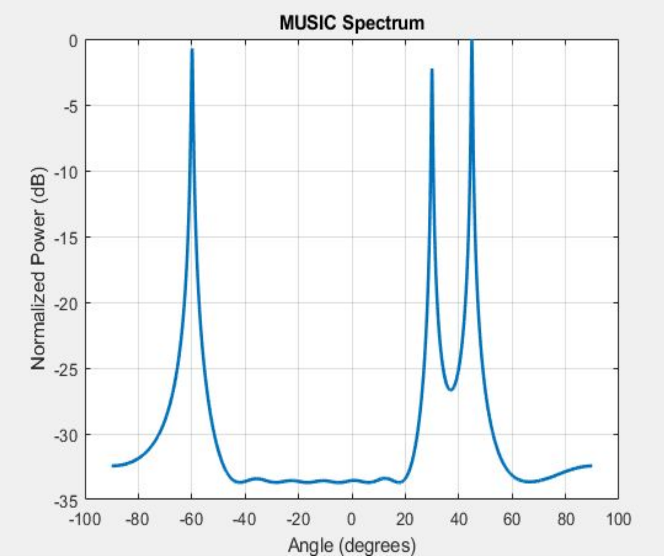


Array element is 10

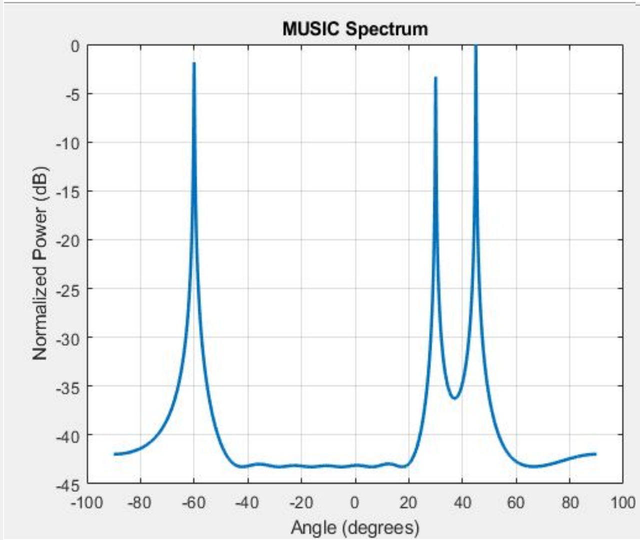
Array element is 25

Array element is 45

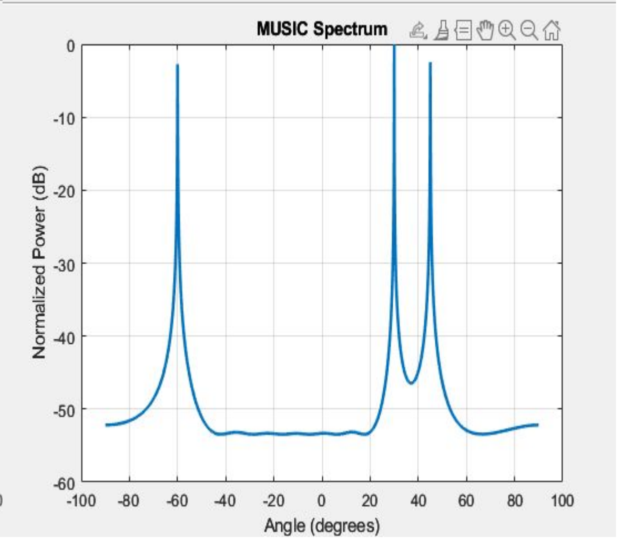
Resolution based on SNR(Results)



