PERFORMANCES STUDIES OF BEAMFORMING TECHNIQUES IN A MASSIVE MIMO SYSTEM

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ABSTRACT

Massive MIMO technology could become a revolutionary technology in wireless communications, increasing cellular capacity and efficiency in high-traffic urban areas. For example, the diversity introduced by multipath propagation is exploited to allow the transfer of data between a base station and several users in the same time and frequency resource. The use of millimeter waves allows us to implant more antenna in a system with reduced forms. The use of the beamforming technique optimizes Massive MIMO technology. Three beamforming approaches for receiving signals in the presence of interference, with knowledge of the direction of arrival, have been developed. The phase shift technique is less efficient than the other two. On the other hand, the efficiency of the two other techniques depends on the estimation of the signal's direction of arrival.

Keyword: - *Beamforming, LCMV, MIMO, MVDR*

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1. INTRODUCTION

Since future generations, cellular networks migrate to higher carrier frequencies hence the thought of using millimeter waves. These waves are very sensitive to noise due to natural phenomena and environments. The use of the MIMO technique is therefore a solution for this problem. The MIMO system has two kinds of techniques like spatial multiplexing and spatial diversity. The multiplexing technique is used to increase the transmission rate by transmitting independent data signals in different antennas, but the signal quality may be degraded. The MIMO multiplexing technique allows long-range data transfer with a spectral efficiency that varies according to the number of antennas used at the base stations. The idea is therefore to process the matrix of the channel between the transmitters and the receivers and to use functionalities of detectors at the level of the mobile terminals and of precoders at the level of the base stations to reduce the noises and the interferences in order to estimate efficiently the actual minimum and maximum bit rates of the transmission channel. The other technique is spatial diversity, this technique is used to improve the quality of the signal received by the receiver by sending the same signal on each antenna to reduce signal fading, and the use of this technique can reduce the flow of transmission. MIMO technology is therefore potentially an attractive method to combat severe signal attenuation.

However, the performance of the channel estimation is limited by the signal to noise and interference ratio at the base station, which limits the ability to design an effective beamforming solution avoiding interference. In addition, the environment is full of wave scattering objects, the different components of the signals present in the radiocommunication systems are also deflected in various directions following their interactions with the said objects.

Faced with these problems and for improving the performance of the MIMO system, the technique of beamforming or beamforming is one of the solutions that can be used. In this study, we will focus on the performance of different beamforming techniques.

2. BEAMFORMING ALGORITHM

There are two main categories of beamforming :

- Conventional beamforming : with this type of beamforming, it is possible to point the beam in the desired direction.
- Adaptive beamforming : Also, this one permits to focus the beam in the desired direction; but, in addition, it permits to reject all eventual interferences.

Concerning this research, we are going to study the Phase Shift technique which is a Conventional beamforming, the MVDR (Minimum Variance Distortionless Response) technique and the Linear Constrained Minimum Variance (LCMV) which are Adaptive beamforming.

2.1 Conventional beamforming

The conventional beamforming is a beamforming's classical method based on knowing the directions of the incidence from different sources. It guides the beam in the direction of the desired signal independently of the overall signal received.

The principle of this technique is to estimate, firstly, the arrival angle of all sources. After that, weightings are calculated so as to sum in phase the signals from a direction h_0. Weighting according to conventional beamforming is given by :

$$\mathbf{w}_{FFC} = \mathbf{h}_0 \qquad (1)$$

Thus, the antenna array focuses in this direction where optimal amplitude is obtained. The signal at the output of the beamformer is written :

$$y(t) = \mathbf{h}_0^H x(t) \qquad (2)$$

Where,

$\mathbf{h}_0^H$ represents the directional vector's Hermitian of the intended direction.

$x(t) = \mathrm{s}(t) + \mathrm{n}(t)$ is the vector of the received signals on the antenna array.

So, we obtain :

$$y(t) = \mathbf{h}_0^H.\mathbf{h}_0.\mathrm{s}(t) + \mathbf{h}_0^H.\mathrm{n}(t) \qquad (3)$$

This device performs at the same time an electronic pointing of the antenna in the direction of the h_0 and a spatial filtering to attenuate the signals which arrived from other directions (side lobes) of the main direction. In terms of complexity, this technique is simple to implement, because knowing the direction of arrival (DOA) of the transmitted signal is enough for its implementation. It is called suboptimal because it does not maximize the signal-to-noise ratio but has the advantage to not distort the useful signal. In addition, it does not take into account the presence of any jammers that can disrupt the useful signal. This leads us to introduce the second type of beamforming.

2.2 Adaptative beamforming

Adaptive beamforming occurs when the vector of weight, that has been calculated, depends on the signal. Indeed, this category of beamforming seeks to introduce a dependence on some signal information. Various methods based on computation and updating the vector of weights or the complex filters w are used to improve the quality of the communication channel. Among these methods, the most used are the Minimum Variance Distortionless Response (MVDR) and the Linear Constrained Minimum Variance (LCMV).

3. DIFFERENTS CRITERIAS FOR THE ADAPTATIVE BEAMFORMING

The main problem of optimal antenna filtering is to implement a complex spatial or spatio-temporal filter, linear and invariant in time, noted w, and whose output $\mathrm{y}(t) = w^H \mathrm{x}(t)$ optimizes a criterion to order two, with eventual constraints.

3.1 Minimizing the power of noise under a directional constraints

This is used by the MVDR technique. The principle of this beamforming method is to choose filters that minimize noise and interferences at the output of the beamformer. This is equivalent to the maximization of the signal to interference plus noise ratio (SINR) at the output of the beamformer. The powers of the useful signals and interferences are estimated from the correlation matrices of the signals. The weights are calculated to maximize the ratio of these powers and to cancel eventual interferences.
Equation 4 leads to the minimization of the power of noise under a directional constraint. It is often called Minimum Variance Distortionless Response (MVDR) criterion. If the directional vector $\mathbf{h}_0$ is known, this criterion consists in finding the filter w which minimizes the power of the noise at its output under a unit gain constraint in the direction of the desired signal.

$$\mathbf{w}_{\mathrm{Max\ SINR}} = \min_{\mathbf{w}} E\{|\mathbf{w}^H \mathbf{n}|^2\} \tag{4}$$

The sought filter is a solution of the following Hermitian form:

$$\mathrm{Min}_{w}\, \mathbf{w}^H R_n \mathbf{w}, \tag{5}$$

With the directional constraint

$$\mathbf{w}^H \mathbf{h}_0 = 1 \tag{6}$$

Applying the method of Lagrange multipliers, the solution of this equation is given by:

$$\mathbf{w}_{\mathrm{MVDR}} = \frac{R_n^{-1} \mathbf{h}_0}{\mathbf{h}_0^H R_n^{-1} \mathbf{h}_0} \tag{7}$$

Also, it can be seen here that $\mathbf{w}_{\mathrm{MVDR}}$ minimizes the SINR.

3.2 Minimization of output power under linear constraints

Linearly Constrained Minimum Variance (LCMV) is considered as an extension of MVDR (6) with multi-constraint. The basic principle of the LCMV criterion is to constrain the filter's response (the beamformer); so that, the beamformer let the signals from the desired signal's direction to pass, with specified gain and phase. The beamformer is chosen to minimize the output power under the imposed constraints; this tends to preserve the useful signal by minimizing the contribution of the noise at the output and interferences which arrived from other directions than the useful one.
The vector w is solution of the following problem:

$$\mathrm{Min}_{\boldsymbol{w}}\, \mathbf{w}^H \mathbf{R}_n \mathbf{w} \tag{8}$$

with the constraints :

$$\mathbf{C}^H \mathbf{w} = \mathbf{g} \tag{9}$$

Where,

- C is called constraint matrix of dimensions N × L, with L the number of constraints supposed linearly independent and N the number of sensors.
- $\mathbf{g}$ is the response vector with dimension (L × 1) containing the desired gains and / or phases.

