

MIMO Sonar and SIMO Sonar: A Comparison

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Abstract--- In the single input multiple output (SIMO) sonar system, the transmitting antennas send coherent waveforms which form a highly focused beam. In the multiple input multiple output (MIMO) sonar system, the transmitter sends independent broad waveforms. These waveforms can be extracted at the receiver by a matched filter bank. The extracted signals can be used to obtain more diversity or to improve the spatial resolution for clutter. MIMO sonar can achieve superior performance through waveform diversity over SIMO sonar.

This paper work focuses on the comparison of the performance of MIMO sonar against SIMO sonar for the target detection and localization. The capon beam forming problem for SIMO and MIMO sonar systems is formulated and the two systems are being compared for the case where the transmitter and receiver arrays are co-located. The capon beam formed output in MIMO offers advantages in terms of resolution and output signal to noise ratio compared to that of SIMO. Simulation results confirm the theoretical observations and demonstrate the effectiveness of the proposed MIMO sonar technique.

Index Terms--- SIMO, MIMO, Beam Forming

I. INTRODUCTION

Recently, the concept of multiple input multiple output sonar has drawn considerable attention due to the additional degrees of freedom and improvement in performance it offers over SIMO sonar. In SIMO sonar, the transmitting antennas are limited to transmit scaled versions of the same waveform. The MIMO sonar employs multiple antennas to emit several independent waveforms and multiple antennas

to receive the echoes reflected by the target. By transmitting independent waveforms via different antennas, the echoes due to the targets at different locations are linearly independent of each other, which allow the direct application of many data-dependent beam forming techniques to achieve high resolution and excellent noise rejection capability[4]. Therefore, adaptive receive filter such as Capon filter can be directly employed in MIMO sonar applications.

The SIMO and MIMO systems are studied in this paper work and for the comparison of these two systems the Capon beam forming method is formulated and simulated. The beam former design problem has been investigated extensively for several decades due to its wide applications in many fields including array processing, spatial filtering, interference suppression, smart antenna systems etc. Beam forming techniques are mainly classified into two types which are conventional and adaptive. The most well-known adaptive beam former namely the minimum variance distortion less response (MVDR) beam former which is also a capon beam former is proposed in this paper.

The problem selected for the paper work is the comparison of SIMO sonar against MIMO sonar for target detection. The comparison was done using Capon beam forming technique. The comparison of beam formed outputs is made for the above specified systems. The simulations are done in Matlab. Benefits of capon beam forming in MIMO sonar compared to that of SIMO sonar are 1) Resolution enhancement and 2) Improved output signal to noise ratio.

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II. GENERAL DESCRIPTION OF SIMO SONAR

Single input multiple output (SIMO) sonar transmits a single waveform that is fed to the different antennas in the transmitter with different phases. Here a single waveform is scaled and transmitted. Therefore there is high correlation between signals transmitted at the different antennas.

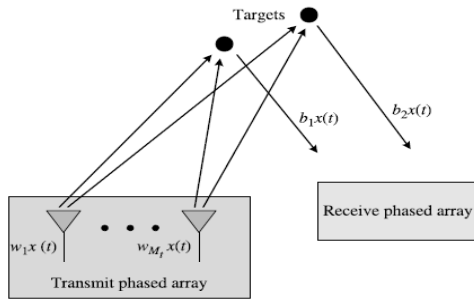


Fig.1: SIMO Sonar

In the system shown in figure1, the scaled versions of the same signal $x(t)$ is transmitted through the different antenna elements in the transmitter consisting of M_t antenna elements. The weight which is applied to each of the element is different and they are represented by $w_1, w_2 \dots w_{M_t}$. The transmitted waveforms hit the targets and get reflected from it. The reflected signals are collected by the receiver array. Here b_1 and b_2 represents the reflection coefficients. The disadvantage of the system is that it suffers from large variations in the received power.

III. GENERAL DESCRIPTION OF MIMO SONAR

Multiple input multiple output sonar utilizes multiple antennas at both the transmitter and the receiver. The system simultaneously transmits different independent signals from each antenna. The antennas at each end of the sonar system have to be sufficiently separated. So the target provides uncorrelated reflection coefficients between each transmit/receive pair of antennas.

