Interference Control in the Coexistence of Radar and Communications Systems

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***Abstract*—A new method is proposed to control the generated interference between coexistent MIMO radar and MIMO cellular base-station. This new method is based on a subspace expansion using the polynomial method. The polynomial method is more flexible in controlling generated interference compared to the previous methods mentioned in literature. This method, with some modifications can be used as a general control method in any MIMO based system. It is a useful tool to improve the ratio of generated interference to radar performance.**

Keywords- . *Spectrum sharing and coexistence, interference control, MIMO radar, objective subspace expansion.*

I. Introduction

The free available radio frequency spectrum is a scarce resource due to the large number of current applications. The emerging technologies, such as broadband mobile applications, require more spectrum to meet the demands of their users. It is expected that 5G will attain data rates that exceed 1 Gbps. This high data rate will need a larger bandwidth compared to those currently available.

The Federal Communication Council (FCC) and the National Telecommunication and Information Administration (NTIA) are the two main organizations in the USA who regulate and organize the RF spectrum usage for both the federal and private sectors. Currently, the FCC and NTIA are working to make approximately 500 MHz available by the year 2020 [1]. This 500 MHz is intended to be used mainly by wireless broadband applications such as the 4G/5G systems. NTIA did some field measurements to address the spectrum occupancy in the maritime radar working at $3.55 - 3.65$ GHz frequency band near San Diego, and found that the spectrum was idle with no radar activity for 40 percent of time during weekdays. The NTIA report indicates that the spectrum used by radar is underutilized and sharing the spectrum with radar systems could be a solution to make better use of the spectrum available [2].

One of the main challenges associated with spectrum sharing is being able to control the interference visibility by the two sharing systems. Controlling the interference within a time-varying environment would require intelligent systems such as cognitive radios (CR), which are equipped with learning and cognitive capabilities [3][4]. Such intelligent systems require a flexible platform that translates their decisions into actual radio operations. In this paper, we propose such a flexible platform. The developed platform controls the generated interference by MIMO radar and that received by the cellular base-station. This control method is based on a subspace expansion using a polynomial method. We have found that the proposed polynomial method could tune the generated interference to any desired threshold.

A. Paper Organization

This paper is organized as follows. In section II, we describe the system model for both the communication system and MIMO radar. In section III, we illustrate the main problem as well as the associated challenges in the coexistence problem. In section IV, we review the previous solutions proposed in literature and present our solution. We also compare the method, capabilities, and limitations. In section V, we analyze our proposed method and explain how it can be used. Section VI explains the related simulation results, and proves the flexibility of the proposed method. In section VII, we discuss the recommendations and present some insights on how to use the method as a general control platform for any MIMO working system. We conclude this work in section VIII.

B. Notations

Upper case letter P indicates a matrix and lower case letter with bar $\bar{x}$ indicates a vector. The $(*)$ in s^* indicates the conjugate transpose (Hermitian) operation. The (T) in P^T indicates the transpose operation. The (.) in $(H_{eq}).^{\beta}$ indicates an element wise operation.

II. System Model

The system model consists mainly of two systems sharing a common spectrum. The first one is a co-located MIMO radar that detects and tracks targets, while the second one is a MIMO cellular base-station that serves a number of single antenna mobile users. The channel between the radar and the communication system is assumed to be a block-fading channel. In addition, we assume that the two systems cooperate with each other to estimate the MIMO channel between them. First, we present each system model individually, and later present the coexistence model in section III.