The method of Lagrange multipliers can be used to solve this problem, we obtain:

$$\mathbf{w}_{\mathrm{LCMV}} = \mathbf{R}_n^{-1}\mathbf{C}(\mathbf{C}^H \mathbf{R}_n^{-1}\mathbf{C})^{-1}\mathbf{g} \tag{10}$$

4. SIMULATION ON THE PERFORMANCES OF BEAMFORMING TECHNIQUES

This simulation illustrates how to apply beamforming to a received signal by an antenna array. For this, three beamforming techniques are illustrated and compared :
Phase Shift Beamforming
MVDR Beamforming
LCMV Beamforming
In this simulation, we will compare and discuss the performance of these three techniques according to certain parameters such as noise power, interferences and the number of elements of the antenna array.

4.1 Generate signal

First, we define the signal we want to send. The representation of the signal is a simple rectangular pulse with amplitude 1V, as defined in figure 1:

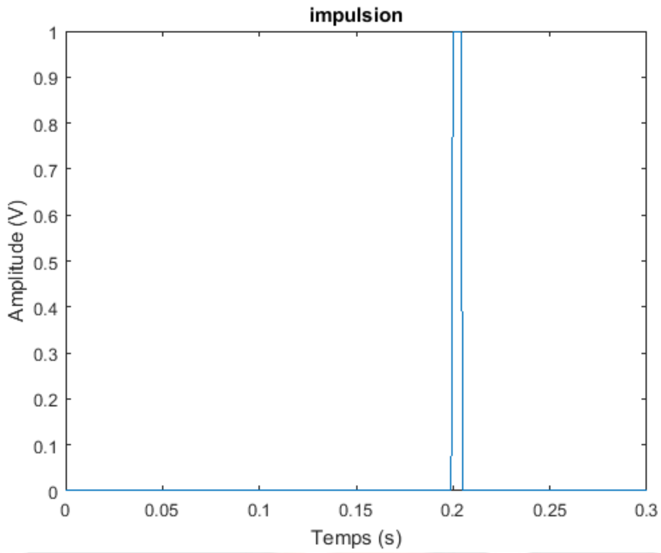

Fig -1: Signal's baseband representation

For this example, we supposed that the signal's frequency is 6 Ghz and the signal reaches 45 degrees in azimuth and 0 degrees in elevation.

4.2 Influence on noise power variation for all three techniques

The received signal often contains thermal noise.

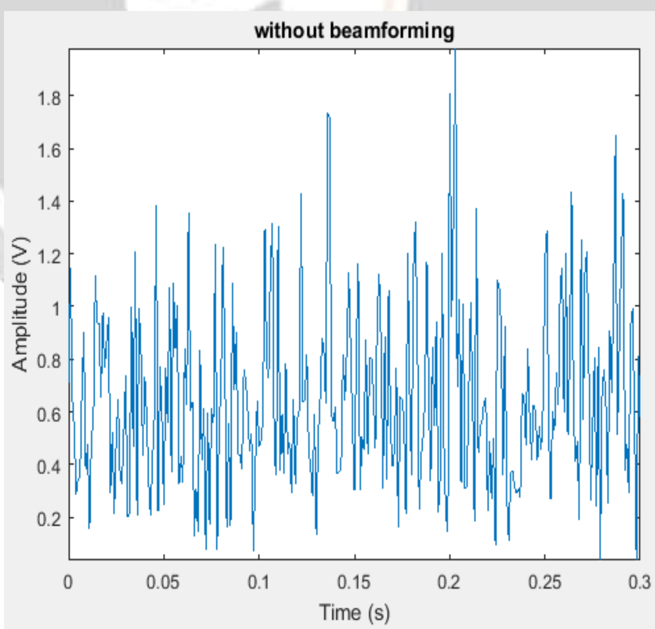

Fig -2: Received signal with noise (SNR = 3 dB) without technique of beamforming

In this simulation, we use 8x8 patch antenna array and the SNR's value is varied to compare the performance of these three techniques. In this part, for each SNR's value, we will compare the three techniques for a noisy channel without interference; then, noisy channel with 2 interferences, and finally, if there is an error on estimating the arrival angle of the signal, this error will be set at 3°.

- **SNR = 3 dB**

With supposition that there is no interference, we will see the signal at the output of each technique.

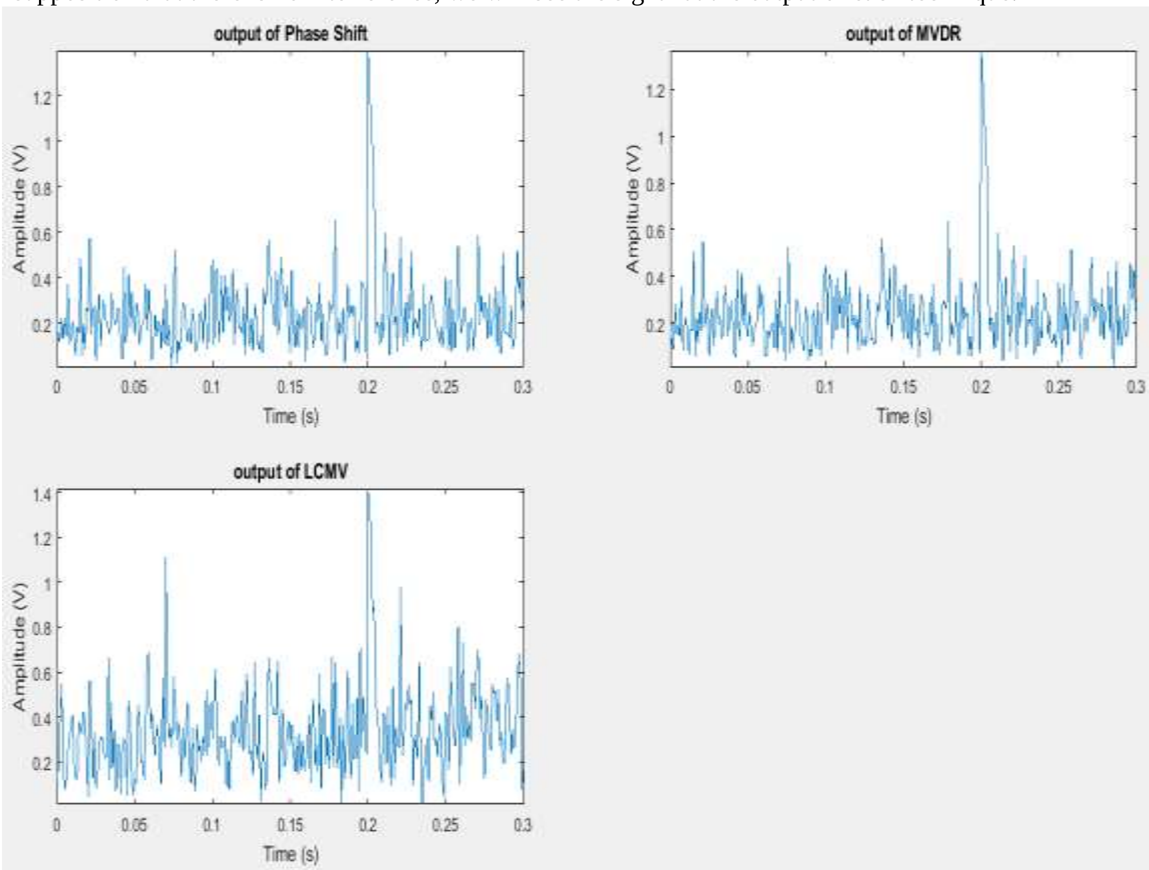

Fig -3 : Comparison of the three techniques for SNR = 3dB without interference

According figure 3, at very low SNR, the noise's power is half of the signal, it is still possible to reconstitute the signal at reception using the MVDR technique or the phase shift technique. But for the LCMV technique, the signal is not perfectly reconstituted because of the high power of the noise. It is seen at the output of the LCMV in figure 3 that there is also another peak having an amplitude 1V at 0.07s.
We also know that the presence of interference can degrade the signal, in this part, we will create 2 interferences arriving at 30 ° and 50 ° in azimuth and 0 ° in elevation and we will see the result of the three techniques in the face of existence interference.