A representation of MIMO sonar is shown figure 2. Here $x_1(t), x_2(t), \dots, x_{M_t}(t)$ indicates the different signals which are transmitted through the M_t antenna elements in

the transmitter[1]. These different signals travels through the channel, hits the targets and gets reflected from it. The antenna elements in the receiver array collect each of the signals that are transmitted by each of the sensors in the transmitter.

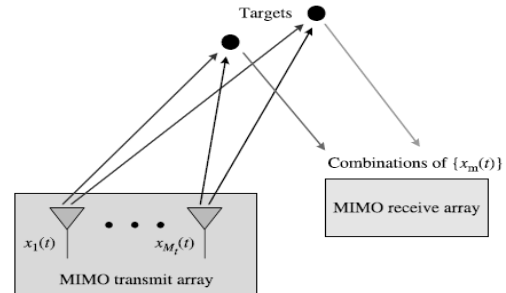


Fig. 2: MIMO Sonar

IV. CAPON BEAM FORMING IN SIMO

The block diagram for the SIMO system is figure 3. The transmitter arrays and receiver arrays are assumed to be co-located. The distance from the transmitter array to the target is R_1 and from receiver array to the target is R_2 . Since the arrays are co-located, $R_1 \cong R_2$.

So $R_1, R_2 \gg \left(\frac{L^2}{\lambda}\right)$ where λ is the wavelength

corresponding to the highest frequency component in the signal and L is the array aperture. The angle between the transmitter array and target is θ_t and from receiver array and target is θ_r . The spacing between the arrays is represented by 'd'. The target is considered to be far apart from both the arrays. Under these assumptions θ_t is nearly equal to θ_r .

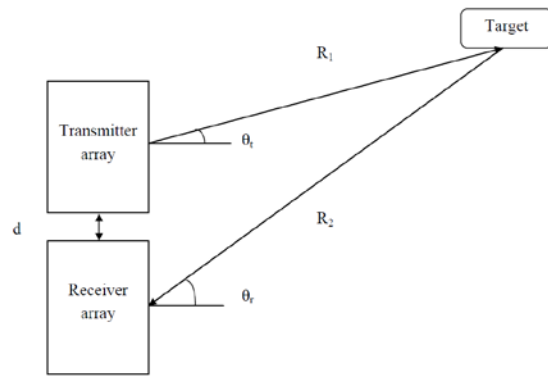


Fig. 3: The SIMO System

A. Transmitter Array for SIMO

The transmitter consists of M sensors which transmits scaled versions of the same signal through it. The distance between the sensors is d_t . The first sensor in the array transmits signal with a delay 1. Similarly the M^{th} sensor which is the last one transmits the same signal with a delay M. So the delay vector can be represented as

$$\tau = [0, d \cos \theta / c, 2d \cos \theta / c, \dots, (M-1)d \cos \theta / c] \quad (1)$$

The spacing between the sensors in transmitter, d_t is equal to N times d_r , where N is the number of sensors in the receiver and d_r is the spacing between the sensors in the receiver. The simplified block diagram for transmitter array is shown in figure 4.

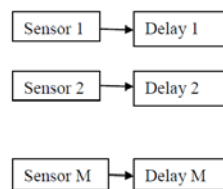


Fig.4: Transmitter Array with M Sensors

B. Receiver for SIMO

The block diagram for SIMO receiver is shown in the Figure 5. The receiver consists of N sensors which receive the signal with different delays. There are N matched filters which extracts different versions of the transmitted signal. So the number of extracted signals is equal to the number of

sensors in the receiver. These N signals are then given as inputs to the capon beam former which produces the beam formed output.