SNR is 5

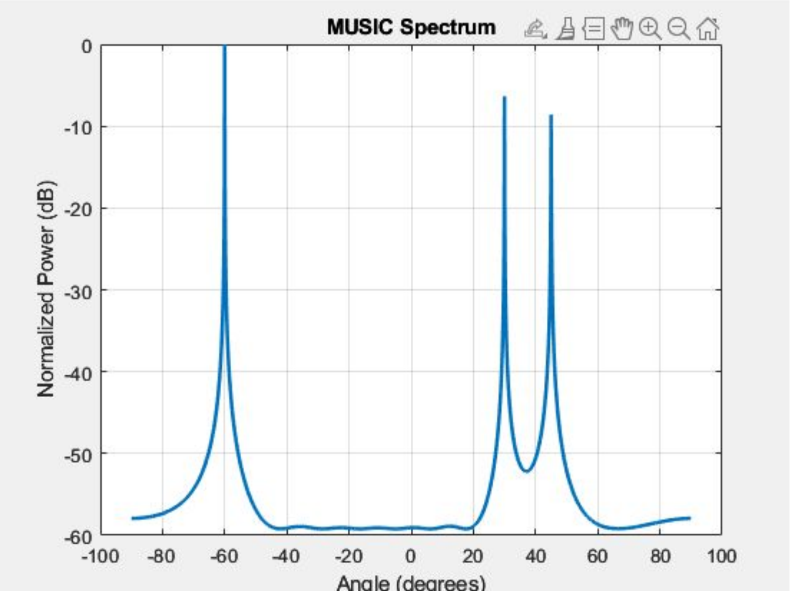


SNR is 15

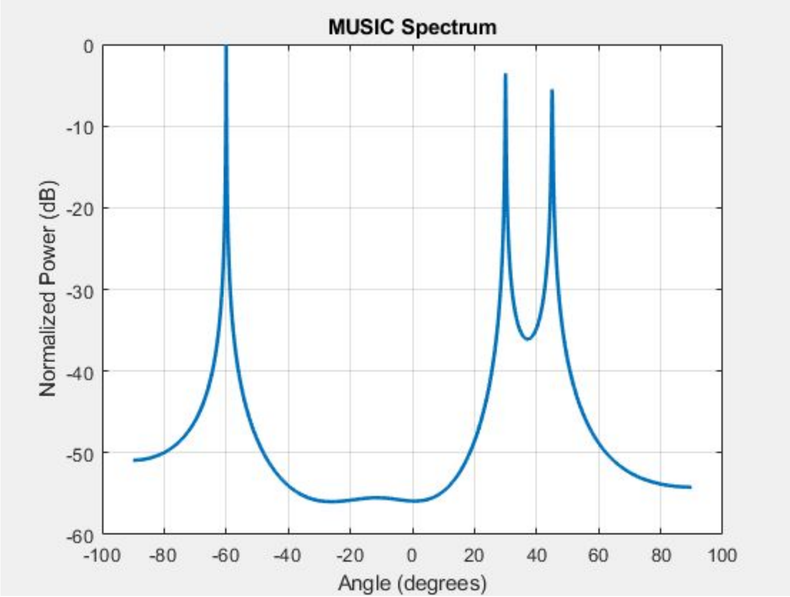


SNR is 25

Resolution based on spacing between elements(Results)

