

# ***Direction of arrival estimation in smart Antenna for tracking system***

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**Abstract.** The aim of this paper is to present a comparison between three of the main algorithms for the estimation of Direction Of Arrival (DOA) used in smart antenna systems to eliminate fading and interferences, namely Conventional Beamformer, CAPON (Maximum Likelihood Methods 'Minimum Variance Distorsionless Response') and Multiple Signal Classification (MUSIC), which represent three different methods with different calculation techniques. In this work we also simulate several execution scenarios, using MATLAB, to evaluate the factors impacting the precision and the resolution of the DOA estimation in the case of MUSIC algorithm, as it is arguably the most used one, this evaluation is achieved by varying the SNR (signal-to-noise ratio), the spacing between element, the number of array elements and the number of samples (snapshots).

**Keywords—***Smart Antenna, DOA Estimation, MUSIC Algorithm.*

## **1 Introduction**

A tracking system measures the coordinates of a specific target and provides input data that it can exploit to determine its path and predict its future position; nevertheless, these types of systems do have some limitations, namely:

- They are not stable and can be affected by external interferences which are caused by third-party systems.
- The shape of the antenna's beam can only detect a passing target in a small angular aperture, hence, unsuitable for detecting targets in wide areas.
- They can't recognize multiple targets.

In order to overcome the above-mentioned limitations, we have identified four axes of improvement for the tracking systems:

- To maximize the interest signal while adaptively canceling the interferences.
- To add a secondary low beam to be able to reject interferences.
- To achieve a strong directionality of the principal beam.
- To improve the target tracking accuracy,

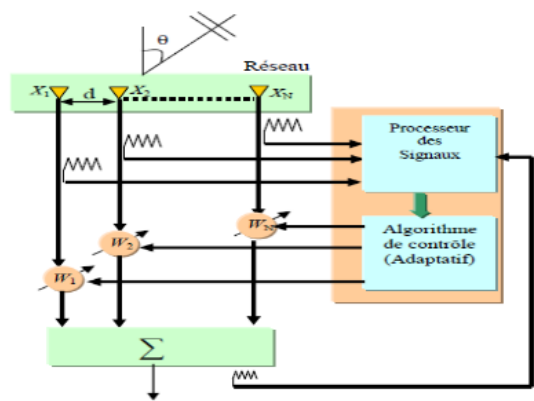
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It turned out that an advanced type of smart antenna, called "adaptive antenna", do perfectly meet these requirements and do include all of the upper-mentioned features; in fact, this type of antenna manages to change its radiation diagram based on the position of the target.

Our adaptative system relies on sophisticated signal treatment algorithms that are able to continuously detect the useful signals and track them whilst neglecting the nonrelevant ones coming from the other paths, this is achieved by combining two algorithms; mainly, the DOA estimation algorithms that estimates the arrival direction of the signal, and the adaptative algorithm that uses this estimation to calculate the ponderation  $w$ , in figure 1 of each element array to be able to point the main beam towards the target and create zeros in the direction of interferences to reduce levels of disturbing signals coming from other systems (1)

**Figure 1: representative diagram of a smart antenna**



These DOA algorithms which are the main focus of this paper, are considered to be one of most crucial steps in the making of smart antenna systems as it helps to eliminate fading and interferences.

In this paper, we will be implementing a network of smart antennas as they meet the need of our tracking system. The emphasis will be on the first feature of adaptive antennas, namely the angle of arrival detection, and we will make use of the most widely adopted algorithm and exploit its results to try and improve the filtering of the relevant signals, thus improving the detection accuracy and precision of our tracking system.

In the 1st section of this this paper we will give an overview of the main methods used to estimate the direction of the arrival angle as well as the analytical model of the signal using different DOA algorithms, then in the 2nd section, we will evaluate the performances of the MUSIC algorithm, which is the most used one, by analyzing the impact of changing input parameters on the resulting DOA estimation.

2 Estimation of Direction of Arrival

Over the past few years, there has been a growing fascination with various methods of estimation Direction of arrival (DOA) using an antenna array. These methods are differentiated based on their technique, the necessary information, and the calculation method. (Such as conventional methods, projection on the noise subspace or source subspace, maximum likelihood (2), ...