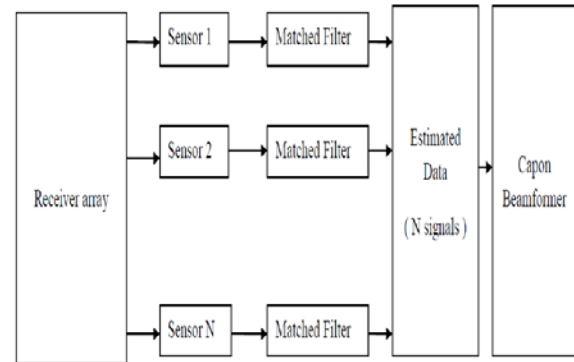


Fig. 5: Receiver for SIMO

C. Capon Beam Forming System in SIMO

The steps to obtain the final capon beam formed output starting from the beginning are explained as follows. First is the generation of continuous wave signal of desired frequency. Sample this continuous wave signal to form discrete signal. The discrete signal is transmitted from the first sensor with delay 1. The same discrete signal is transmitted from second sensor with delay 2. Similarly, the same discrete signal is transmitted from sensor M with delay M. So the delay design should be done for each antenna element. Each of these signals forms an $L \times 1$ array where L is the number of samples. These signals from the transmitter gets mixed up with noise before reaching the receiver. The signal arriving the sensors in the receiver will be immersed in noise; the noise being considered is band limited random with unit variance. The matched filter for each of the N receivers filters the transmitted signal. The estimate of the transmitted signal will be obtained at the output of the N matched filters in the receiver. Total estimate of N signals will be available in the receiver.

The matched filtered output will be an $L \times N$ array for SIMO. Divide the filtered output into P blocks. Find the Fourier transform of each block. Block will be of size FFT length XN after FFT calculation. Select the bin corresponding to the transmitted signal frequency from each

of the block. Calculate the cross spectral density matrix, R using exponential smoothing method. This method selects the weight for the most recent observation and weights for older observations are automatically computed as

$$R_{i+1} = (1 - \alpha)R_i + \alpha(C_i C_i^H) \quad (2)$$

Where R_{i+1} is the correlation matrix for current block and R_i is the correlation matrix for previous block. C_i is $1 \times N$ array for SIMO which corresponds to the selected bins of the filtered output of the previous block. Exponential forgetting factor,

$$\alpha = \frac{1}{1 + \left(\frac{T_c}{T_s}\right)} \quad (3)$$

Where T_c is the Time constant for averaging and T_s is the sampling interval which is obtained by dividing FFT length by the sampling frequency. Next step is the inversion of cross spectral density matrix. After that design the weight vector for SIMO. Final step is the calculation of beam formed output power.

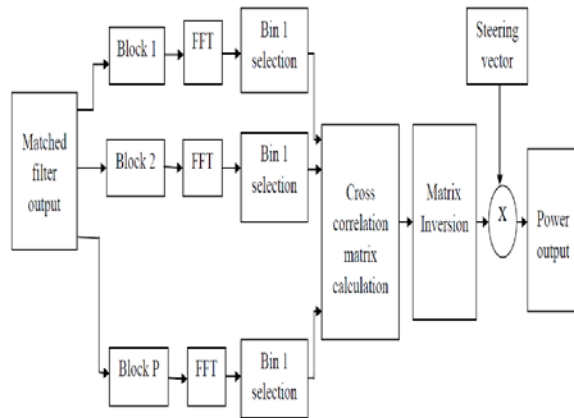


Fig. 6: Capon Beam Forming System in SIMO

V. CAPON BEAM FORMING IN MIMO

The MIMO system block diagram is similar to that of SIMO system shown in figure 3.

A. Transmitter array for MIMO

The transmitter consists of M sensors which transmits M different independent signals. The distance between the sensors is d_t . The first sensor in the array transmits the first signal with no delay. The second sensor transmits a different signal with a different delay. Similarly the sensor M which is the last one transmits the last signal with delay M . The spacing between the sensors in transmitter, d_t is equal to N times d_r , where N is the number of sensors in the receiver and d_r is the spacing between the sensors in the receiver.

B. Receiver for MIMO

The receiver consists of N sensors which receives the different signals with different delays. M matched filters are provided at the output of each sensor. The matched filter at the output of each sensor extracts all the transmitted signals. The number of extracted signals is equal to the number of sensors in the transmitter (M) multiplied by the number of sensors in the receiver (N). So an estimate of MN signals are available at the output. These MN signals are then given as inputs to the capon beam former which produces the beam formed output.