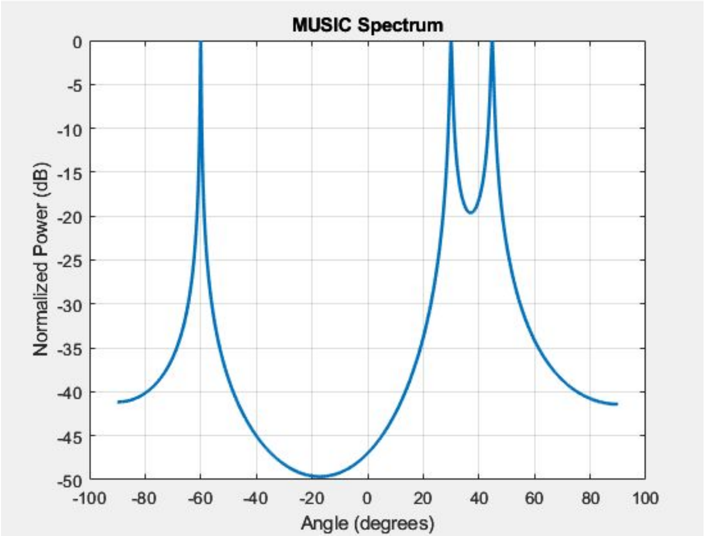


Spacing is half wavelength

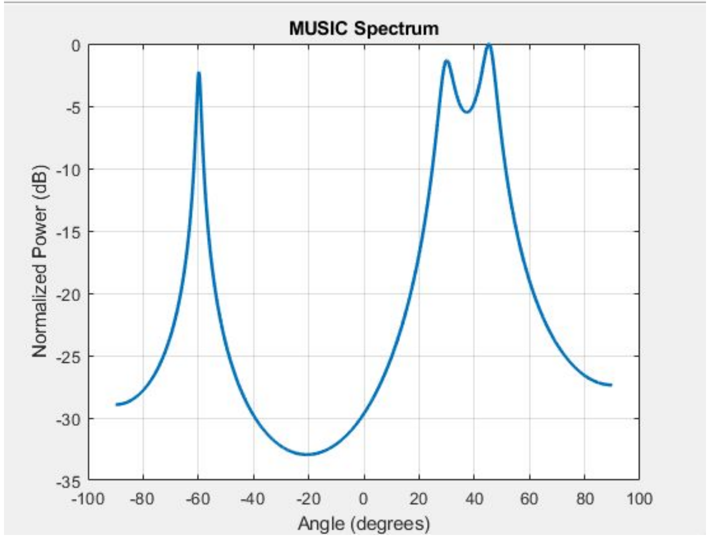


Spacing is quarter wavelength

Resolution based on spacing between elements(Results)



Spacing is one-eighth wavelength



Spacing is one-sixteenth wavelength

Literature Survey-2

REFERENCE	METHODOLOGY	RESULT	SCOPE OF IMPROVEMENT
Huang, Liwei & Chen, YuLin & Chen, Huiqin. (2017). Research of DOA Estimation Based on Modified MUSIC Algorithms. 10.2991/amcce-17.2017.189.	**MUSIC algorithms** in **DOA estimation,** expounds the principle of **Root-MUSIC algorithm**, **Beamforming MUSIC algorithm**, **Spatial smoothing** MUSIC algorithm	**Root-MUSIC** algorithm has **high precision** under **high SNR.** **Beamforming MUSIC** algorithm can accurately estimate DOA when incidence **angle difference is large**. **Spatial smoothing MUSIC algorithm** can effectively estimate the **DOA of coherent signal** with the cost of reducing antenna aperture.	**Root-MUSIC** typically operates at a **single frequency.** Extending the algorithm to leverage frequency diversity, such as exploiting multiple **frequency bands** or **broadband signals**, can provide additional information for **DOA estimation**.