As a result of extensive research, these methods have been classified into two distinct categories (3):

**Global methods:** Preformed beam, Lagunas Estimator..

These methods offer a representation for the powers and angular positions of the sources, by projecting the directional vector into the observation space without having to determine, beforehand, the number of the sources. However, these classic methods do not offer a good resolution.

**High resolution methods:** Capon estimator (4), MUSIC, Root-MUSIC, ESPRIT, ...

These methods require a prior knowledge of uncorrelated sources number, before estimating their characteristics. This issue is solved, firstly, by methods of estimation of the sources numbers (5) (6) (7) and, secondly, by applying an HR method to estimate the DOA. These high-resolution methods are known to be more accurate than conventional techniques.

## 2.1 Signal model for smart antenna using DOA.

Before outlining details about the algorithms of detection, we will proceed by making some hypothesis to simplify our conclusion:

Let's consider an N antennas array that receive signals emitted by M point sources in the far field ( $M < N$ ). The waves emitted by the sources, come from different directions ( $\theta_1, \theta_2, \dots, \theta_M$ ). The received signals are, by then, noisy linear combinations of the source signals. By conducting L observations, we can modelize the reception vector  $\mathbf{x}(t)$  of the antenna array for one observation, as "(1)":

$$\mathbf{x}(t) = A(\theta)\mathbf{s}(t) + \mathbf{n}(t) \quad (1)$$

Where:

$$A(\theta) = [a(\theta_1), a(\theta_2), \dots, a(\theta_M)]$$

$A(\theta)$ . The array steering vectors of the sources. It is providing the angles of arrivals information.

$$\mathbf{s}(t) = [s_1(t), s_2(t), \dots, s_M(t)] \quad (2)$$

$\mathbf{s}(t)$  is the original signal from the M sources

$\mathbf{n}(t)$  is the white-noise vector.

The covariance matrix  $R_{xx}$  with dimension (M x M) for one observation would be as:

$$R_{xx} = E\{\mathbf{x}(t)\mathbf{x}^H(t)\} = A\{s(t)s^H(t)\}A^H + E\{\mathbf{n}(t)\mathbf{n}^H(t)\}$$

$$R_{xx} = AR_{ss}A^H + \sigma^2 I \quad (3)$$

Where H denotes the Hermitian matrix operation,  $\sigma^2 I$  is the noise covariance matrix for each element of the array.

**Conventional beamformer.** is a classic DOA method, which scans the beam to evaluate the received power in each direction and finds the signal DOAs from the maxima of the array output (8).

However conventional beamforming methods have a defect: when there are multiple signal sources, spatial spectrum estimation includes the signal source power of different directions other than the sources.

The conventional beamformer spatial spectrum is given by:

$$P_{CB}(\theta) = \mathbf{a}^H(\theta) \mathbf{R}_{xx} \mathbf{a}(\theta) \quad (4)$$

**Maximum Likelihood Methods (Minimum Variance Distorsionless Response).** the Capon method is a beamforming technic aiming to improve the conventional methods (9). The key concept is rejecting of all undesired direction signals. Its pseudo-spectrum is given by:

$$P_{cap}(\theta) = \frac{1}{\mathbf{a}^H(\theta) \mathbf{R}_{xx}^{-1} \mathbf{a}(\theta)} \quad (5)$$

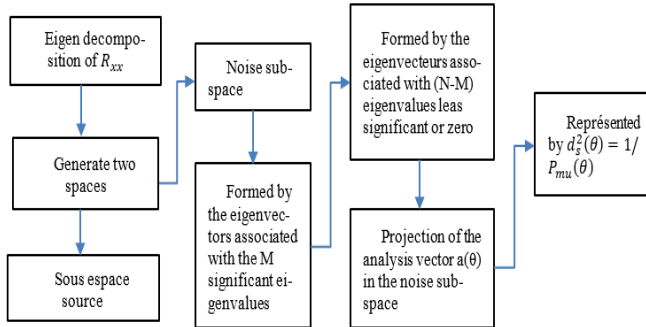
**MUSIC (Multiple Signal Classification).** These days, the subspace-based algorithms, such as MUSIC (10), ESPRIT (11), Root-MUSIC (12), etc., are often deployed. They are, all, high resolution algorithms, where the eigen structure of the covariance matrix is explicitly required. In this paper, and because of its approved performances, our main focus will be the MUSIC algorithm (13).

