IEEE International Conference on Communication information and Computing Technology (ICCICT), June 25-27, 2021, Mumbai, India

2021 International Conference on Communication information and Computing Technology (ICCICT) | 978-1-6654-0430-3/21/$31.00 ©2021 IEEE | DOI: 10.1109/ICCICT50803.2021.9510162

Classification and Trends in Adaptive Beamforming Techniques of MIMO Radar

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Abstract*—Different beamforming techniques are looking forward to playing an important role in the next generation Multiple Input and Multiple Output (MIMO) radar based system. For the enhancement in resolution and for identification of more number of targets, MIMO radar is very useful. We get more flexibility in beampattern design using the MIMO concept in the radar system. Beamforming is used in sensor arrays for signal transmission or reception in particular directions. For improving resolution of target and reducing interference of signals from undesirables,a powerful technique is used in signal processing of MIMO radar known as beamforming. Various sorts of calculations are researched utilizing conventional beamforming and Adaptive beamforming to alter the necessary weighting on radio wire components. Effects of various errors are illustrated. Also, Linearly Constrained Minimum Variance (LCMV) and Minimum Variance Distortionless Variance (MVDR) calculations introduced which are the techniques gone under versatile beamforming and their belongings are talked about. The most useful algorithms which are the versatile techniques for beamforming as mentioned above are discussed in this paper.From the comparison of LCMV and MVDR algorithms with different number of array elements concluded which is better in different situations of the MIMO radar system.

***Index Terms*—MIMO, Beamforming, MVDR, LCMV, Resolution, Diversity.**

I. Introduction

In Phased array radar, electromagnetic signal radiated into a specific region and detecting target from the echo. For the detection of targets and rejection of interference from other sources, different methodologies have been developed for transmitting and receiving beams. For getting more resolution and reducing fading effect, thoroughgoing research is going on, in which the development of MIMO radar has been the focus [1]. In signal processing of MIMO radar beamforming is a powerful technique. To form a strong beam towards the direction of interest without any interference the signal amplitude and phases are adjusted and processed signal received over different antennas.This is the basic idea behind the beamforming[2].MIMO radar is an advanced type phased array of radar in which independent signals from multiple transmit antennas are transmitted and these waveforms received by an antenna arrays. These wave-forms are processed after the extraction by a set of matched filters. Based on an array configuration, MIMO radar can be arranged as sparse antennas (Bistatic MIMO Radar) for catching the target's radar cross sections and Colocated antennas (Monostatic MIMO radar) to bind a beam towards a specific direction in space [3]. The target Radar cross section RCS are the same for all antennas in colocated transmitting and receiving antennas. A larger virtual array can be formed by phased differences of transmitting antennas with phase differences of receiving antennas [4]. So the long virtual array can be produced by colocated MIMO with the beamformer. The colocated MIMO radar with different beamforming techniques are focused in this paper.

This paper provides in detail study on classification of beamforming techniques. A framework of MIMO technique and advantages of applying beamforming to MIMO radar are presented in section 2. Detailed discussion about classification of beamforming and beamforming approaches are provided in same section. Conventional and adaptive beamforming techniques are discussed in detail. In the same section,different types of algorithms which are based on adaptive algorithm's concept are discussed.In section 2, comparison of Conventional, MVDR and LCMV are discussed. In section 3,issues in adaptive arrays are discussed and beamforming trend in future research are discussed in section 4.

II. RELATED WORKS

A. Beamforming Concept

In MIMO systems ,beamforming technique is used in smart antennas. Efficient signal processing algorithms with antenna arrays are known as smart antennas. The Direction of arrival of signal is a spatial signal identifier which is evaluated by smart antennas[5]. Direction of Arrival estimation and beamforming,are two closely related key aspects of array processing. For maintaining the desired signal beamformers are acting as spatial filters to suppress interference and noise. To maintain the desired signal, its spatial signature has to be known. Assuming far-field sources, DOAs are estimated using spatial signatures. Therefore, beamformers are often applied after the source DOAs have been estimated.A few strategies like the Multiple Signal Classification (MUSIC) strategy, Estimation of Signal Parameters through Rotational Invariance Procedures (ESPRIT), and the grid pencil technique are utilized [6] to gauge the Direction of Arrival (DOA) of approaching signs.By using these methods, DOA can be computed based on peaks of