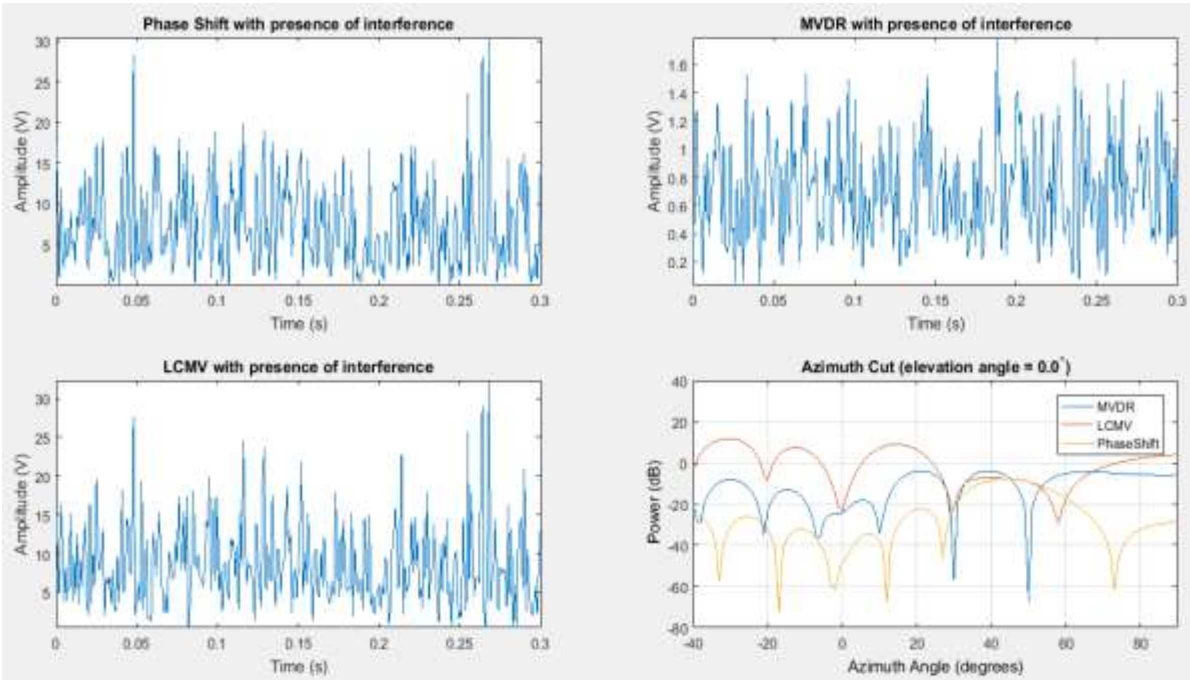

Fig -4 : Comparison of the three techniques for SNR = 3 dB with 2 interferences

From figure 4, because of the presence of interfering signals and with very high noise power (SNR = 3dB), the signal is no longer reconstituted for the three techniques.

- **SNR = 9 dB**

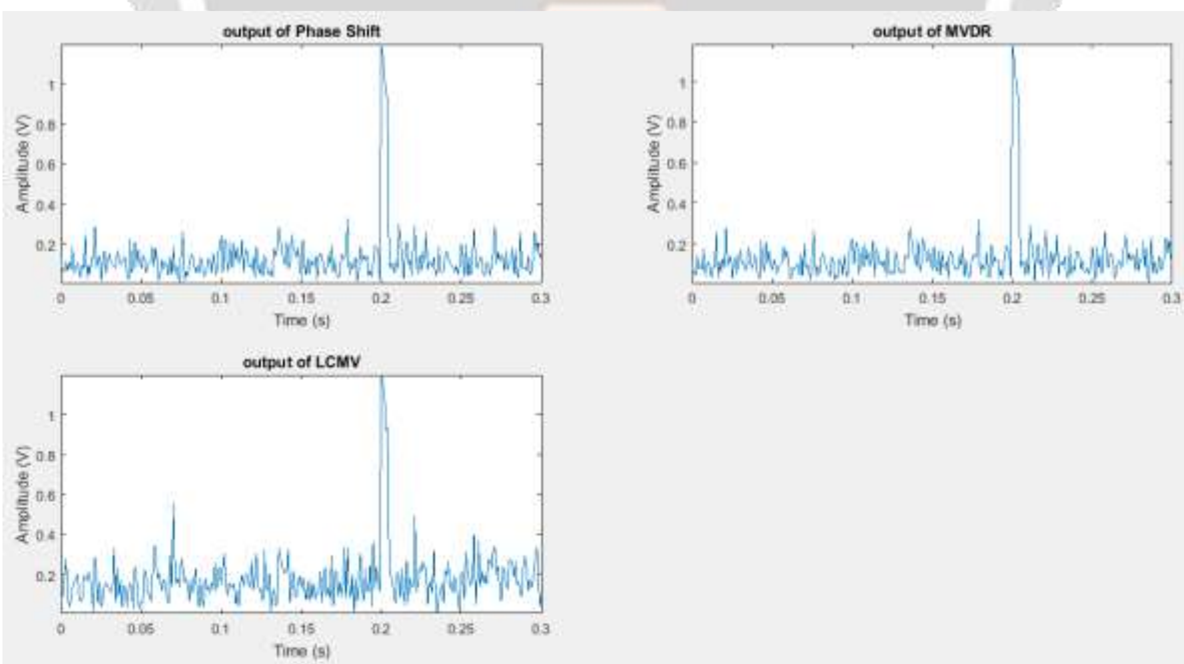

Fig -5 : Comparison of the three techniques for SNR = 9 dB without interference

According to figure 5, the signal is reconstituted at the output of the LCMV technique by improving the SNR (noise power reduction) without interfering signal.

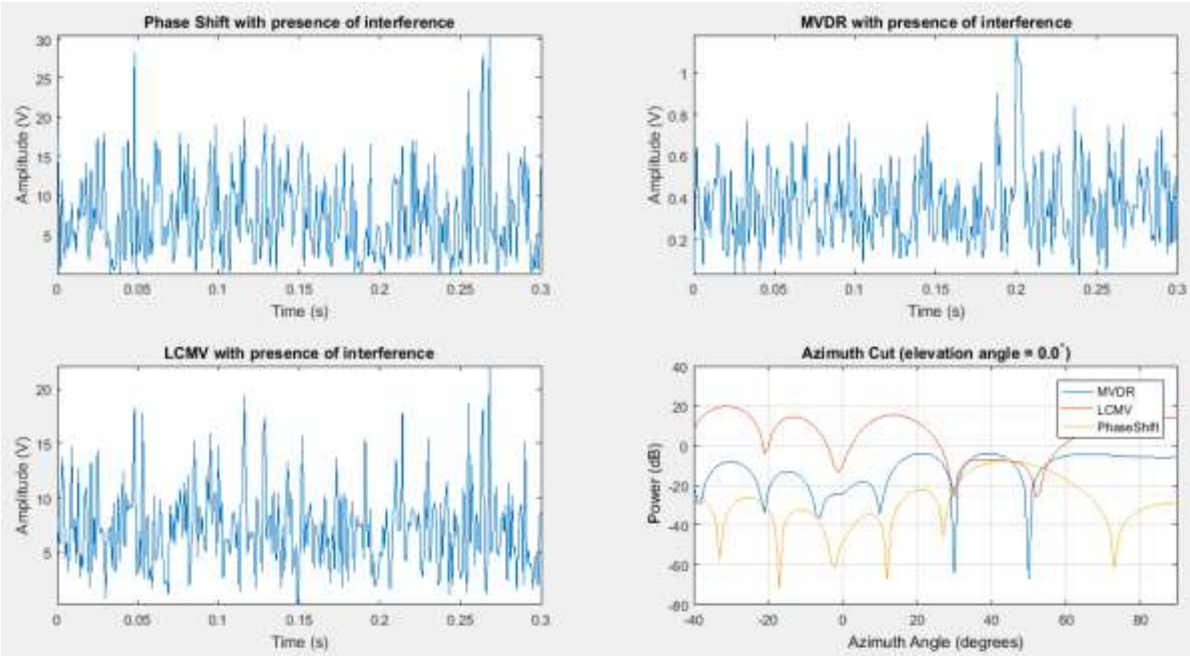

Fig -6 : Comparison of the three techniques for SNR = 9 dB with 2 interferences

From figure 6, the signal is not yet restored to the value of SNR = 9 dB in the presence of the interfering signals. But we see an improvement on the MVDR technique.