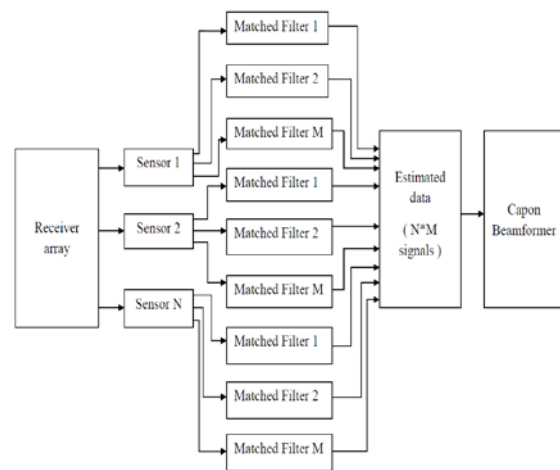


Fig. 7: Receiver for MIMO

C. Capon Beam Forming System in MIMO

The essence of the Capon beam former is to minimize the noise power while maintaining a distortion less response towards the direction of the target of interest[1].

The Capon beam former can be formulated as follows

$$\min_w w^H R_{yy} w \text{ subject to } w^H b^c(\theta) = 1 \quad (4)$$

Where w is the weight vector used to achieve noise suppression while keeping the desired signal undistorted. R_{yy} is the sample covariance matrix of the observed data samples in the receiver. In the beam forming steps the optimum SNR weights used is given by

$$W_{capon} = \frac{[R_{yy}^{-1} b^c(\theta)]}{[b^T(\theta) R_{yy}^{-1} b^c(\theta)]} \quad (5)$$

The output of the Capon beam former is

$$U_{capon} = \frac{[b^T(\theta) R_{yy}^{-1} Y]}{[b^T(\theta) R_{yy}^{-1} b^c(\theta)]} \quad (6)$$

The steps to obtain the final Capon beam formed output starting from the beginning are explained as follows. First is the generation of M different continuous wave signals of desired frequencies. Then sample these continuous wave signals to form discrete signals. The first discrete signal is transmitted from the first sensor with delay 1. The second discrete signal is transmitted from the second sensor with delay 2. Similarly, the last discrete signal is transmitted from sensor M with delay M . Each of these M signals form an $L \times 1$ array where L is the number of samples. The sum of these signals from the transmitter gets mixed up with noise before reaching the receiver. The signal arriving the sensors in the receiver will be immersed in noise; the noise being considered is band limited random with unit variance. So the next step is the generation of noise specified.

The M matched filters for each of the N sensors in the receiver filters all the transmitted signals. Total estimate of MN signals will be available in the receiver. The design of

matched filters is the next step. The matched filtered output will be an $L \times (M \times N)$ array for MIMO. Divide the filtered output into P blocks. Find the Fourier transform of each block. Block size is $[FFT \text{ length} \times (M \times N)]$ after FFT calculation. Select the bins corresponding to the transmitted signal frequencies from each of the block. Calculate the cross spectral density matrix, R using exponential smoothing method. Next step is the inversion of cross spectral density matrix. Design the weight vector for MIMO. Final step is the calculation of the beam formed output power.