The advantages of MUSIC are:

- The ability to simultaneously measure multiple signals.
- High resolution for antenna beam signals and precision measurement (14) .
- Real-time processing after using high-speed processing technology.

Once the correlation matrix is determined, we proceed with the steps bellow in figure 2. We calculate the spectrum function; and then defining the estimated value of DOA by searching the peak in the representation of the spectrum function.

Figure 2: Different steps of MUSIC algorithm



The Pseudo-spectrum, is given as:

$$P_{mu}(\theta) = \frac{1}{\mathbf{a}^H(\theta) \mathbf{E}_n \mathbf{E}_n^H \mathbf{a}(\theta)} \quad (6)$$

Where:

$$E_n = [V_{M+1}, V_{M+2}, \dots, V_n] \tag{7}$$

$E_n$  is the noise subspace eigenvector.

3 Simulation and results

3.1 Simulation environment

In this part, for the algorithms performance evaluation, we will present a comparative study of the different DOA algorithms simulations, next, we will introduce changes into some parameters while observing their influences on the results. In order to ensure this, we will propose a system with the bellow parameters:

Table 1. The system parameters

| Parameters                  | Value                    |
|-----------------------------|--------------------------|
| Antenna                     | ULA                      |
| Number of element (N)       | 10                       |
| Spacing between element (d) | $\lambda/2$              |
| Angle of arrivals           | $\Theta=0$ ; $\theta=20$ |
| Number of snapshot (NS)     | 200                      |

All sources are deemed uncorrelated. The simulations presented in this section are realized with MATLAB R2021a.

3.2 Results and discussions

The three figures, below, represent the pseudo-spectra as a function of the angles ranging from -90 ° to + 90 °, the peaks position determine the values of the angles of arrival, using the estimation methods: beamforming, Capon and MUSIC.

Figure 3. Estimation DOA using conventional DOA

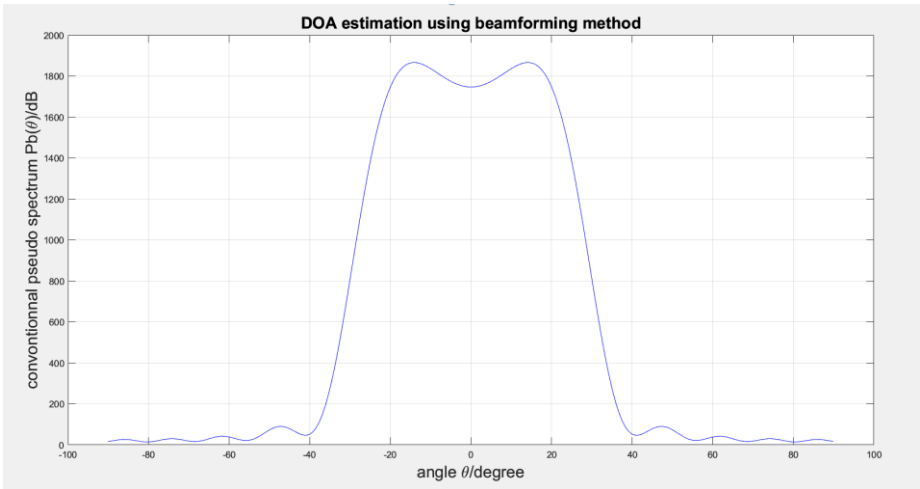
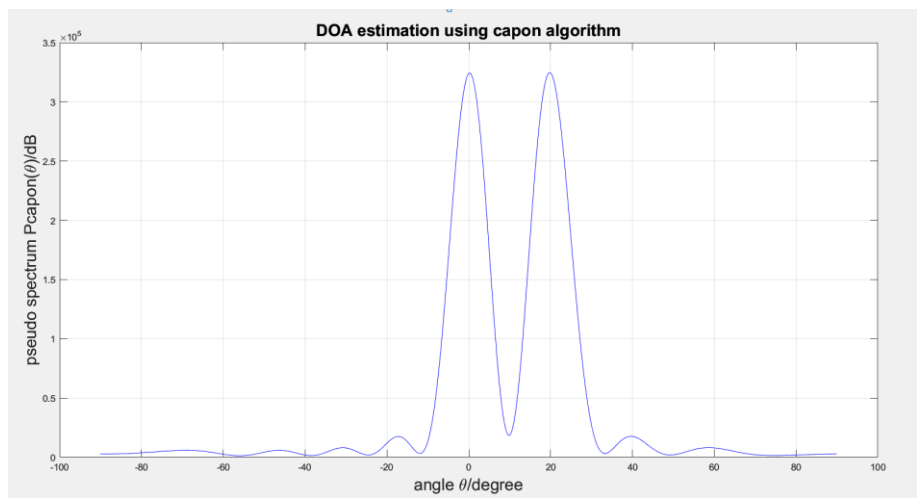