Note : For the previous simulations, we have not yet set the estimation error on the direction of arrival of the signal because the signal is already scrambled by the 2 interferences.

- **SNR = 20 dB**

From the results of the previous simulations, it is known that the three techniques are effective in the absence of interfering signals with SNR> 9 dB. Therefore, the following result is the signal at the output of the three techniques in presence of 2 interfering signals with SNR = 20 dB.

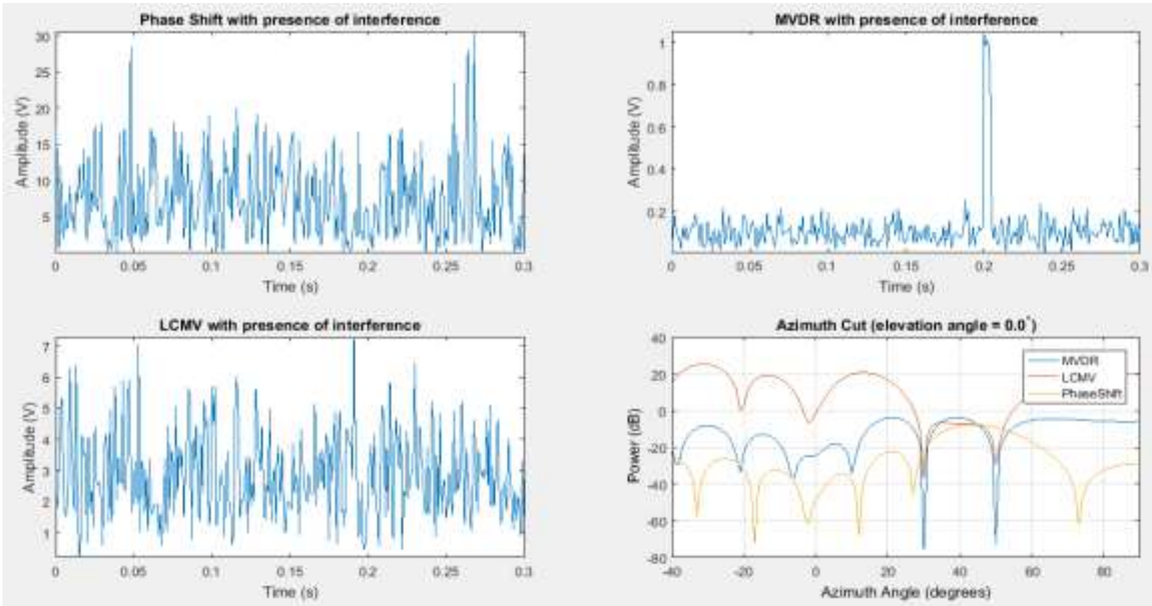

Fig -7 : Comparison of the three techniques for SNR = 20 dB with 2 interferences

From figure 7, the signal is reconstructed using the MVDR technique even if there are 2 interferences and it was supposed that there is no error in estimating the signal's direction of arrival. Looking at the MVDR response model, we see two deep null values along the interference directions (30 and 50 degrees). For the LCMV technique, we still see two null values for both directions but this is not enough to remove interference. Unlike for the case of phase shift, interference is not suppressed. Thus, MVDR preserves the target signal and suppresses interference signals.

For the rest, we create an incompatibility direction between the direction of the incoming signal and the desired direction.

It is reminded that the signal enters at 45 degrees in azimuth. If, with some information, we expect the signal to arrive from 42 degrees in azimuth, then we use 42 degrees in azimuth as the desired direction in each technique. However, as the real signal arrives at 45 degrees in azimuth, there is a slight mismatch in the signal direction. Here is the signal received at the output of each technique:

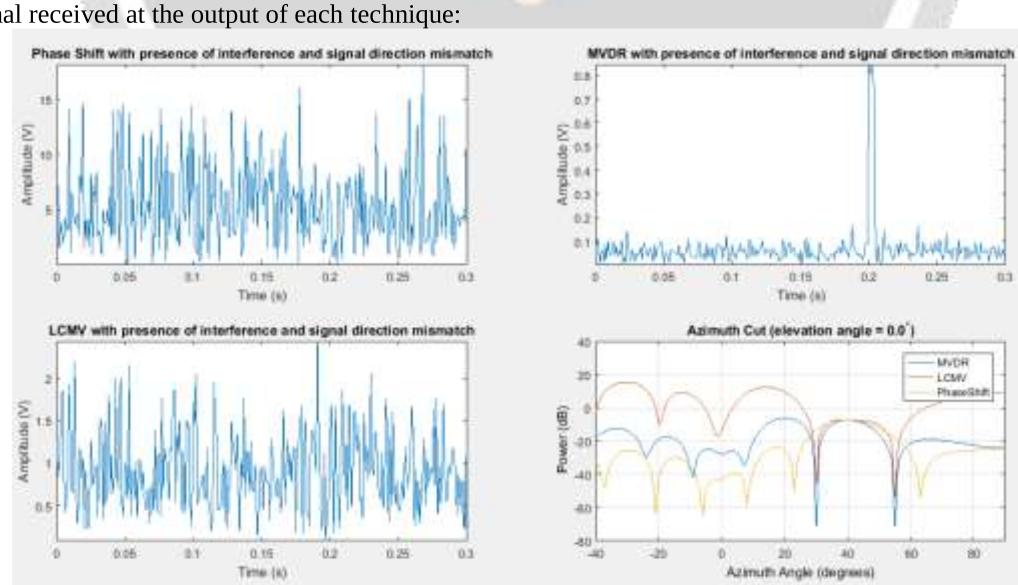

Fig -8 : Comparison of the three techniques for SNR = 20 dB with 2 interferences with error on the estimation of the arrival angle

From figure 8, the signal is still visible for the MVDR technique for SNR = 20 dB even though the amplitude decreases to 0.8V, unlike the other two techniques. For the LCMV and phase shift technique, according to their response, the interfering signal is not suppressed so we cannot have the useful signal at the output of these two techniques.

- **SNR = 50 dB**

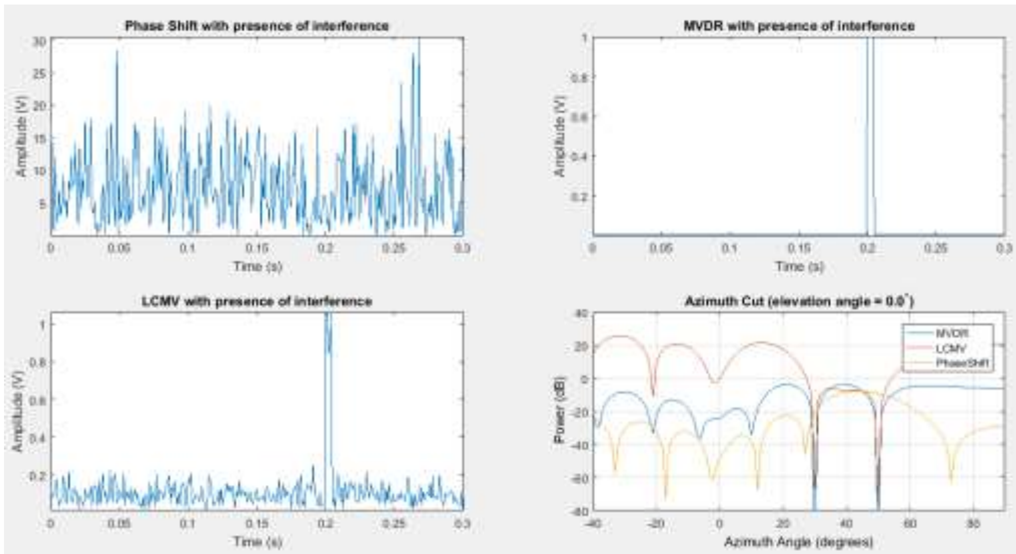

Fig -9 : Comparison of the three techniques for SNR = 50 dB with 2 interferences without error on the estimation of the arrival angle

It can be seen in figure 9 that despite the presence of the two interferences, the signal is well reconstituted if there is no error in estimating the arrival angle of the signal for SNR = 50 dB. Based on the response of both systems (MVDR and LCMV), we see two deep zero values along the interference directions (30 and 50 degrees). Unlike the phase shift technique, interference is not suppressed.

