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Iterative Covariance-Based Beampattern Matching Design in MIMO Communication

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ABSTRACT

The important role of multiple-input multiple-output (MIMO) systems in 5G and 6G wireless communication is expected to be crucial. These advanced systems, which have been deployed since 2021, offer significant advantages over previous communication generations. Unlike earlier versions, MIMO systems can transmit a variety of probing signals through their antennas, which may or may not be correlated. This diversity in waveforms provided by MIMO communication enables improved capabilities and performance.

Numerous research papers have proposed various approaches for beamforming in MIMO communication. Our research aims to provide valuable iterative approach for beamforming in a MIMO communication systems with uniform linear array constellation. We will investigate the beam patterns generated by this iterative algorithm using the covariance-based MIMO communication waveform method. MATLAB simulations will be employed to analyze and assess the effectiveness of these methods.

KEYWORDS: *MIMO communication; Beamforming; Beampattern Design; covariance based;*

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I. INTRODUCTION

The field of multiple input multiple output (MIMO) communication has gained significant attention from researchers worldwide due to the introduction of 5G and 6G networks. Unlike previous generations, MIMO communication allows for the selection of transmitted probing signals to maximize power around user locations or approximate a desired transmit beam-pattern. This flexibility in signal correlation provides additional design options for communication systems.

In MIMO communication, transmitting antennas are positioned closely together, resulting in identical channel observations for users of interest. This enables the use of MIMO concepts to enhance spatial resolution. Numerous studies have highlighted the advantages of MIMO communication, including improved interference rejection capability, enhanced parameter identifiability, and increased flexibility for transmit beampattern design. This is particularly relevant in radar-related MIMO applications. References on MIMO radars with colocated antennas can be found in [1], while other papers like [2] focus on MIMO waveforming for applications such as sidelobe blanking.

The most widely used method for MIMO communication waveform design is the covariance matrix-based approach [6]-[10]. In this approach, the cross-correlation matrix of transmitted signals is considered instead of the entire waveform. This allows for manipulation of the spatial domain. In references [6, 8], the cross-correlation matrix is designed to transmit power within a desired range of angles. In [7], the cross-correlation matrix is designed to control spatial power and minimize cross-correlation between transmitted signals at specific user locations, thereby improving spatial resolution in the receiver. [9] optimizes waveform covariance based on the Cramer-Rao bound matrix, while [10] designs signal waveforms to achieve low peak-to-average power ratio (PAR) and higher range resolution using an optimized covariance matrix. Authors in [11, 12] investigate 3D beampattern design in uniform and planar MIMO communication, and [13] explores beampattern matching design in non-uniform MIMO communication.

Numerous studies have explored beampattern design and waveforming in MIMO communication. The covariance-based method, which designs the cross-correlation matrix of transmitted signals, is widely

recognized for its effectiveness. This paper aims to design the beampattern of a MIMO communication system to increase transmitted power around user locations and reduce sidelobe levels to minimize interference from other antennas.
The study is divided into five sections as follows:
Section I provided a brief overview of MIMO communication.
Section II examines the use of covariance-based beamforming in MIMO communication.
Section III discusses the utilization of a model that concentrates the transmitter power at known desired locations and we will introduce our iterative algorithm in this section.
Sections IV present an analysis of an algorithm with some examples. These designs are compared with an ideal beamforming approach and other algorithms which are introduced by other authors, and numerical results are provided.
Section V focuses on the conclusion, and the paper includes references at the end.

II. Covariance Based Method for MIMO Communication Beampattern Design

Let's consider a set of N sender antennas positioned at known locations in a spherical coordinate system along the z-axis. These antennas are aligned along the z-axis and are driven by specific signals on a carrier frequency f_c or with a wavelength of λ. Each antenna produces a signal in the far field at a specific point in space, characterized by distance d and direction $Ar(\theta, \phi)$ from the antenna.