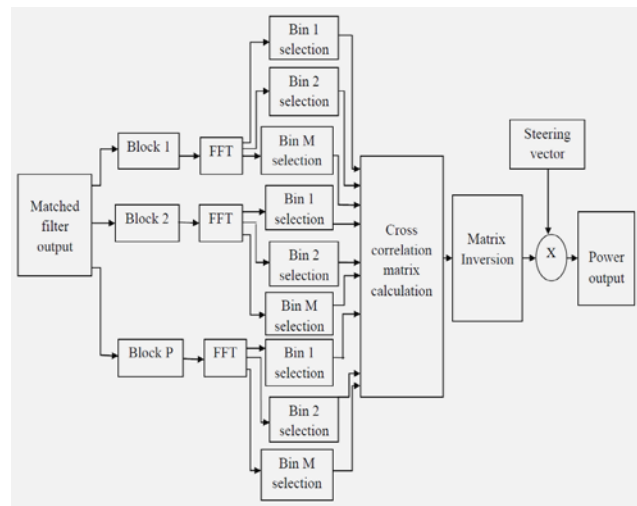


Fig. 8: Capon Beam Forming System in MIMO

VI. RESULTS AND DISCUSSIONS

The target set for this paper is to evaluate the performance of SIMO and MIMO systems through Capon beam forming technique and compare the outputs for both cases. Capon beam forming output in MIMO offers advantages in two aspects compared to that of SIMO. Output SNR improvement and resolution improvement.

A. Conventional & Capon Beam Forming Output for SIMO

Values of parameters considered for simulation are given below,

- Signal frequency = 2200 Hz
- Sampling frequency = 12000 samples/s

- FFT length = 2048
- Number of sensors in transmitter (M) = 3
- Number of sensors in receiver(N) = 10
- SNR = -5dB
- Noise bandwidth=1000 Hz
- Number of blocks for calculating correlation matrix = 30

DOA stands for direction of arrival of signal

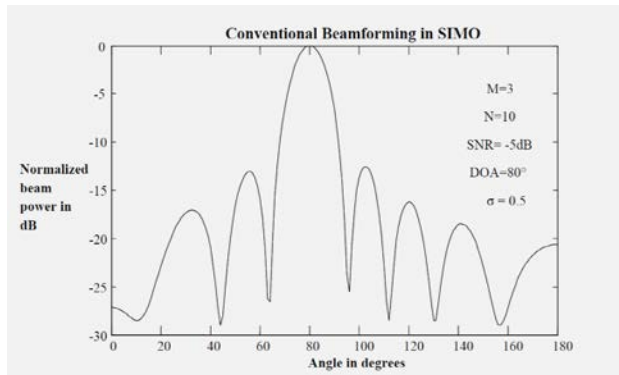


Fig. 9: Conventional Beam Forming Output in SIMO for DOA=80°

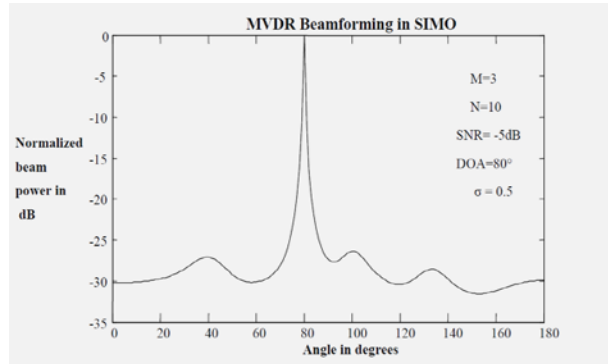


Fig.10: Capon Beam Forming Output in SIMO for DOA=80°

B. Conventional & Capon Beam Forming Output for MIMO

Values of parameters considered for simulation are given below,

- Signal frequencies - 2100Hz,2400Hz,2700Hz
- Sampling frequency = 12000 samples/s
- FFT length = 2048
- Number of sensors in transmitter (M) = 3

- Number of sensors in receiver(N) = 10
- SNR = 5dB
- Noise bandwidth=1000 Hz
- Number of blocks for calculating correlation matrix = 30
- Reflection coefficient of the target(σ)=0.2