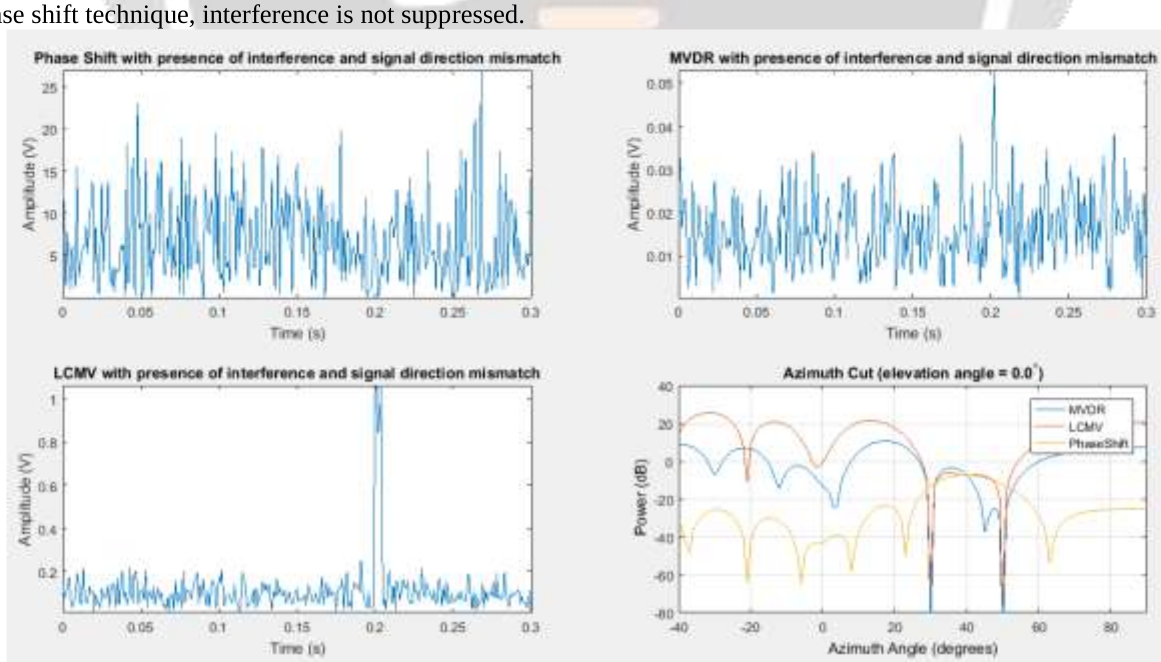

Fig -10 : Comparison of the three techniques for SNR = 50 dB with 2 interferences with error on the estimation of the arrival angle

From figure 10, we see that the MVDR technique tries to suppress the signal arriving at 45 degrees, because it is treated as an interference signal due to the error of the estimate on the arrival angle of the signal. We see that the

receiver can not differentiate the target signal and the interference, it is the fact of "Signal self nulling". The signal is no longer reconstituted by applying the MVDR technique.
On the other hand, for the LCMV technique, the target signal can be detected again, even if there is a discrepancy between the desired direction and the arrival direction of the signal. The LCMV response model shows that the beamformer puts the stresses in the specified directions, and canceling the interference signals at 30 and 50 degrees. It can be noted that the LCMV beamformer is able to maintain a flat response region around 45 ° in azimuth, while the MVDR beamformer creates a zero, as shown in figure 10.

Overall interpretation on the influence of noise variation for the three techniques:
From the simulations done earlier, the variation in noise power can change the performance of each technique.

- SNR <10 dB: when the noise power is high, the signal can still be recuperated on reception if there is no interference. But if there is interference, the signal is no longer reconstituted.
- 10 dB ≤ SNR <30 dB: Only the MVDR technique can suppress interference and the signal is recovered even if there is a small error in estimating the angle of arrival.
- SNR ≥ 30 dB: Both MVDR and LCMV are capable to delete interference and recovering the wanted signal if there is no error in the estimation of the arrival angle of the signal. If there is an error in estimating the arrival angle, the signal is no longer recovered at the output of the MVDR technique due to the automatic cancellation of the signal. On the other hand, the signal is well recovered at the exit of the LCMV technique with the adoption of the constraint to avoid the automatic cancellation of the signal.

4.3 Influence of the number of interferences for the three techniques

In the presence of powerful interferences, the target signal may be masked by the interference signal. For example, interference from a nearby radio tower may discrupt the antenna array in that direction. If this signal is high, it can interfere the radar in several directions, particularly when the desired signal is received by a side lobe.
For this simulation, we will set the other parameters such as the noise power (SNR = 50 dB) and the number of elements of the antenna array (8x8).

- **<u>Number of interference = 4</u>**

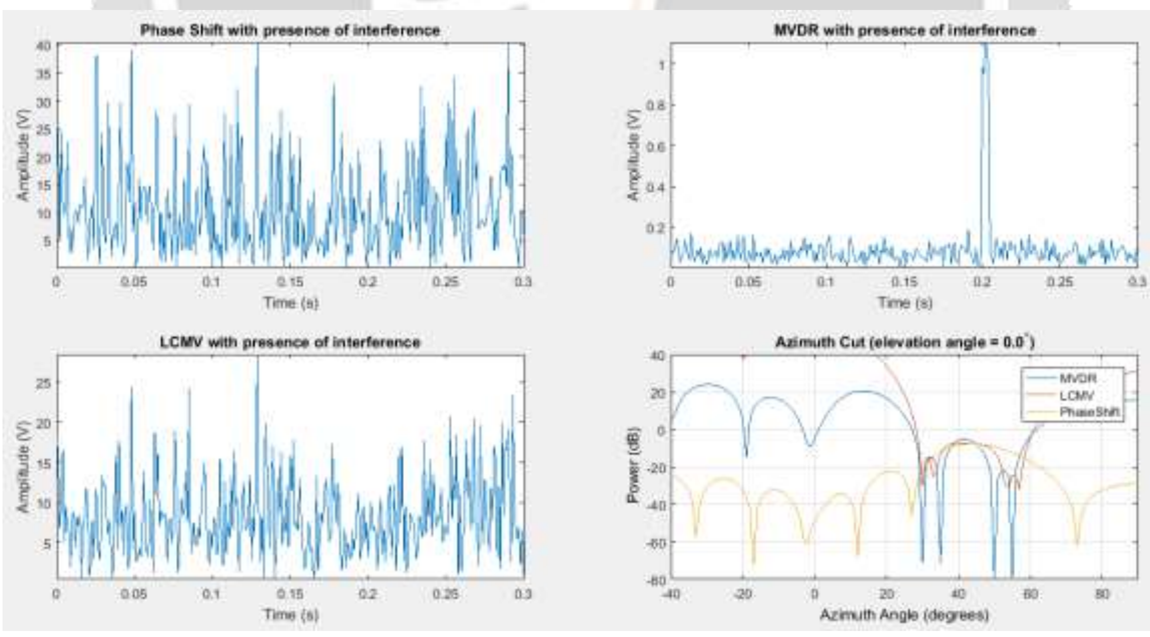

Fig -11 : Comparison of the three techniques for SNR = 50 dB with 4 interferences without error on the estimation of the arrival angle