The complex envelope of the total radiated signal at this point and in discrete form is given by Equation (1), where $EC_i(n, d, \theta, \phi)$ represents the signal produced by the i-th antenna.

$$EC_i(n, d, \theta, \phi) = \frac{1}{\sqrt{4\pi d}} y_i\left(n - \frac{d}{c}\right) e^{j\left(\frac{2\pi}{\lambda}\right)\boldsymbol{P}_i^T \boldsymbol{Ar}(\theta,\phi)} \quad (1)$$

In this equation y_i is the complex envelope of each antenna's transmitted signal and P_i is the position of the i-th antenna. In the far field, these signals and their powers combine in a linear manner. The resulting combined signal from all the transmitted signals in the far field can be expressed as Equation (2).

$$EC(n, d, \theta, \phi) = \sum_{i=1}^{N} EC_i(n, d, \theta, \phi)$$

$$= \frac{1}{Kd} \sum_{i=1}^{N} y_i\left(n - \frac{d}{c}\right) e^{j\left(\frac{2\pi n z_i}{\lambda}\right)\sin(\theta)} \quad (2)$$

The resulting power of the combined signals, which will be transmitted to the users through the communication channel, is given by Equation (3), which is a sum of cross-correlations between the transmitted signals [2].

$$P(\theta, \phi) = \frac{1}{K^2} \sum_{k=1}^{N} \sum_{l=1}^{N} R_{kl} e^{\frac{j2\pi}{\lambda}(z_k - z_l)\sin(\theta)} \quad (3)$$

The cross-correlation between two signals is defined as R_{kl} in Equation (4).

$$R_{kl} =< y_k(t) y_l^*(t) > \quad (4)$$

By defining a steering vector $\boldsymbol{s}(\theta)$ in Equation (5), which represents the conjugate transpose of the antenna response vector at θ, the power density $P(\theta, \phi)$ written in (3) can be expressed as Equation (6).

$$\boldsymbol{s}(\theta) = \left[e^{j\left(\frac{2\pi z_1}{\lambda}\right)\sin(\theta)}, \ldots, e^{j\left(\frac{2\pi z_N}{\lambda}\right)\sin(\theta)}\right]^T \quad (5)$$

$$\mathrm{P}(\theta, \phi) = \frac{1}{4\pi} \mathbf{s}^*(\theta) \mathbf{R} \mathbf{s}(\theta) \quad (6)$$

Equation (6) represents the power density $P(\theta, \phi)$ for the users in terms of the cross-correlation matrix R represented in (7).

$$\mathbf{R} = \sum_{k=1}^{N} \sum_{l=1}^{N} s_k(t) s_l^*(t) \quad (7)$$

These equations describe the desired beam pattern generated by the cross-correlation matrix. In the following examples, we demonstrate different beam patterns produced by such a matrix. Figure 1 displays the beam patterns of a 10-element uniform linear array (ULA) with half-wavelength spacing, generated by different signal cross-correlation matrices (8), (9), and (10).

It is important to note that these figures illustrate the directional characteristics of the array and provide information about the distribution of power in different directions.

$$\begin{bmatrix} 1 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 1 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} 0.8^0 & \cdots & 0.8^9 \\ \vdots & \ddots & \vdots \\ 0.8^9 & \cdots & 0.8^0 \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} \tag{10}$$

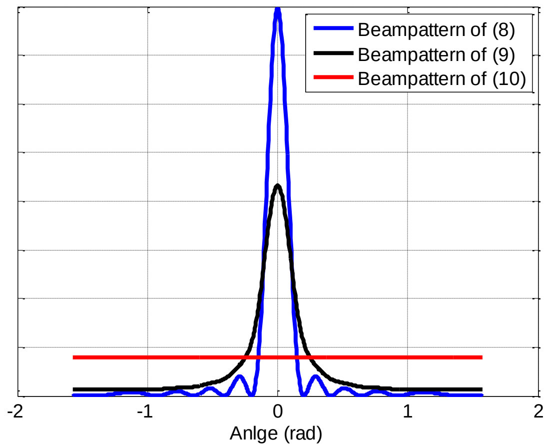

Fig. 1. Beampattern respect to (7). The blue one is corresponds to cross-correlation matrix of (8), The black one is corresponds to cross-correlation matrix of (9) and the red one is corresponds to cross-correlation matrix of (10)