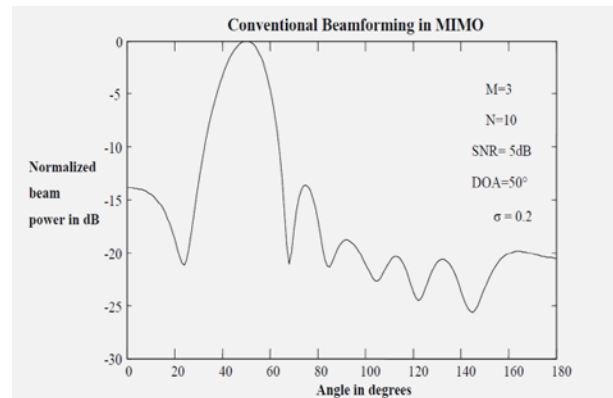


Fig.11: Conventional Beam Forming Output in MIMO for DOA=80°

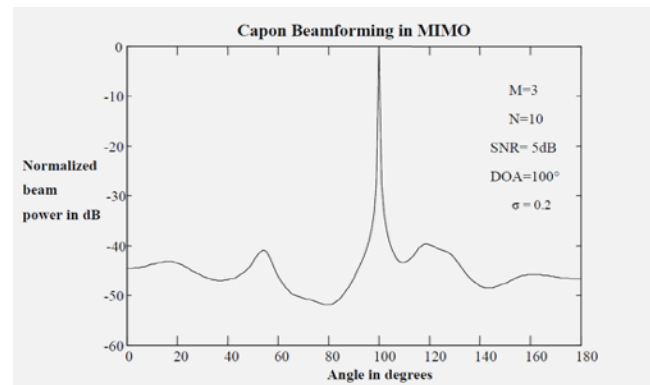


Fig.12: Capon Beam Forming Output in MIMO for DOA=80°

C. Capon Beam Forming Output for Two Signals at Two Different Angles

Values of parameters considered for simulation are given below,

- SNR = 6 dB
- Direction of arrival of the first desired signal = 30°
- Direction of arrival of the second desired signal = 80°

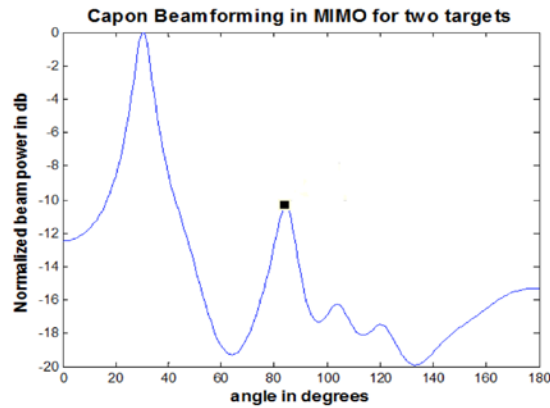


Fig.13: Capon Beam Forming Output in MIMO for Two Signals at 30° & 80°

D. Capon Beamforming Output for a Signal at $\theta_1=70^\circ$ in the Presence of an Interference Signal at $\theta_2=50^\circ$

Parameter value used for the simulation are given below.

SNR=7dB

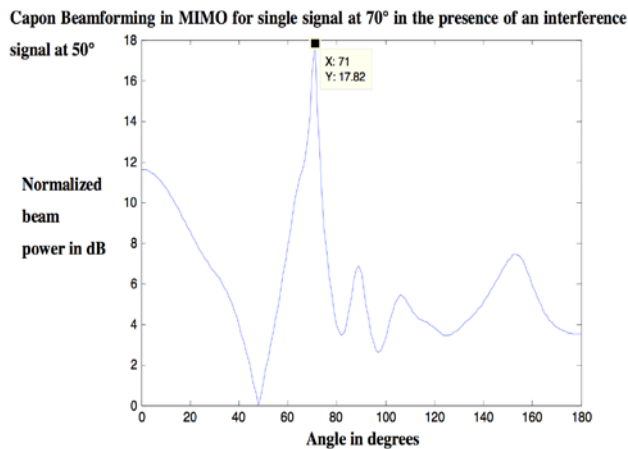


Fig.14: Capon Beam Forming Output in the Presence of an Interference Signal at 50 Degrees

E. Comparison of Output Signal to Noise Ratio for SIMO & MIMO

The output SNR in the case of SIMO is proportional to $10\log_{10}(N)$. The output SNR in the case of MIMO is proportional to $10\log_{10}(MN)$. For the case where the number of sensors in transmitter is 3, number of sensors in receiver is 10, the output SNR for SIMO is equal to 10 dB. The output SNR for MIMO is equal to 15 dB. So the

theoretical improvement in output SNR for MIMO compared to SIMO is 5 dB. The comparison of output SNR is made from the simulation results and the SNR improvement for MIMO is noted for different values of input SNR's. It can also be seen that the improvement in output SNR is decreased as the input SNR is decreased. Also the output gets distorted as input SNR is very low. A graph showing the comparison is indicated in Figure 15.