Figure 3 clearly illustrates the resolution limitation, as evidenced by the interaction between the two peaks, despite a 20° gap between the two sources.

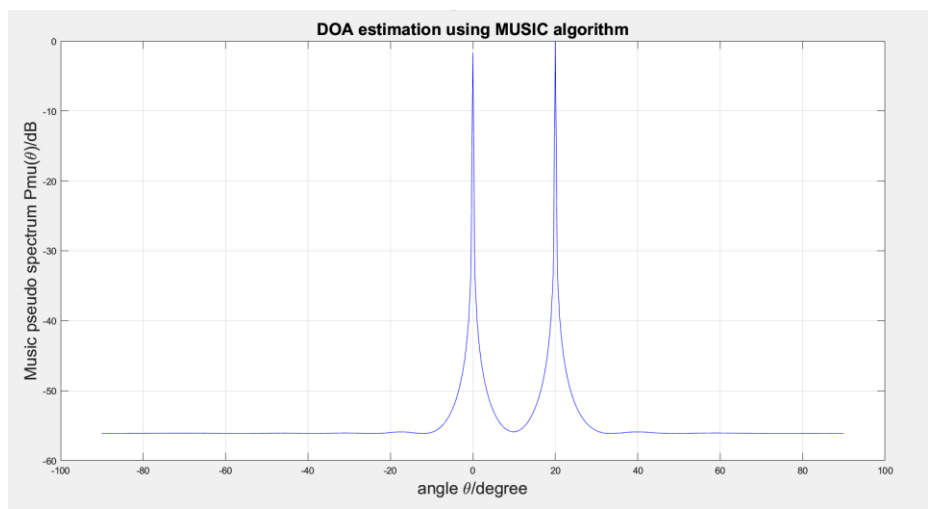
The figure 4 (Capon) presents point sources with acceptable peaks, which shows that the resolution is exceeding the beamforming.

Figure 4. DOA estimation using capon algorithm



In figure 5, we can easily distinguish narrower peaks, and thus a more precise location proving the high resolution of the MUSIC technic which can draw a distinction between two close sources.

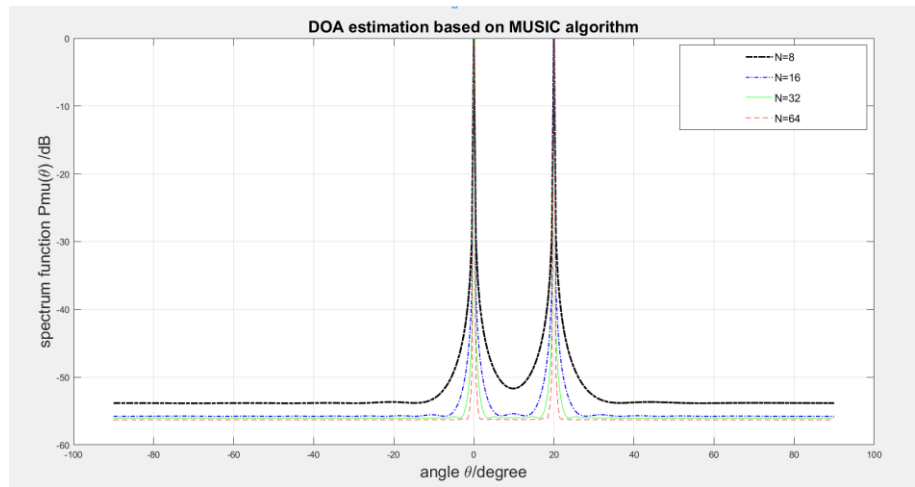
Figure 5. DOA estimation using MUSIC algorithm



