A Study on Various Types of Beamforming Algorithms

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Abstract

This paper deals with the study of various types of Beamforming algorithms. A beam former is a processor used in conjunction with an array of sensors to provide a versatile form of spatial filtering. The sensor array collects spatial samples of propagating wave fields, which are processed by the beam former. The objective is to estimate the signal arriving from a desired direction in the presence of noise and interfering signals. A beam former performs spatial filtering to separate signals that have over lapping frequency content but originate from different spatial locations.

Keywords: Beamforming, Conventional Beamforming, Capon Beamforming, Adaptive, LMS

I. INTRODUCTION

Beamforming is the combination of radio signals from a set of small non-directional antennas to simulate a large directional antenna. The simulated antenna can be pointed electronically, although the antenna does not physically move. There are many terrestrial radar applications using beamforming such as mining, weather monitoring where a weather radar can determine the rain locations with a resolution of several hundreds of meters, it is also used to identify the range, altitude, direction, or speed of moving and fixed targets such as aircraft, ships, motor vehicles. In the case of mining as it progresses and monitoring different sections of the pit walls becomes necessary, relocating monitoring devices is not only costly and time consuming, but can also be dangerous on unstable slopes. So a beamforming that can be software controllable is used, here arrival angle of a signal source can be found by steering beam formed antenna and also it minimize the contributions of strong interferers from unknown directions while passing the desired signal from a chosen look direction. When we combine signal from multiple antennas it automatically boosts the signal-to-noise ratio compared to a single antenna. In beamforming, both amplitude and phase of each antenna element are controlled.

Combined amplitude and phase control can be used to adjust side lobe levels and steer nulls better than can be achieved by phase control alone. The combined relative amplitude ak and phase shift qk for each antenna is called a “complex weight” and is represented by a complex constant wk (for the kth antenna). A beamformer for a radio transmitter applies the complex weight to the transmit signal (shifts the phase and sets the amplitude) for each element of the antenna array. In beamforming, both amplitude and phase of each antenna element are controlled. Combined amplitude and phase control can be used to adjust side lobe levels and steer nulls better than can be achieved by phase control alone. The combined relative amplitude ak and phase shift qk for each antenna element is called a “complex weight” and is represented by a complex constant wk (for the kth antenna). A beamformer for a radio transmitter applies the complex weight to the transmit signal (shifts the phase and sets the amplitude) for each element of the antenna array. The rest of the paper is organized as follows Section II studies Classical Beamforming, Section III studies Statistically Optimum Beamforming, Section IV deals with Adaptive Beamforming.

II. CONVENTIONAL DOA ESTIMATION METHOD/ BARTLETT METHOD

The Conventional Beamforming Method (CBF) is also referred to as the delay-and-sum method or Bartlett method. The idea is to scan across the angular region of interest (usually in discrete steps), and whichever direction produces the largest output power is the estimate of the desired signal’s direction. More specifically, a s the look direction θ is varied incrementally across the space of access, the array response vector a(θ) and received signal auto covariance matrix Rxx are calculated and the output power of the beamformer is measured by

\[ P_{CBF}(\theta) = \frac{a^H(\theta)R_{xx}a(\theta)}{a^H(\theta)a(\theta)} \]

This is also referred to as the spatial spectrum and the estimate of the true DOA is the angle θ that corresponds to the peak value of the output power spectrum. The poor resolution is a significant weakness of the method.
III. CAPON’S MINIMUM VARIANCE METHOD

The Capon’s minimum variance method is also known as the Minimum Variance Distortion less Look (MVDL). The MVDL is an attempt to overcome the poor resolution problem associated with the delay-and-sum method and it results in a significant improvement. In this method, the output power is minimized with the constraint that the gain in the desired direction remains unity. Solving this constraint optimization problem for the weight vector we obtain

\[ W = \frac{R_{xx}^{-1} a(\theta)}{a^H(\theta) R_{xx}^{-1} a(\theta)} \]

This gives the Capon’s Spatial Spectrum

\[ P_{\text{Capon}}(\theta) = w^H R_{xx} w = \frac{1}{a^H(\theta) R_{xx}^{-1} a(\theta)} \]

The MVDL only requires an additional matrix inversion compared to the CBF and exhibits greater resolution in most cases. Computing the spatial power spectrum for one range of \( \theta \) does not prevent the algorithm from subsequently computing the spectrum for another range of \( \theta \) using the same data. The spatial characteristics of the data for all directions are compactly represented by \( R_{xx} \), and they are needed to be computed only once. Thus, the method does not have blind spots in time during which transient signals, away from directions of constantly transmitting sources, can appear intermittently and fail to be detected. Another advantage is that by steering the antenna electronically rather than mechanically, the speed of the scan through a region of interest is limited by computational speed instead of mechanical speed.

IV. ADAPTIVE BEAMFORMING

For time-varying signal environments, such as wireless cellular communication systems, statistics change with time as the target and interferers move around. For the time-varying signal propagation environment, a recursive update of the weight vector is needed to track a moving interference so that the spatial filtering beam will adaptively steer to the target time-varying DOA, thus resulting in optimal transmission/reception of the desired signal. To solve the problem of time-varying statistics, weight vectors are typically determined by adaptive algorithms which adapt to the changing environment.