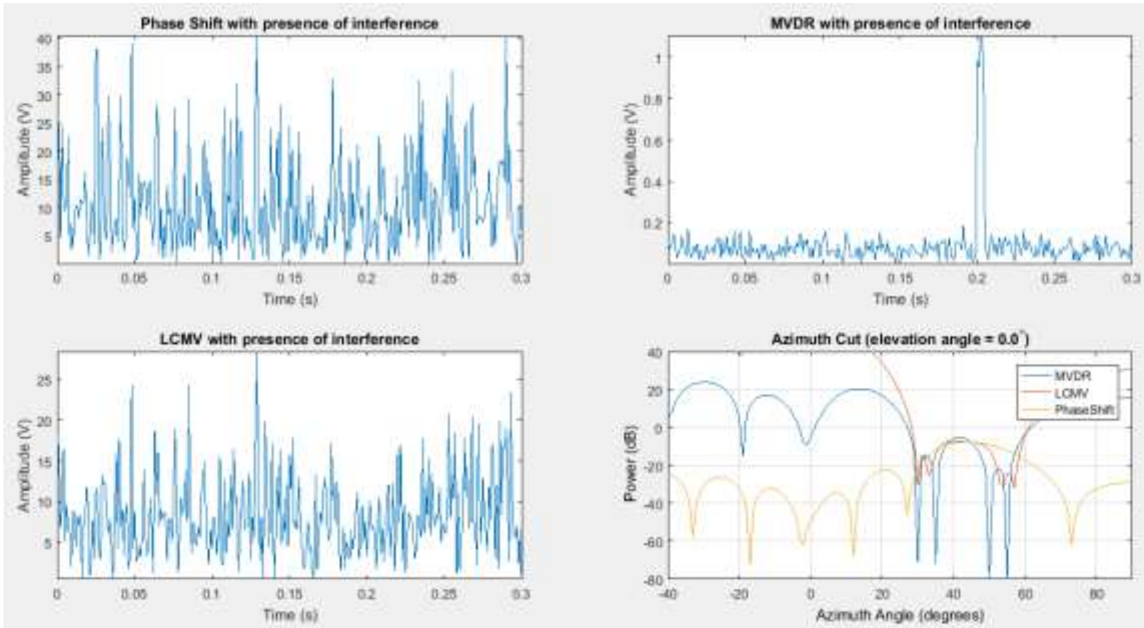

Fig -12 : Comparison of the three techniques for SNR = 50 dB with 4 interferences with error on the estimation of the arrival angle

- **Number of interference = 6**

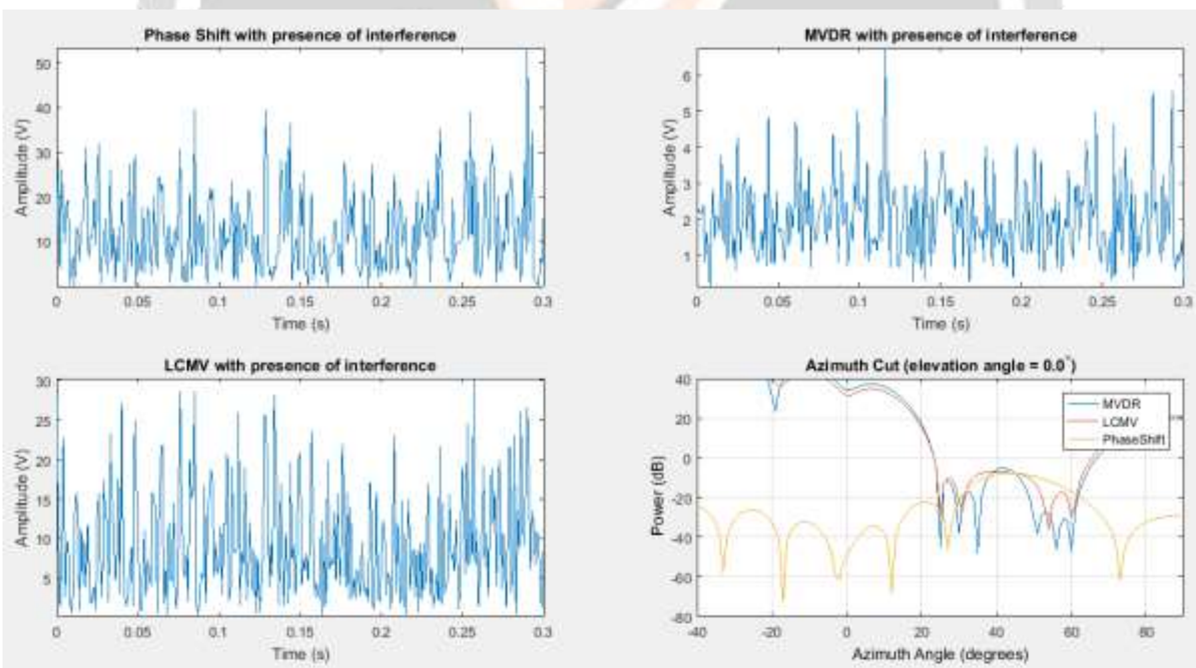

Fig -13 : Comparison of the three techniques for SNR = 50 dB with 6 interferences without error on the estimation of the arrival angle

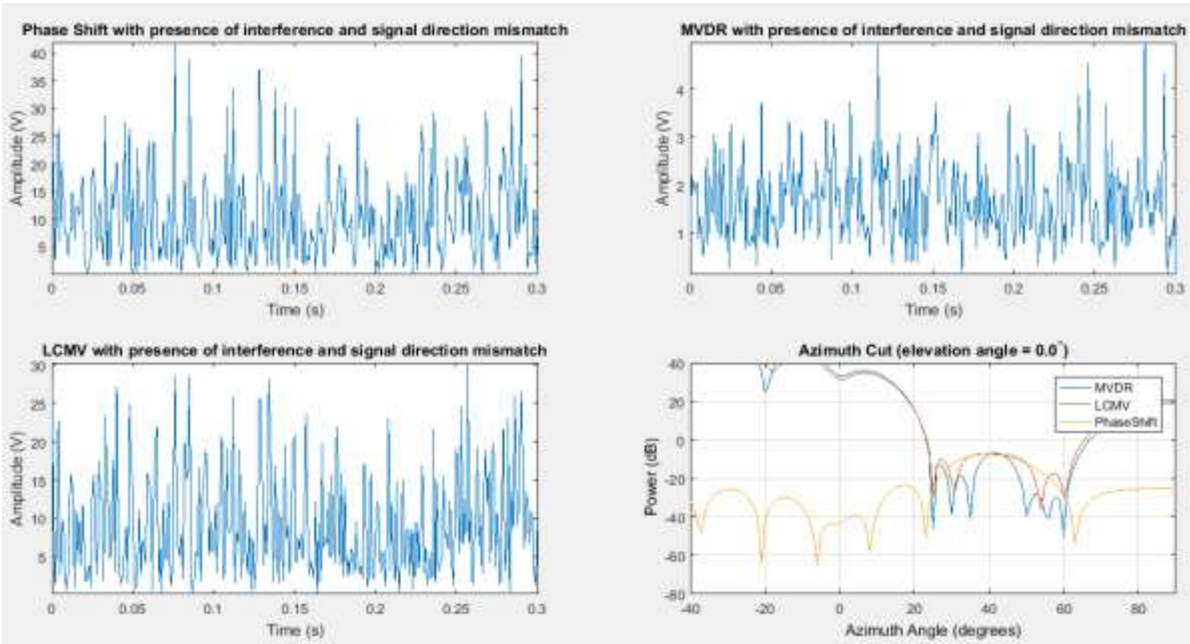

Fig -14 : Comparison of the three techniques for SNR = 50 dB with 6 interferences with error on the estimation of the arrival angle

Global interpretation on the influence of interference's number for the three techniques
From the results of the simulation for the variation of the interference's number, we notice that the signal is scrambled according to the number of the interferences. For 4 interferences, the MVDR technique can recover the wanted signal by suppressing interference. On the other hand for LCMV, according to its answer, because of the effect of the constraint to avoid the automatic cancellation of the signal, the interference arriving at 50 degrees is not deleted; consequently, the useful signal is scrambled.
For 6 interferences, the signal is totally scrambled regardless of the technique used even if the power of the noise is low.