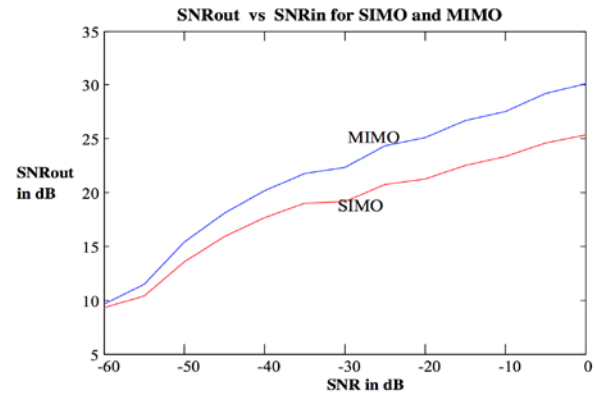


Fig. 15: Output SNR comparison

F. Comparison of 3dB Beamwidth & Resolution for SIMO & MIMO

The beamwidths of the Capon beamforming output for SIMO is proportional to $(1/N)$ & for MIMO is proportional to $1/(MN)$. Resolution is inversely proportional to 3dB beamwidth. Resolution for SIMO is proportional to N and Resolution for MIMO is proportional to MN . For M equal to 3 & N equal to 10, resolution for SIMO is 10 and resolution for MIMO is 30. In general, resolution is nearly M times for MIMO compared to that of SIMO. Resolution is measured by measuring the 3dB beamwidth in the beamforming outputs for SIMO & MIMO.

The 3dB beamwidths of SIMO and MIMO sonars are noted and the simulation results are used to compare the beamwidths which is shown in Figure 16.

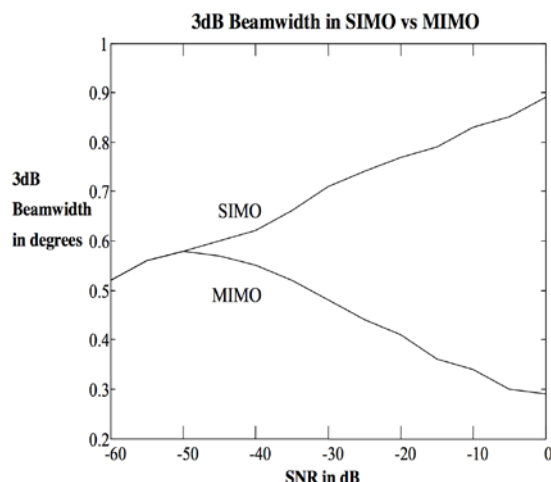


Fig.16: Comparison of 3dB beamwidth

VII. CONCLUSION AND FUTURE WORK

The main aim of the paper work is to compare the performance of SIMO and MIMO adaptive detectors. For the comparison, capon beamforming of the match filtered output in the receiver for a SIMO sonar and MIMO sonar is performed as the simulation part. The conventional beamforming techniques calculate the weight vectors independently of the data, an adaptive beamformer compute the weights in such a way as to improve the beamforming output. The adaptive algorithm used is MVDR. MVDR is maximum SINR beamformer which compute the weights adaptively depending on the sensor data. The weight vector thus obtained through the MVDR filter exhibits high beam resolution and interference suppression.

The comparison of the two sonar systems is made for the case where the transmitter and receiver arrays are co-located. Capon beamforming output in MIMO offers advantages in two aspects compared to that of SIMO. They are output SNR improvement & resolution improvement. Simulation results confirm the theoretical observations and demonstrate the effectiveness of the proposed MIMO sonar technique.

The target reflection coefficient for each target including the target of interest can be estimated from the

capon beamformer output by applying least square method. The estimates of the reflection coefficients can be used to form a spatial spectrum or sonar detection graph. The locations of the targets and their complex amplitudes can then be estimated by searching for the peaks in the spectrum. The optimum waveform design for the required output condition can also be done as a future work.

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