In MIMO communication, the signal cross-correlation matrix usually consists of complex values, except for the real-valued diagonal elements. However, in the case of conventional communication, all transmitter signals are correlated with each other. This means that the absolute value of all elements in the matrix R is equal to 1, as shown by the blue element in Fig. 1.

III. Problem Formulation and Optimization

Now, let's consider the objective of maximizing the power transmitted to users in a 5G cellular network while minimizing power in other directions. To achieve this, we can formulate the cost function based on the previous section as follows:

$$J(\mathbf{R}) = \min_{\hat{R}} \frac{1}{K}\sum_{k=1}^{K} |\boldsymbol{P_d}(\theta_k) - \boldsymbol{a}^*(\theta_k)\boldsymbol{R}\boldsymbol{a}(\theta_k)|^2$$
$$\textit{Subject to}:$$
$$\boldsymbol{R} \geq 0$$
$$diag(\boldsymbol{R}) = P_t \tag{11}$$

Where in this equation, K is the total number of the users in the area, $P_d(\theta_k)$ is desire transmitted power at the k-th user location, $\boldsymbol{R} \geq 0$ means the covariance matrix must be semi-definite and P_t is the total transmitted power.

In this paper we want to add 2 more constraints to this problem in order to become more practical, first one would be the maximum allowable sidelobe level, and the second one would be beampattern flatness level at users' locations. So the problem in (11) can be rewritten as follow:

$$\min_{\hat{R}} \frac{1}{K}\sum_{k=1}^{K} |\boldsymbol{P_d}(\theta_k) - \boldsymbol{a}^*(\theta_k)\boldsymbol{R}\boldsymbol{a}(\theta_k)|^2$$
$$\textit{Subject to}:$$
$$\boldsymbol{R} \geq 0$$
$$diag(\boldsymbol{R}) = P_t$$
$$\max\left(\boldsymbol{a}_{\boldsymbol{sl}}^*(\theta_k)\boldsymbol{R}\boldsymbol{a}_{\boldsymbol{sl}}(\theta_k)\right) < SLL$$
$$\left|\max\left(\boldsymbol{a}_{\boldsymbol{ml}}^*(\theta_k)\boldsymbol{R}\boldsymbol{a}_{\boldsymbol{ml}}(\theta_k)\right) - \max\left(\boldsymbol{a}_{\boldsymbol{ml}}^*(\theta_k)\boldsymbol{R}\boldsymbol{a}_{\boldsymbol{ml}}(\theta_k)\right)\right| < FN \tag{12}$$

In this equation, $\boldsymbol{a_{sl}}(\theta_k)$ refers to beampattern sidelobe level at k-th user location, $\boldsymbol{a_{ml}}(\theta_k)$ is mainlobe level of transmitted beampattern at k-th user angle, SLL is allowable maximum level of sidelobe level and FN is flatness of the beampattern for a desire direction.

Here in this paper, to solve the problem in (12) we want to use Iterated Weighted Least Squares (IWLS) method, so we will write (12) in a iterative form as bellow:

$$\min_{R_j} \frac{1}{K}\sum_{k=1}^{K} \left|\boldsymbol{P_d}(\theta_k) - \boldsymbol{\omega_i}\left(\boldsymbol{a}^*(\theta_k)\boldsymbol{R_i}\boldsymbol{a}(\theta_k)\right)\right|^2$$
$$\textit{Subject to}:$$
$$\boldsymbol{R_i} \geq 0$$
$$diag(\boldsymbol{R}) = P_t$$
$$\max\left(\boldsymbol{a}_{\boldsymbol{sl}}^*(\theta_k)\boldsymbol{R_i}\boldsymbol{a}_{\boldsymbol{sl}}(\theta_k)\right) < SLL$$
$$\left|\max\left(\boldsymbol{a}_{\boldsymbol{ml}}^*(\theta_k)\boldsymbol{R_i}\boldsymbol{a}_{\boldsymbol{ml}}(\theta_k)\right) - \max\left(\boldsymbol{a}_{\boldsymbol{ml}}^*(\theta_k)\boldsymbol{R_i}\boldsymbol{a}_{\boldsymbol{ml}}(\theta_k)\right)\right| < FN \tag{13}$$

Where $\boldsymbol{\omega}$ is the updated weighting matrix and X_i refer to X variable at iteration i. The optimization problem in (13) can be efficiently solved with the MATLAB based CVX toolbox [14]. The details of the proposed algorithm presented in Algorithm 1. It is obvious that the every IWLS algorithm has a regularization parameter, Γ_i, and the algorithm will converges faster when the regularization parameter for the weighting matrix, is chosen appropriately.

Algorithm 1: IWLS-BPM Algorithm

1: Initiate:

$\boldsymbol{\omega_0} = diag([\omega_0(\theta_1), \omega_0(\theta_2), \dots ,\omega_0(\theta_k)])$, $\Gamma_1 > 0$, $\rho < 0.01$

2: Foreach $\boldsymbol{i = 1 : i_{\max}}$

$\boldsymbol{\omega}_i(\theta_k) = (|\Gamma_i \boldsymbol{I} - P_d(\theta_k)|)^{\left(\frac{\rho}{2}-1\right)}$

Update the regularization factor such that

$0 < \Gamma_i \leq \Gamma_{i+1}$

Solve the optimization problem (13) to find $\boldsymbol{R}_i$

$i = i + 1$

If (Algorithm Converged)

Break;

End If

End For

IV. Simulation Results

In our simulations, we consider a MIMO communication with a collocated ULA of M = [20, 35, 50] elements, with half wavelength spacing. We assumed that each antenna element will be fed with the same power level. The desired pattern is a non-symmetric beampattern with two desire location at -20^0 with $BW = 10^o$ and in $+40^o$ with $BW = 25^o$ as shown in figures 2 to 4. The proposed algorithm results are compared with the results of authors in [12] and [13], this is why we have chosen the same desire beampattern as of the [13]. The proposed approaches for the beampattern matching problem are compared with two approaches, namely, covariance-based pattern design in uniform and linear array [12] and iterative based algorithm in non-uniform linear array [13], in which the covariance matrix is synthesized based on the deviation error with a desire beampattern. Obviously, an improved performance is achieved by the proposed algorithm via transmitting more power in the main-lobes region and the sidelobes ripple is virtually zero in all the out-main-lobe region compare to uniform array and also our proposed algorithm has almost the same result as a non-uniform array which is a good performance because non-uniform array has a one more degree of freedom.

Fig. 3 shows the performance of the proposed approach together with the techniques in [12] and [13], when the desired beampattern is non-symmetric. It is seen that the [12] approach provides worse performance compared to the proposed approaches. This provides relatively low power levels in the main-lobe with high ripple levels in the side-lobes. As a matter of fact, the [12] based approach failed to accurately design the desired beampatterns. But on the other hand the IWLS approach provides an excellent performance in designing an arbitrary beampattern in terms of high in-main-lobe power level and relatively very low in-side-lobe ripple level and it is seen that the results of this proposed algorithm is very close to that of the [13] which is a non-uniform iterative algorithm. It should mention that, the more the number of antennas in the array, the more will be the convergence time required by the IWLS-based approach.