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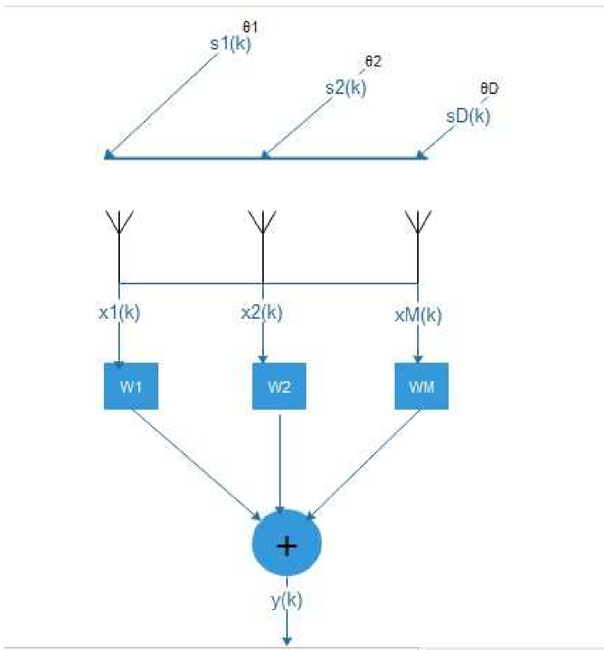

Fig. 1. antenna array M with D arriving signals

spectrum. For angle of arrival estimation some mathematical parameters are very important such as eigen values, eigen vectors and Array correlation matrix. The properties of eigen values are used for estimation of many DOA[7]

The mathematics behind beamforming is given as below: Consider some element array with several arriving signals are arriving at it at theta directions as shown in the figure 1: $s(k)$ = complex signal arriving at time k

$x(k)$ = Received signal at time k includes AWGN noise

$$x(k) = [a(\theta 1)\ a(\theta 2)\ ....a(\theta D] \begin{bmatrix} s1_k \\ s2_k \\ \vdots \\ sD_k \end{bmatrix} + n(k)$$

$$x(k) = \overline{A} * \overline{s(k)} + \overline{n(k)} \tag{1}$$

$a(\theta_i)$ = Steering vector for the θ_i DOA

$W1, W2, W3....Wm$ = M array weights Then the output y(k) can be written as

$$y(k) = \overline{W}^T .x(k) \tag{2}$$

$n(k)$ = Noise vector at each antenna element

$\overline{A}$ = Noise vector at each antenna element

$$\overline{A} = [a(\theta 1)\ a(\theta 2)\ ....a(\theta D]$$

Assuming that all the signals are zero mean, stationary processes then MxM Correlation matrix is composed of signal and noise samples at time k. And, it can be defined as follows:

$R_{xx} = E[\overline{x}.\overline{x}^H]$, replacing $\overline{x} = \overline{A} * \overline{s} + \overline{n}$

and simplifying the equation we get:

$$R_{xx} = AR_{ss}\overline{A}^H + R_{nn} \tag{3}$$

Where $E[.]$ = expected value

R_{ss} = DxD source correlation matrix

R_{nn} = MxM Noise correlation matrix

Relationship network has M eigen values and related M eigen vectors. The biggest eigenvalues compare to the signs, while the rest are related with the clamor. Thus, this connection grid can be isolated into two subspaces: signal subspace and calmor sub-space. Mx(M-D) clamor subspace and MxD signal subspace[8].The relationship network are the exhibit loads that related with signal eigenvectors radiates in the ways of the signals.The commotion eigenvectors related with the connection lattice are the cluster loads that have nulls in the ways of the signals.It is to take note of that assuming signs are not zero mean, fixed cycles relationship framework is otherwise called a covariance grid. Thus, the core of the DOA assessment is eigen investigation of covariance matrix.Eigen examination of Covariance grid can recuperate unique information. This is extremely helpful and principle building square of DOA assessment algorithms[9]. A few researchers ordered the beamforming as per their actual qualities or some are arranged by their signal processing methods as given beneath.

B. Conventional Beamforming and Adaptive Beamforming

The beamforming techniques are classified into two main categories: conventional beamforming and adaptive beamforming[10]. A beamformer in which a set of weights and time delays are fixed for formation of beam, is known as conventional beamformer. Direction of interest and location of sensors are estimated using Butler Matrix which is used in Phase shift beamformer as a conventional beamformer. However Adaptive beamformer collects the information according to properties of signals which are actually received by array. This will improve rejection of unwanted signals from other directions. The beamforming (spatial filtering) operation can be divided into two sub processes [10]

i. Synchronization: Every sensor output is delayed by some amount of time and then synchronized in desired directions. ii. Weight and addition: For this stage, after the received signal is aligned and weighted, all the results are added together to form one output[11] .