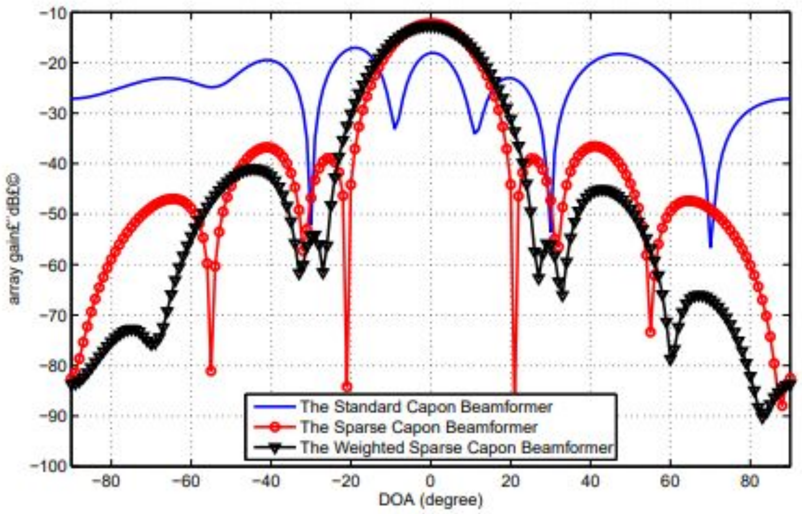
Literature Survey-3

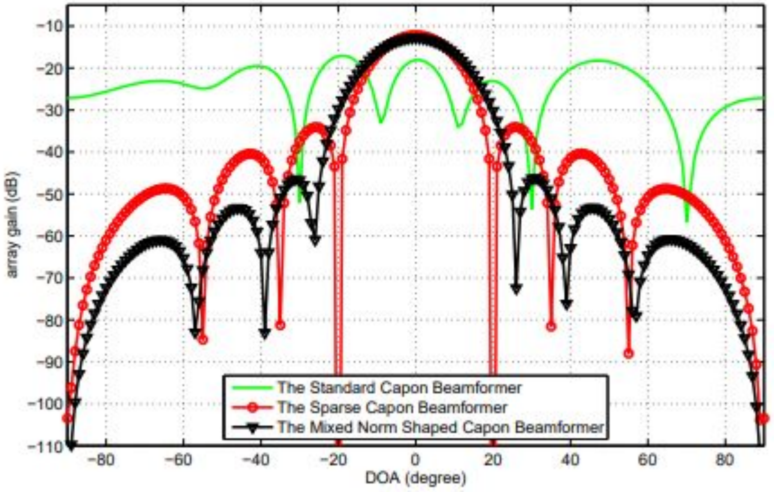
REFERENCE	METHODOLOGY	RESULTS	SCOPE OF IMPROVEMENT
Shukry, Mohamed & Al-azzo, Mujahid. (2022). Root-MUSIC Based Technique-Direction of Arrival (DoA) Estimation for Ultrasonic Waves Sources.	**Direction of arrival (DoA) estimate**, a comparison between the **classical method, fast Fourier transform (FFT)**, and the current method, **Root-MUSIC (Root-Multiple Signal Classification), is examined.** These two techniques are implemented using practical data of a single **source** and **two sources** for DoA estimation	In the FFT method the error is increased with fewer values of the **number of samples N and begins decreasing, but still high**, **as N increases**. For the **Root-MUSIC** method, it is noticed that the percentage error in **most cases less than 15%** for the two experiments of singlesource, **go less than 10% for the experiment of two sources.**	To improve **accuracy** with fewer **snapshots** or **sensors**. This can lead to more efficient and accurate **DOA estimation**, particularly in **resource-constrained** environments.

Literature Survey-4

REFERENCE	METHODOLOGY	RESULTS	SCOPE OF IMPROVEMENT
Liu, Y., 2013. Robust capon beamforming via shaping beam pattern. *arXiv preprint arXiv:1302.6173*.	**High sidelobe level** and **direction of arrival (DOA)** estimation sensitivity are two major **disadvantages** of the **Capon beamforming**.	Gives an overview of a series of robust **Capon beamforming methods** via **shaping beam pattern**, including **sparse Capon beamforming**, **weighted sparse Capon beamforming**, **mixed norm based Capon beamforming, total variation minimization** based Capon beamforming, **mainlobe-to-sidelobe power ratio maximization** based Capon beamforming	The beam pattern shaping constraint can be combined with other robust **Capon beamforming** techniques, such as **ellipsoid methods**, **diagonal loading methods**. moreover, it is natural to generalize the beam pattern shaping constraints to the **3-D beamforming**.

Literature Survey-4[12]





Liu, Y., 2013. Robust capon beamforming via shaping beam pattern. *arXiv preprint arXiv:1302.6173*.

Literature Survey-5

REFERENCE	METHODOLOGY	RESULTS	SCOPE OF IMPROVEMENT
Sheng, Xiaohong & Hu, Yu Hen. (2005). Maximum likelihood multiple-source localization using acoustic energy measurements with wireless sensor networks. Signal Processing, IEEE Transactions on. 53. 44 - 53. 10.1109/TSP.2004.838930.	A **maximum likelihood (ML)** acoustic source location estimation method is presented for the application in a **wireless ad hoc sensor network**. This method uses **acoustic signal energy measurements** taken at **individual sensors** of an **ad hoc wireless sensor** network to estimate the **locations** of multiple acoustic sources	The **Cramér–Rao Bound (CRB)** of the **ML source location** estimate has been derived. The CRB is used to **analyze** the impacts of **sensor placement** to the accuracy of location estimates for **single target scenario**.	Include parameter **sensitivity analysis** and **sequential Bayesian estimation**

Conclusions

- **Conventional-FFT** works good with **single sources**.
- But in case of **multiple sources** at **lower angle difference** spectrum **leakage** happens.
- Increase of array **element number**, **array element space**, and **signal-to-noise ratio**, MUSIC algorithm for DOA estimation has **higher resolution**.
- It requires precise knowledge of the **microphone array geometry** and the **speed of sound** in the environment
- In **Beamforming** different **algorithms** are being used which will be chosen according to application.

Future Work

- **ASL** can be done using **signal processing** using **Beamforming** techniques and also using **ML.**

- Some other techniques, such as **Root-MUSIC algorithm**, **Beamforming MUSIC algorithm**,**Spatial smoothing** MUSIC algorithm can be used for higher accuracy.

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THANK YOU