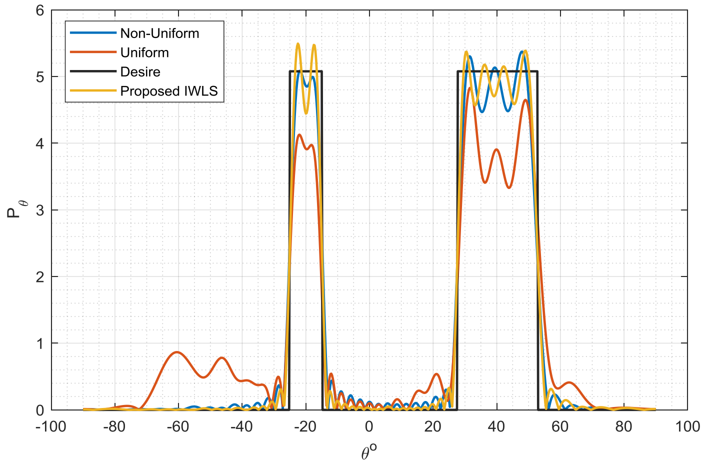

Fig. 2. Beampattern Design With N=20 Antennas

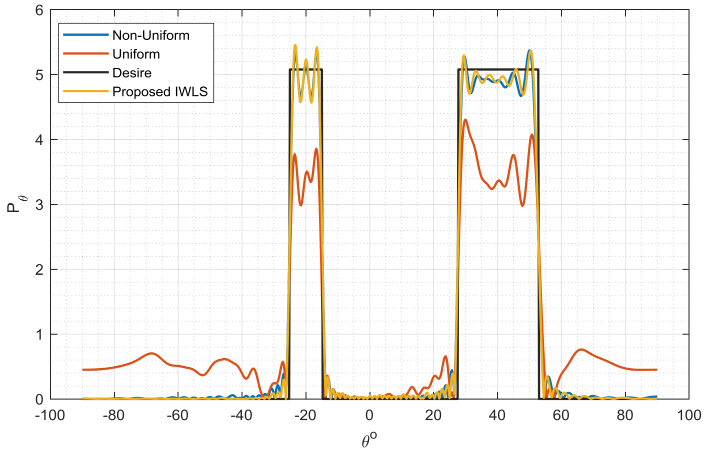

Fig. 3. Beampattern Design With N=35 Antennas

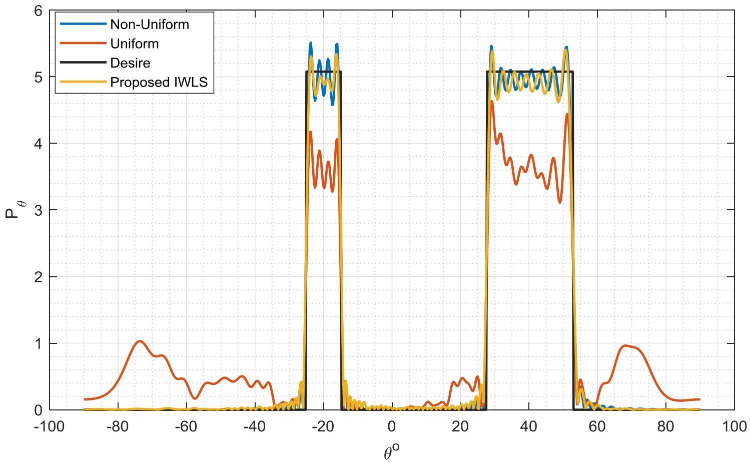

Fig. 4. Beampattern Design With N=50 Antennas

V. Conclusion

An exceptional performance algorithm has been presented for the development of beampatterns in MIMO communication systems, showcasing its remarkable synthesis capabilities. The excellence of this algorithm becomes evident especially when dealing with a large number of array elements. Moreover, the suggested algorithms outperform the approaches introduced in [12] and exhibit a strikingly similar outcome to [13] when handling arbitrary beampatterns associated with users' locations. The simulation results undeniably validate the efficiency of the proposed algorithm in synthesizing the covariance matrix of desired beampattern waveforms.