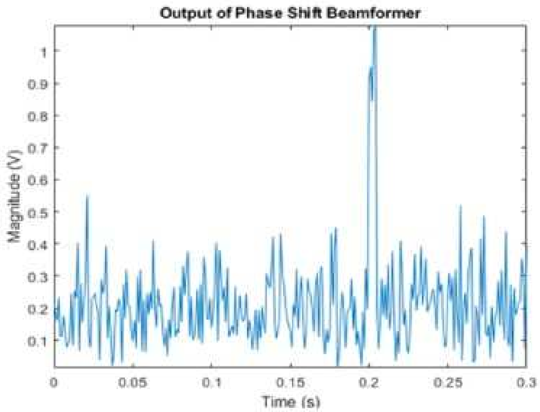

Fig. 2. Output of Conventional beamformer

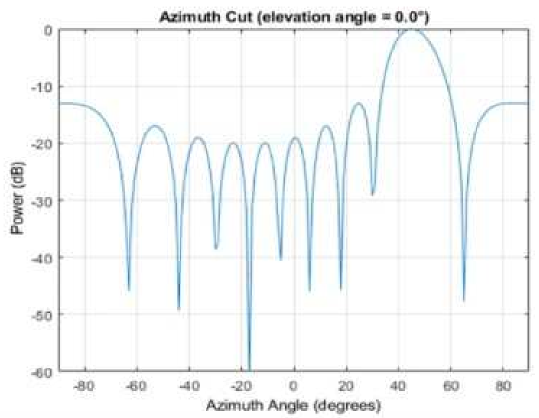

Fig. 3. main beam of Conventional beamformer

1) Conventional Beamforming: Phase shift beamformer is used as conventional beamformer which is easy to implement and simple. One of the favorable circumstances is its solidness against steering errors and signal heading mistakes. Anyway the drawback is wide primary flap and huge sidelobes. Wide primary flap diminishes goals of firmly dispersed sources or targets while impedance may spill into the fundamental projection because of huge sidelobes [12].Consider an example where antenna array received a narrowband signal on which applying digital beamforming. For this example, consider a signal carrier frequency of 100MHz having a uniform linear array with 10 elements separated by half wavelength. The total received signal has 10 columns, where each column represented a one antenna element [12]. Results of the Phase shift beamformer showed in fig.2 using Matlab(© 1984–2020 The MathWorks, Inc.) that the signal dominated over noise and the fig.3 showed that main beam with sidelobes where interference may leak into the main lobe.

2) Adaptive Beamforming: According to different situations, a beamformer which adapts automatically to its response , known as an Adaptive beamformer. M(t) is given as the adaptive array output as follows,

$$M(t) = W^H.N(t) \tag{4}$$

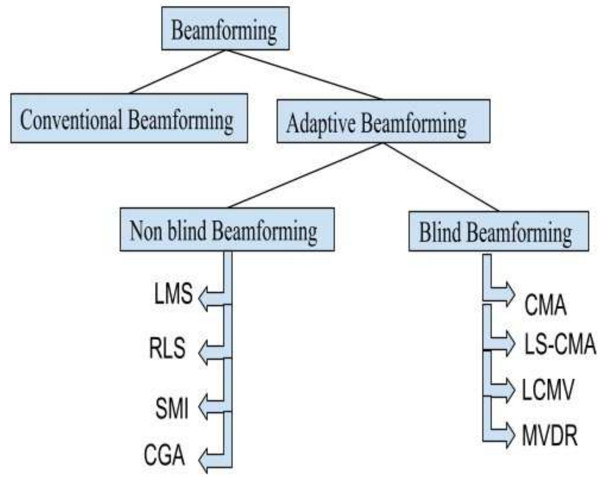

Fig. 4. Different algorithms used in adaptive beamforming

where[W^H] = denotes complex conjugate transpose of the

weight vector

By utilizing M(t), Weights are processed in an iterative way. The error signals are created for changing the loads in the calculation by contrasting reference signal and the reaction of loads, toward the end each emphasis.

$$Z(t) = D(t) - W^H.N(t) \tag{5}$$

Where D[t]= the reference signal which is similar to original signal

Then, the target following should be possible as a beam can be framed towards the ideal signal[13].There are some basic DOA assessment methods which depend on training signal.