4.4 Influence on the variation of elements of the antenna antenna array

In this simulation, we will alter the number of antenna elements used and see if it can influence the performance of the three techniques. We will set the SNR's value to 3 dB, that means that the noise power is half of the signal and the number of interference will be set to two. We have already seen in the first simulation the result for a dimension of 8x8 (the signal was not recovered in the presence of interference for this parameter). The error on the estimate of the arrival's direction is fixed at 3 degrees.

- **Size of the antenna: 10x10**

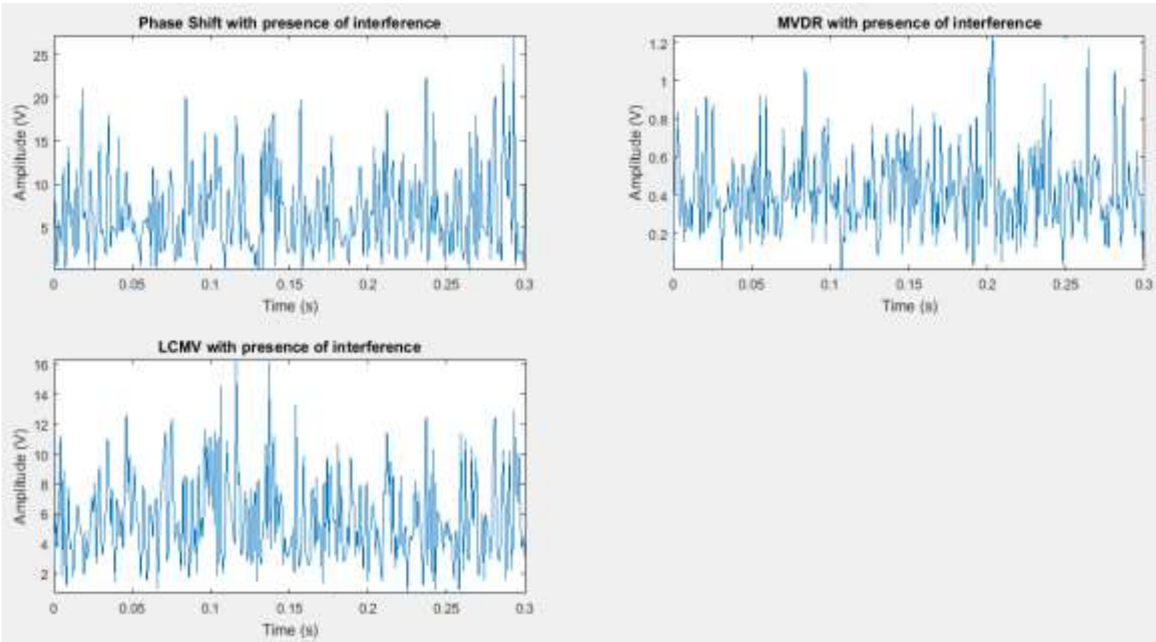

Fig -15 : Comparison of the three techniques using a 10x10 antenna array without error on estimation of the arrival angle

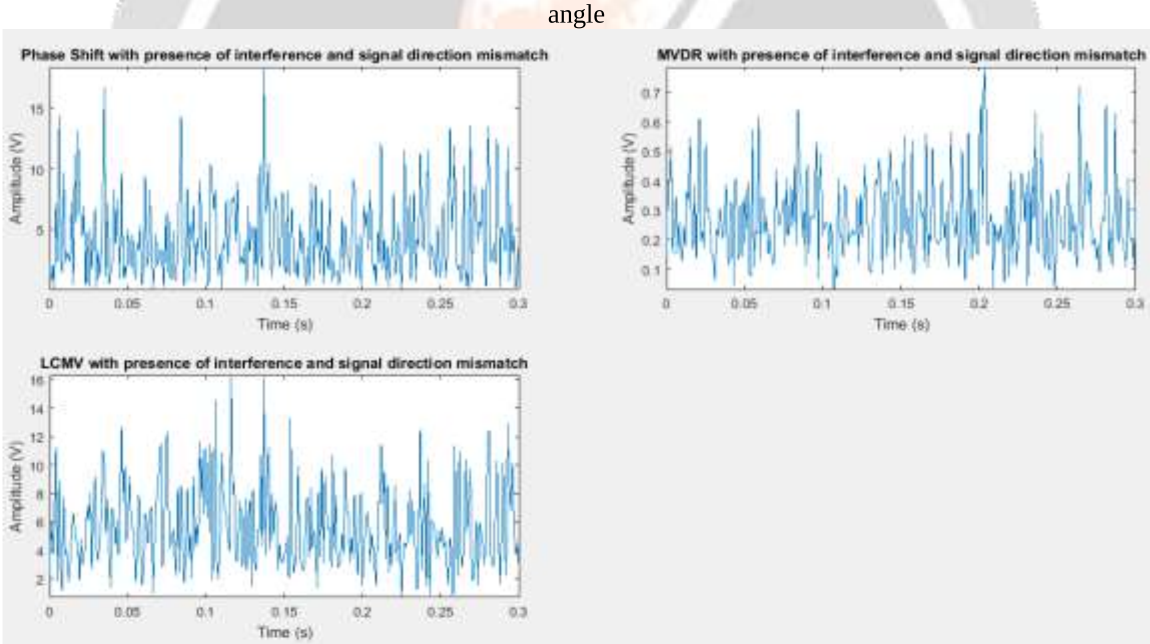

Fig -16 : Comparison of the three techniques using a 10x10 antenna array with error on the estimation of the arrival angle

From figure 15 and 16, the signal is not yet recovered using an antenna array of 10x10 dimension with the value of SNR = 3 dB.

- **Size of the antenna: 20x20**

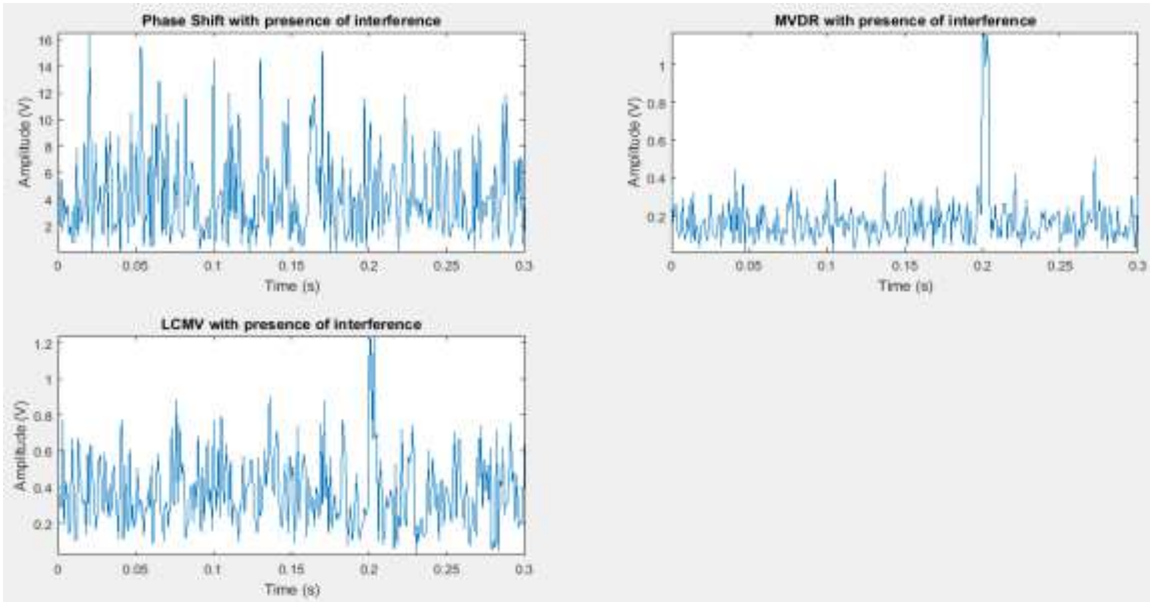

Fig -17 : Comparison of the three techniques using a 20x20 antenna array without error on the estimation of the arrival angle