![Functional diagram of an N-element adaptive array](image)

Fig. 2.1: Functional diagram of an N-element adaptive array

Fig 2.1 shows a generic adaptive antenna array system consisting of an N-element antenna array with a real time adaptive array signal processor containing an update control algorithm. The data samples collected by the antenna array are fed into the signal processing unit which computes the weight vector according to a specific control algorithm. Steady-state and transient-state are the two classifications of the requirement of an adaptive antenna array. These two classifications depend on whether the
array weights have reached their steady-state values in a stationary environment or are being adjusted in response to alterations in the signal environment. If we consider that the reference signal for the adaptive algorithm is obtained by temporal reference, a priori known at the receiver during the actual data transmission, we can either continue to update the weights adaptively via a decision directed feedback or use those obtained at the end of the training period. Several adaptive algorithms can be used such that the weight vector adapts to the time-varying environment at each sample; among which LMS can is explained below.

### A. The LMS Algorithm

The LMS algorithm is probably the most widely used adaptive filtering algorithm, being employed in several communication systems. It has gained popularity due to its low computational complexity and proven robustness. It incorporates new observations and iteratively minimizes linearly the mean-square error. The LMS algorithm changes the weight vector \( \mathbf{w} \) along the direction of the estimated gradient based on the negative steepest descent method. By the quadratic characteristics of the mean square-error function \( E \{ \| e(k) \|^2 \} \) that has only one minimum, the steepest descent is guaranteed to converge.

The LMS algorithm is a member of a family of stochastic gradient algorithms since the instantaneous estimate of the gradient vector is a random vector that depends on the input datavector \( \mathbf{x}(k) \). It requires about \( 2N \) complex multiplications per iteration, where \( N \) is the number of weights (elements) used in the adaptive array. The convergence characteristics of the LMS depend directly on the eigen structure of \( \mathbf{R}_{xx} \). Its convergence can be slow if the eigenvalues are widely spread. When the covariance matrix eigen values differ substantially, the algorithm convergence time can be exceedingly long and highly data dependent. Therefore, depending on the eigenvalue spread, the LMS algorithm may not have sufficient iteration time for the weight vector to converge to the statistically optimum solution and adaptation in real time to the time-varying environment will not be able to be performed. In addition, employing the LMS algorithm, it is assumed that sufficient knowledge of the desired signal is known so as to generate reference signal sequences.

### V. Result and Discussion

MATLAB is the simulator used to simulate the beamforming techniques. Firstly, we have done simulations to understand the beamforming. Then we have done the simulations of conventional DOA estimation, Conventional beam former & capon beam formers, and adaptive beam former and the performance is analyzed.

Simulation Parameters:
- Number of antennas : 32
- Distance between adjacent antennas: \( \lambda/2 \)
- Signal Magnitude : 10

### A. Conventional Beamforming

For a uniform linear array with 32 number of antennas, inter-element spacing \( (d) = 0.5\lambda \) , the plot of Beampattern vs array look angle for a single source is shown for conventional beamforming in figure 5.1. Signals are coming from different directions from -90 to 90 and array is looking at 40 degrees.
Fig. 5.1: Beam pattern plot for conventional Beam forming with desired signal at 40 degrees.

B. Capon Beamformer

For a uniform linear array with 32 number of antennas, inter-element spacing \(d = 0.5\lambda\), the plot of Beampattern vs array look angle for a single source for capon beamforming is shown in figure 7.5 here our desired signal direction is at 40 degrees and interference at 60 degrees. Desired signal direction=40degrees, Interference direction=60 degrees, Signal Power=1dB, Noise Power=5dB, Interference power=1000dB.

Fig. 5.2: Beampattern plot for Capon Beamforming with desired signal at 40 degrees and interference at 60 degrees.

For a uniform linear array with 32 number of antennas, inter-element spacing \(d = 0.5\lambda\), the plot of Beampattern vs array look angle for a single source for capon beamforming with interferences at directions at 0,10,30,60 and 80 degrees and desired signal at 40 degrees is shown in figure 5.3.

Fig. 5.3: Beampattern plot for Capon Beamforming with desired signal at 40 degrees and interference at 0,10,30,60 and 80 degrees.
C. Adaptive Beamforming

For a uniform linear array with 32 number of antennas, inter-element spacing \((d) = 0.5\lambda\), the plot of Beampattern vs array look angle for a single source for Adaptive Beamforming with interferences at directions at 11 degrees and source at 0 degrees. Here the interference signal magnitude is \& times the signal power. Here we have simulated it with the help of Generalized Side Lobe Canceller Structure.

![Input desired signal, Input Interference Signal, Real Input Received at Beam former](image1)

Fig. 5.4: Input desired signal, Input Interference Signal, Real Input Received at Beam former

![Beamformers Output](image2)

Fig. 5.5: Output from the Conventional Beamformer

![Error](image3)

Fig. 5.6: Output from the Adaptive Beamformer in which LMS algorithm is used for correction.

VI. CONCLUSION

Beamforming or spatial filtering combines signals from an array of sensors, to achieve directionality. Each signal is weighted and summed to form a single strong signal from a desired direction of arrival, while suppressing interference. This concept could be useful in various terrestrial radar application scenarios of open cast mining of metallic mineral core. The goal is to optimize the output such that it contains minimum noise. For the simulation purposes Matlab R2013a would be used. LMS algorithm is used here due to its simplicity, low computational complexity and better performance in different running environments. It performs really well in terms of number of iterations required for convergence and the results showed that LMS algorithm is the best algorithm to be implemented in FPGA.
REFERENCES


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