Afterward, we will analyse the performance of the MUSIC algorithm by varying the following parameters:

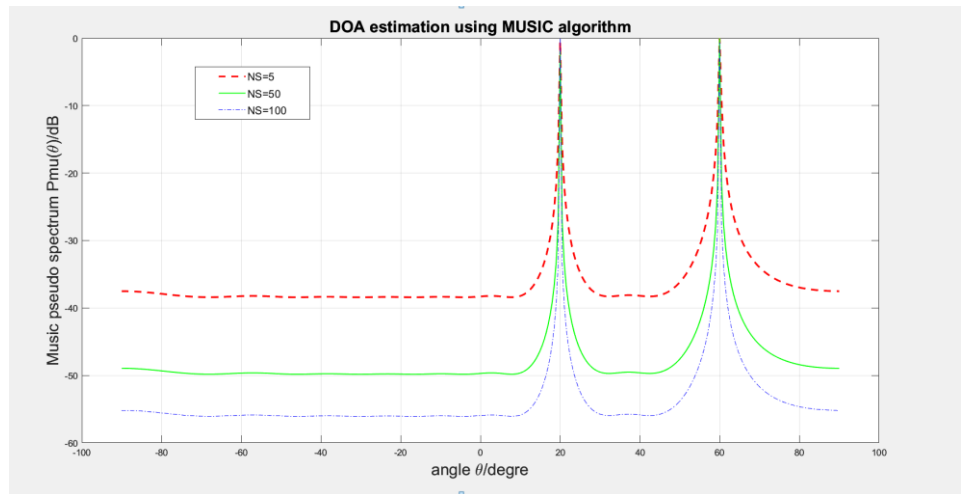
**Number of array elements.** The data presented in Figure 6 indicates that as the number of elements in an array increase, the ability to distinguish signals improves, and the width of signal peaks becomes narrower. Consequently, increasing the number of array elements can lead to more accurate DOA estimation. However, it is important to note that a larger number of elements translates to a greater amount of data that needs to be processed, as well as more calculations, resulting in slower processing speeds.

**Figure 6.** Relation between MUSIC algorithm and the number of array elements



**Snapshots.** As shown in the figure 7, it can be observed that as the number of snapshots increases, the beam width of the DOA estimation spectrum becomes narrower, resulting in a clearer direction of the array element. Additionally, an improvement in the accuracy of the MUSIC algorithm is also evident.

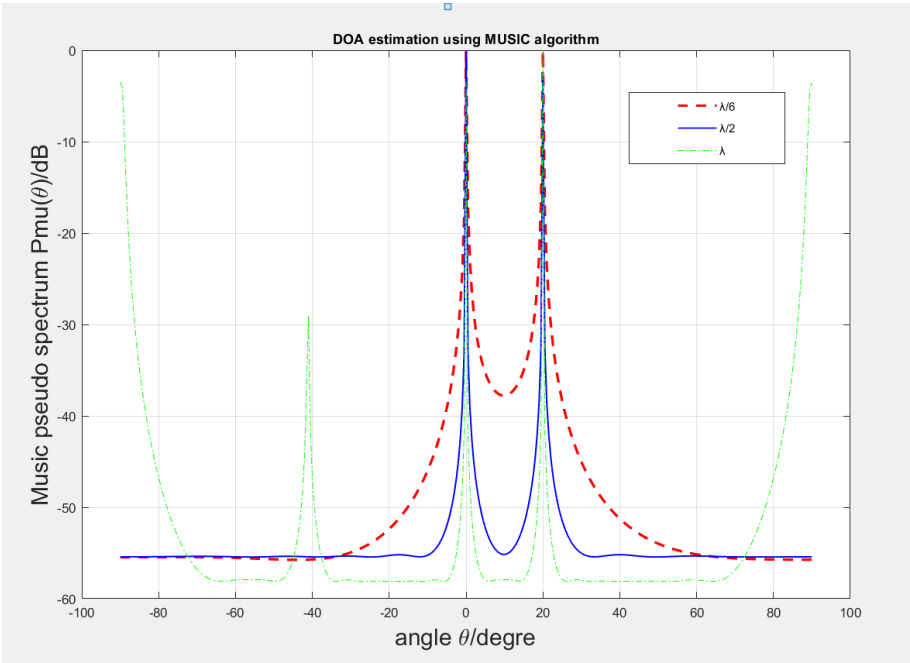
**Figure 7.** Relation between MUSIC algorithm and the number of snapshots (NS)