For increasing the performance of adaptive beamforming

TABLE I
DIFFERENT ALGORITHMS USED IN ADAPTIVE BEAMFORMING

Nonblind Algorithm	Blind Algorithm
LMS: Least-Mean-Square	CMA:Constant Modulus Algorithm
RLS: Recursive-Least-Square	LS-CMA: Least Square CMA
Sample Matrix Inversion	LCMV:Linearly Constrained Minimum Variance
Conjugate Gradient Algorithm	MVDR: Minimum Variance Dis-tortionless Response

antennas,some algorithms have been used which are shown in figure 3. Based on usage of training signals ,above algorithms are classified as blind adaptive algorithms(BAA) and nonblind adaptive algorithms(NBAA). Training signals are used by NBAA which are transmitted by transmitter to receiver during training period. The main objective of a training signal is to determine a weighted path of travel. However, blind adaptive algorithms use some of the known properties of the wanted signal. These calculations don't need any factual information to refresh its unpredictable vector. In NBAA, during the training period data signals can not be sent over the radio channel. This reduces the spectral capability of the system. Therefore, the blind algorithms are of more research interest. So BAA may be categorized into following 3 groups,

1. Algorithms based on Estimation of the DOAs of the received signals
2. Algorithms based on Property-restoral techniques
3. Algorithms based on the discrete-alphabet structure of digital signals [15].

Each of the above categories is a vast research by itself, hence out of these 3 categories researcher's focus on the first class of BAA i.e. estimation of DOAs. Based on the null steering approach ,next developed algorithms are linearly constrained minimum variance (LCMV) and Minimum variance distortionless response (MVDR). In a null steering approach output of weighted sum produces a zero result means nullifying multiuser interference signals by adding weighted version of signals with appropriate weight values.This interaction improves SINR with highlighting the principle projection the ideal way.

3) Minimum variance distortionless response beamforming (MVDR): Recently smart antennas use one of the beamforming algorithms known as MVDR beamforming. By calculating the weight vector ,this algorithm determines the desired signal from interference. The idea of MVDR came back in 1969 which was proposed by Capon. So the MVDR beamformer, also known as Capon beamformer. This beamformer minimizes the signals from all other directions and keeps the desired signal undistorted with suppression of interference. This will give high SNR and low noise. Performance of the MVDR algorithm depends on the incident angle of the received signal. If there is slight change in the incident angle of the received signal, it will be considered as interference and suppressed by the MVDR beamformer. One of the requirements of the MVDR beamformer is the direction of the useful signal must be known[17]. In the direction of desired signal , MVDR output power subject to unity gain constraint must be minimized. When gain constraint is unity, LCMV weight is known as MVDR beamformer. In figure 5(© 1984–2020 The MathWorks, Inc.),figure shows that at 30 and 50 degrees two deep nulls are present along the interference direction. The beamformer has an increase of 0dB, along the objective bearing of 45 degrees. Thus from the response of phase shift and MVDR beamformer, we can say that The phase shift beamformer doesn't suppress the interference at all but MVDR beamformer suppress the interference signals with the maintenance of target signal[18]. Figure 6 shows that as number of array elements increases, performance of MVDR improves but degrade the performance of conventional beamformer.

4) Linearly constrained minimum variance beamforming (LCMV): In 1972 Frost proposed the principal concept of LCMV beamformer. Here by applying straight goals to the weight vectors along the goal heading, essentials of reference signs and strength of the required sign can be reviewed. In LCMV, beamformers select optimum weight vectors which

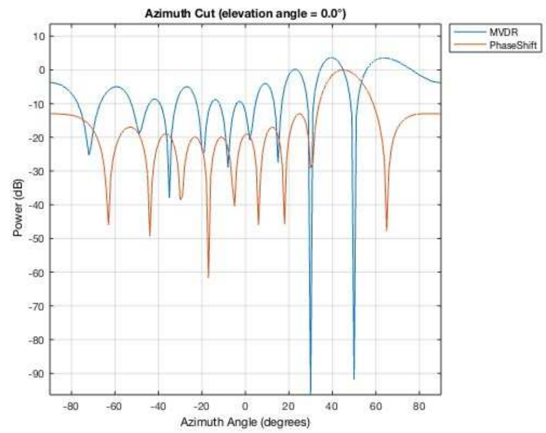

Fig. 5. Comparison of MVDR and Phase shift beamformer beampatterns with N=10,lamda/2 spacing