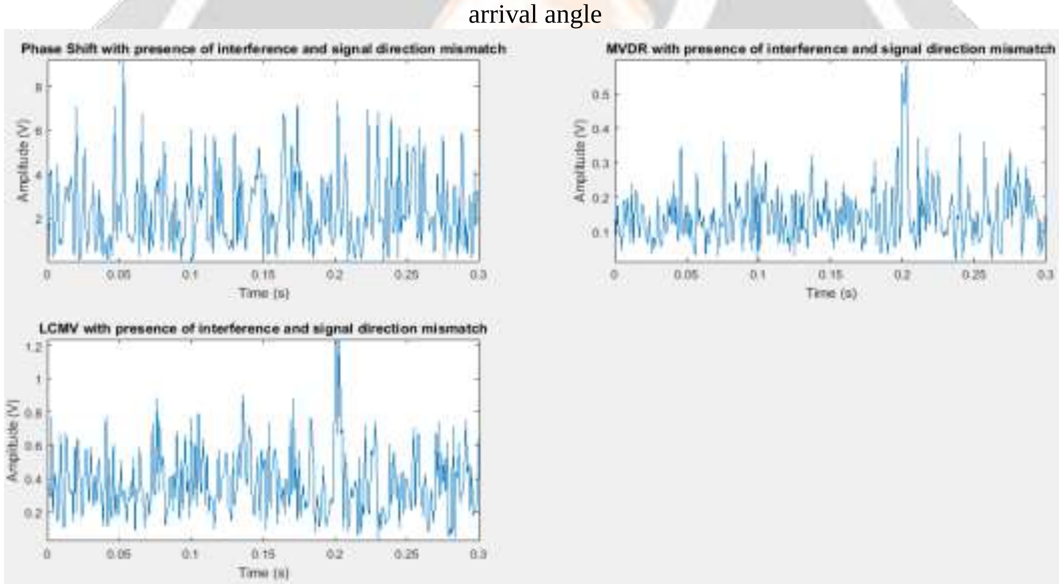

Fig -18 : Comparison of the three techniques using a 20x20 antenna array with error on the estimation of the arrival angle

From figures 17 and 18, by increasing the number of antenna elements that are used, the signal is reconstructed at the output of the MVDR technique and also, there can be seen an improvement in the LCMV technique. On the other hand, the signal is never recovered for the phase shift technique in the presence of interference.

- **Size of the antenna: 25x25**

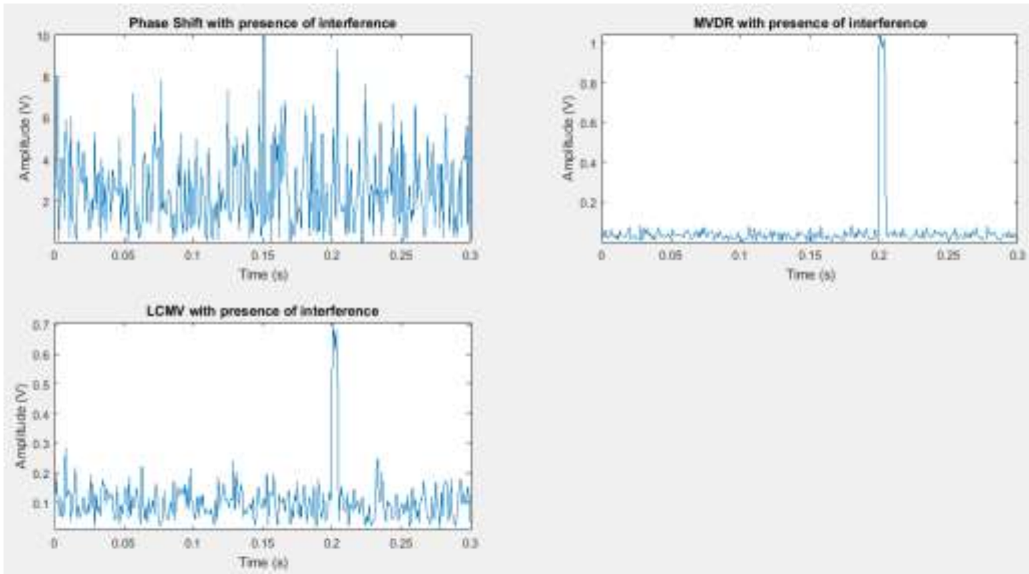

Fig -19 : Comparison of the three techniques using a 25x25 antenna array without error on the estimation of the arrival angle

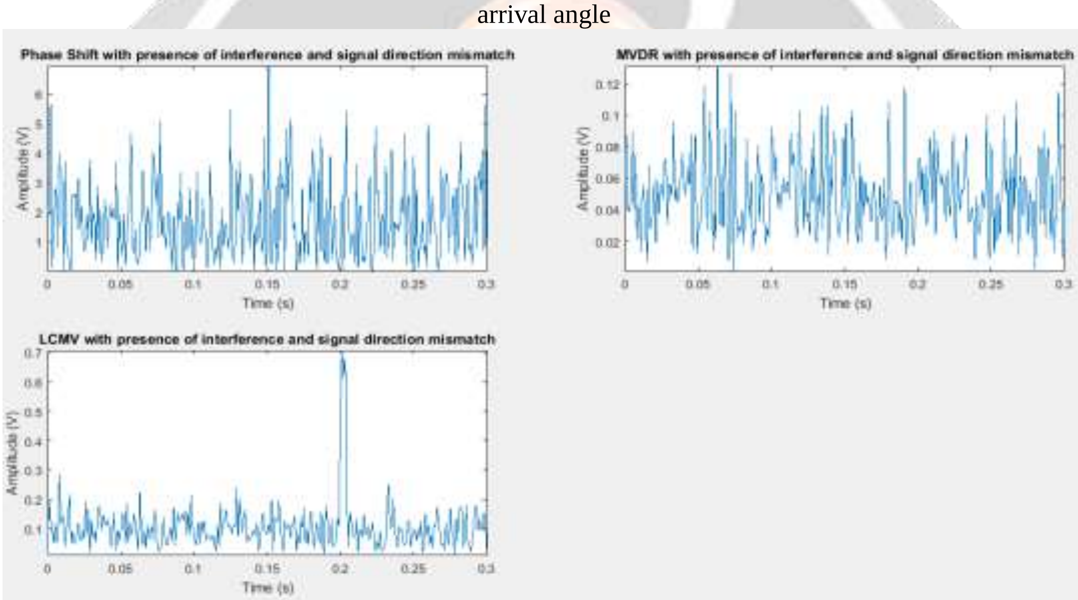

Fig- 20 : Comparison of the three techniques using a 25x25 antenna array with error on the estimation of the arrival angle

Figures 19 and 20 show an improvement of the performance for the MVDR and LCMV technique. We see that it is possible to extract the useful signal at the output of both techniques even if there are interfering signals and high power of noise.
Therefore, according to the results of the different simulations, it is found that increasing the number of antenna elements always improves the performance of the system.

5. CONCLUSION

In this study, a comparison was made between the three beamforming techniques: phase shift beamforming, MVDR beamforming, and LCMV beamforming. We have seen that all three techniques are effectives if there are only noises on the transmission channel. On the other hand, if the channel has interferences, the phase shift technique can no longer extract the useful signal, the advantage of this technique is the non-complexity of the system. To avoid the interference due to the existence of interference, we can use the other two techniques (MVDR and LCMV). Also, the performance of these techniques depends on parameters such as the power of the noise, the number of interference and the number of elements of the antenna array that are used. In comparing the performance of these three techniques, the advantage of each system from others depends on parameters such as noise, interference, and error in estimating the arrival direction of the signal. Therefore, the beamforming technique is important in antennal systems to improve the quality of the received signal.

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