**Spacing between elements.** The resolution of MUSIC algorithm increases as a function of the array element spacing; however, if spacing between the array elements is greater than

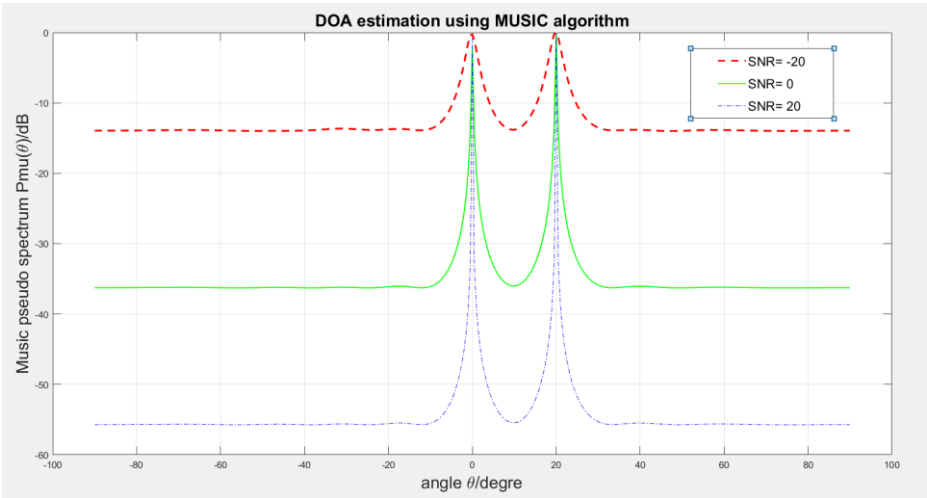
half of the wavelength ( $>\lambda/2$ ), the estimated spectre will show false peaks. And the algorithm loses its estimation accuracy. The simulation results are shown in figure 8.

**Figure 8.** Relation between MUSIC algorithm and the spacing between elements



**SNR.** As illustrated in figure 9, when the SNR (Signal to Noise Ratio) is increased, the beam width of the Direction Of Arrival estimation spectrum narrows, resulting in a more distinct signal direction and improved accuracy of the MUSIC method.

**Figure 9.** Relation between MUSIC algorithm and the SNR



Based on the findings, we have determined that the MUSIC algorithm is a straightforward and uncomplicated method for calculating and estimating the DOA. However, it is essential to note that several other factors can impact the performance of the MUSIC method and DOA estimation in general. These include amplitude and phase inconsistencies of array elements, mutual coupling between array elements, and incorrect positioning of the sensors.

## 4 Conclusion

In this work, we have presented the limitations and the improvement axes of tracking systems, as well as an overview of smart antennas that are used to overcome these limitations. By combining a network of antenna's elements and some of the signal processing techniques - the angle of arrival detection and adaptative algorithms - we have shown that we can achieve an accurate detection and flawless tracking of our system's target. To put it another way, choosing the right DOA algorithm is a key factor to improving the detection accuracy of our tracking system.

For this we compared between the main DOA estimation algorithms and analyzing the impacts of varying input parameters in a MUSIC algorithm implementation, we were able to notice that the MUSIC algorithm shows a high level of accuracy and that its performances could be enhanced with the right set of configuration, we should point out also that the Root-MUSIC method can give even better results and performances with a reduced complexity (15) but it can only be used in a ULA network. Our future work will focus on adding the adaptive Beamforming and completing the chain of our system.

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