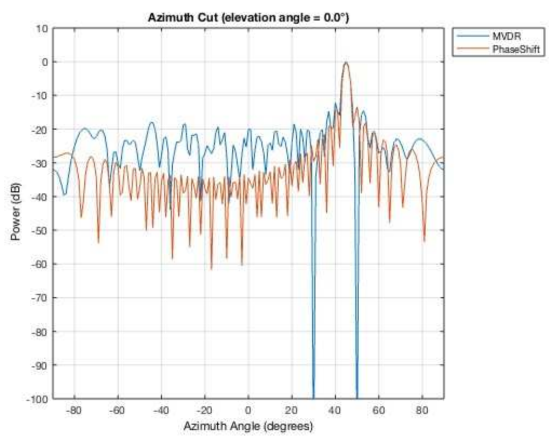

Fig. 6. Comparison of MVDR and Phase shift beamformer beampatterns with N=50,lamda/2 spacing

are also known as spatial filters. This process minimizes the signals from all other directions while keeping the desired signal undistorted. LCMV is useful for suppression of interference and noise in particular directions means desired and undesired signal direction need to be known. The main advantage of LCMV is to avoid self-nulling. Many times because of some interference , the target signal received with slightly different direction rather than desired direction. Because this beamformer considered that it is out of the desired window, so there may be chances of suppression of such wanted signals. This concept is known as self nulling and self nulling can be avoided by use of a LCMV beamformer.Along the target direction or steering vector,LCMV beamformer can put multiple restrictions. Low convergence rate is the main disadvantage of the LCMV technique[19].

The LCMV response pattern shown in fig.7(© 1984–2020 The MathWorks, Inc.) which shows that the beamformer suppress the interference along 30 and 50 degrees and puts the limitations along specified directions. In the event that we

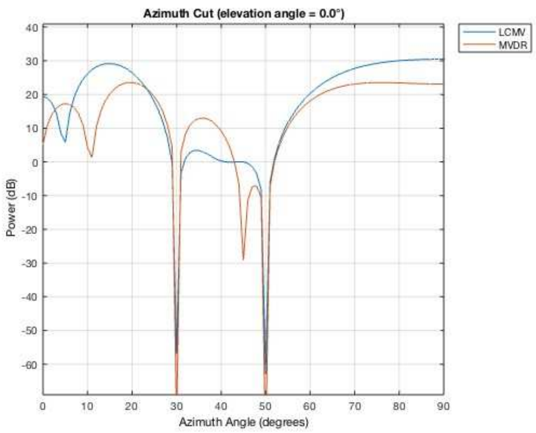

Fig. 7. Comparison of LCMV and MVDR beampatterns with N=10,lamda/2 spacing

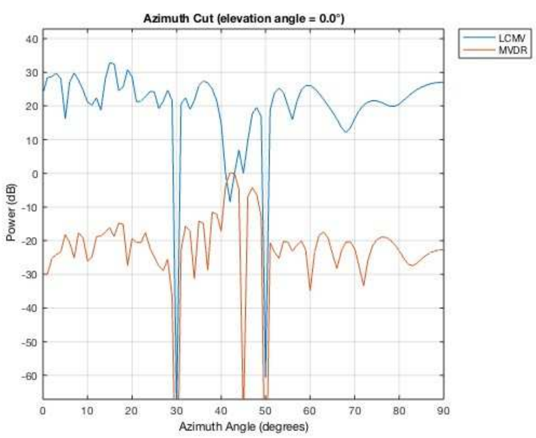

Fig. 8. Comparison of MVDR and LCMV beampatterns with N=50,lamda/2 Spacing

think about the reaction example of LCMV beamformer with the MVDR beamformer, the impacts of requirements can be better observed. Notice how the MVDR beamformer creates a null around the 45 degrees in azimuth and the LCMV beamformer is able to maintain a constant gain response[18,19]. If we compare both LCMV and MVDR, both the techniques have benefits as well as drawbacks in different scenarios. In case of Radar , comparison can be done with the parameters like beampattern and SNR of input and output which shows that MVDR gives better performance than LCMV as desired signal direction is predefined.As shown in table 2 for MIMO radar signal processing MVDR is the best compare to LCMV algorithm. Also CMA algorithm is an adaptive algorithm but it is not stable in dynamic environment ,so it is not used in applications like Radar and Sonar.