REFERENCES

[1] J. Li and P. Stoica, "MIMO Radar with Colocated Antennas," in IEEE Signal Processing Magazine, vol. 24, no. 5, pp. 106-114, Sept. 2007, doi: 10.1109/MSP.2007.904812.

[2] A. Roshanzamir and M. H. Bastani, "Advantages of MIMO waveform in sidelobe blanker system," 2012 IEEE International Conference on Electronics Design, Systems and Applications (ICEDSA), Kuala Lumpur, Malaysia, 2012, pp. 244-247, doi: 10.1109/ICEDSA.2012.6507807.

[3] C. -Y. Chen and P. P. Vaidyanathan, "MIMO Radar Space–Time Adaptive Processing Using Prolate Spheroidal Wave Functions," in IEEE Transactions on Signal Processing, vol. 56, no. 2, pp. 623-635, Feb. 2008, doi: 10.1109/TSP.2007.907917.

[4] V. F. Mecca, D. Ramakrishnan and J. L. Krolik, "MIMO Radar Space-Time Adaptive Processing for Multipath Clutter Mitigation," Fourth IEEE Workshop on Sensor Array and Multichannel Processing, 2006., Waltham, MA, USA, 2006, pp. 249-253, doi: 10.1109/SAM.2006.1706131.

[5] J. Li, P. Stoica, L. Xu and W. Roberts, "On Parameter Identifiability of MIMO Radar," in IEEE Signal Processing Letters, vol. 14, no. 12, pp. 968-971, Dec. 2007, doi: 10.1109/LSP.2007.905051.

[6] D. R. Fuhrmann and G. San Antonio, "Transmit beamforming for MIMO radar systems using partial signal correlation," Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers, 2004., Pacific Grove, CA, USA, 2004, pp. 295-299 Vol.1, doi: 10.1109/ACSSC.2004.1399140.

[7] P. Stoica, J. Li and Y. Xie, "On Probing Signal Design For MIMO Radar," in IEEE Transactions on Signal Processing, vol. 55, no. 8, pp. 4151-4161, Aug. 2007, doi: 10.1109/TSP.2007.894398.

[8] D. R. Fuhrmann and G. San Antonio, "Transmit beamforming for MIMO radar systems using signal cross-correlation," in IEEE Transactions on Aerospace and Electronic Systems, vol. 44, no. 1, pp. 171-186, January 2008, doi: 10.1109/TAES.2008.4516997.

[9] J. Li, L. Xu, P. Stoica, K. W. Forsythe and D. W. Bliss, "Range Compression and Waveform Optimization for MIMO Radar: A CramÉr–Rao Bound Based Study," in IEEE Transactions on Signal Processing, vol. 56, no. 1, pp. 218-232, Jan. 2008, doi: 10.1109/TSP.2007.901653.

[10] P. Stoica, J. Li and X. Zhu, "Waveform Synthesis for Diversity-Based Transmit Beampattern Design," in IEEE Transactions on Signal Processing, vol. 56, no. 6, pp. 2593-2598, June 2008, doi: 10.1109/TSP.2007.916139.

[11] A. Roshanzamir, M. H. Bastani and M. Roshanzamir, "Analysing of 3D beamforming in MIMO radars," 2012 World Congress on Information and Communication Technologies, Trivandrum, India, 2012, pp. 745-749, doi: 10.1109/WICT.2012.6409173.

[12] Roshanzamir, Amirsadegh. "Analysing of 3D MIMO Communication Beamforming in Linear and Planar Arrays." arXiv preprint arXiv:2310.08614 (2023).

[13] Roshanzamir, Amirsadegh. " Beampattern Design in Non-Uniform MIMO Communication " arXiv preprint arXiv:2310.17201 (2023).

[14] Michael Grant and Stephen Boyd, “CVX: Matlab software for disciplined convex programming,” version 2.2 http://cvxr.com/cvx, January 2020.