III. Issues in Adaptive Arrays

Data-dependent beamformers are nothing but the adaptive beamformers. To optimize the performance ,selection of weight vectors are done by the beamformers as a function

TABLE II

Comparison of LCMV and MVDR algorithm

LCMV Algorithm	MVDR Algorithm
Improves SNR	Give High SNR compared to LCMV
Avoids Self Nulling	Can not avoid self nulling
Desired signal and undesired signals direction need to be known	Only desired signal direction need to be known
Computationally complex	less complex
Convergence rate is low	Convergence rate is high
Effective Interference Cancellation	Sub optimal Interference cancellation

of data. Anyway beamformers are exceptionally touchy to mistakes. Much exertion has been put in the course of the most recent decades to structure the strong beamformers. For all intents and purposes, constantly it is hard to get an accurate steering vector and covariance matrix. Many times, the available covariance matrix is sampled covariance matrix which is not properly suppressing the interference and distortion of desired signal. One likewise can not effectively produce the reference signal for the Least Mean Square (LMS) array. By using the reference signal, the steering vector may be obtained. The steering vectors contain random errors when the weights are measured, due to noise present in the sensor feedback loop. These errors are because of quantization errors in weights, signal disturbances and weight errors etc[20]. If the steering vector is not chosen properly, the beamformer may suppress or null the desired signal with the dominant effect of thermal noise or interference power. This reductions the yield SINR, making the exhibit sensitive towards the direction vector errors. At the point when the ideal sign incident angle is different from its evaluated value, at that point another mistake happens, which is known as beam pointing errors. The array gain reduces and beam pattern changes, as there is deviation of array parameters from theoretical values. To overcome the error issue and overhaul the array structure execution under the unacceptable conditions, various plans have been proposed[21]. The methods like Generalized Sidelobe Canceller(GSC) with Notch Filter, Diagonal Loading, Decision Feedback Generalized Sidelobe Canceller,NullSteering Beamformers with Constraints, Linearly Constrained Minimum Beamformer (LCMV) with Split Polarity Transformation, Digital Beamformer with Mainlobe Maintenance and Bayesian Beamformer are proposed by many authors to enhance the performance and robustness of adaptive arrays [21,22] and continuous research is going on for making strong beamformer.

IV. Trends in Future research

During the underlying time frame, adaptive array applications were constrained because of innovation and powerful versatile calculations for ongoing operation.In a real time environment the progresses in hardware and PCs, frameworks can deal with complicated signal processing. Adaptive beamforming innovation has been effectively actualized in military and non military personnel applications. In adaptive array processing phase is used to electronically coordinate the beam. Regardless, these plans need from the prior information concerning DoA and force level of the impinging signals. Initially there was use of nonblind adaptive algorithms which uses LMS, RLS and SMI. Both the unconstrained and obliged estimations exist inside the game plan of LMS computations, anyway with lower assembly rate. The RLS calculation gives quicker union rate, boundary following capacity, and consistent state MSE by utilizing the gain matrix instead of gradient step size but with more unpredictable calculations. In blind adaptive algorithms, there is no requirement of adjusting weights of an array because there is no use of reference signals. More regularly utilized plan for clampdown of interfering signals and noise is LCMV beamformer. The ideal array boundaries are adaptively evaluated dependent on the accessible informational collection, with the utilization of a LMS adaptive filter which brings about LMS-GSC conspire. In order to improve the intermixing speed of the LMS GSC contrive, Discrete Unitary Transforms, for instance, DFT, have been utilized for the decorrelation of the data.By accepting complex signals as a pair of real signals, the computational complexity can be reduced. It is notable that, in an adaptive array, the quantity of accessible degrees of opportunity controls the calculating multifaceted nature. So as to diminish the computational expense (and subsequently quicker reaction), fractional adaptive arrays are developing as a favored decision.

V. Conclusion

This paper addresses a total outline of versatile beamforming procedures in MIMO radar. With the MIMO radar, we get flexibility in beampattern design, higher resolution and improved parameter recognition of more number of targets. Also discussed various recent types of adaptive beamforming techniques and investigated which strategies are more appropriate for use in MIMO Radar frameworks. With the capacity of wiping out interference and lessening power utilization , adaptive beamforming beamforming is more sensible for MIMO radar structures than customary beamforming systems.Ideal algorithm is an ideal calculation, for example, MVDR to assess precisely the DOAs regarding the azimuth and height points.But self nulling cannot be avoided in MVDR.For avoiding self nulling we can use LCMV beamformer which reduce the chances of suppressing target signal.The execution of such beamforming procedures will give the best in MIMO Radar frameworks. To summarize, for handling the complex signal environment, huge efforts have been done since last decade on improving the performance of the beamformer. This includes improvements in algorithms, by the use of digital techniques for signal processing and adaptive beamforming schemes as developing techniques.

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