A. Communication System Model

The communication system consists of one base-station that communicates with a set of mobile stations, as in Fig.(1). This base-station is equipped with M_t and M_r transmit-and-receive antennas, respectively. It also has pre-coder and post-processor modules at its transmitter and receiver. The channel between the base-station and the communication users is assumed to be a block-fading reciprocal channel.
We assume that the base-station, initially, configures its own pre-coder P_B and post-processor F_B to maintain strong communication with users in terms of throughput and quality of service (QoS). Let $U = \{1, 2, \cdots, K\}$ denotes the indexes of users and $\bar{z} = [z_1, z_2, \cdots, z_k]^T$ denotes their collective transmission vector. The

post-processed received vector by the base-station is defined as follows:

$$\bar{y} = F_B(H_{RX}\bar{z} + \bar{w}) \tag{1}$$

where, $\bar{y}$ is the received vector, F_B is the base-station post-processor matrix, H_{RX} is the reciprocal flat fading MIMO channel between users and the base-station, and $\bar{w}$ is the received additive white Gaussian noise (AWGN). It should be noted that the base-station configures its post-processor F_B matrix to maintain strong communication with its connected users in terms of throughput and quality of service (QoS). The F_B matrix could be considered as an indication of the communication system environment. The rank of the post-processor F_B matrix relates to the number of users K and we denote it here as the degree of freedom (DoF) in the communication system side.

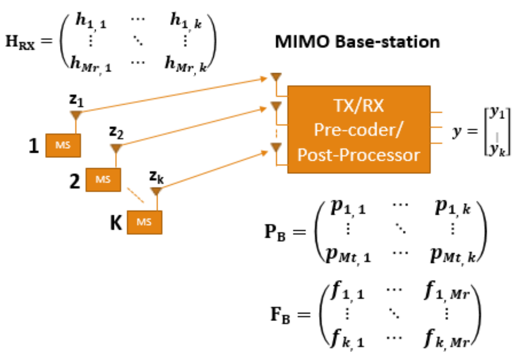

Fig. 1. Communication system model ($M_t = M_r$)

B. MIMO Radar Model

The MIMO radar consists of an array of co-located N_t and N_r transmit and receive antennas. In Fig.(2) the radar transmit-array consists of N_t equally spaced antenna elements. In addition, the whole antenna-array is oriented with ϕ angle. We are using the MIMO radar model posted in [5][6]. The main objective of radar is to be able to estimate the target's information such as the target's direction of arrival (DOA), represented by θ_o, and the target's range R_o. The relationship between the transmitted signal and received echos depends on both radar antenna array configurations, $\{N_t, N_r, \phi, d\}$, and target's information $\{R_o, \theta_o\}$.

We will first explain briefly how MIMO radar works and then model the radar performance mathematically. Later we will use this model to quantify the radar's performance while we control the interference between the coexistent systems. Radar sends a set of probing signals $\bar{s} = \{s_i\}_{i=1}^{N_t}$ as in Fig.(3) and collects received echoes $\bar{r} = \{r_i\}_{i=1}^{N_r}$. Transmitted signals could be specified as follows:

$$\bar{s}[n] = P_R \cdot \bar{x}_R[n] \tag{2}$$

where P_R is the radar pre-coder matrix, $\bar{x}_R = [x_1, \cdots, x_{N_t}]^T$ is the radar probing vector and n is the time frame index. Received echoes vector $\bar{r} = [r_1, r_2, \cdots, r_{N_r}]^T$ could be formulated such that each received echo is:

$$r_j[n] = \alpha \sum_{i=1}^{Nt} A_{ij}(\theta_o)s_i[n] + w_j[n], \;\; j = 1, \cdots, N_r \tag{3}$$

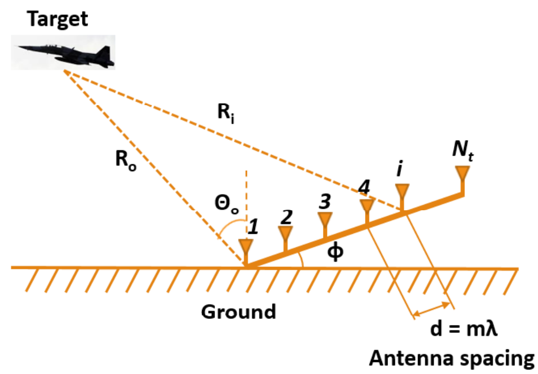

Fig. 2. MIMO radar antenna array ($N_t = N_r$)

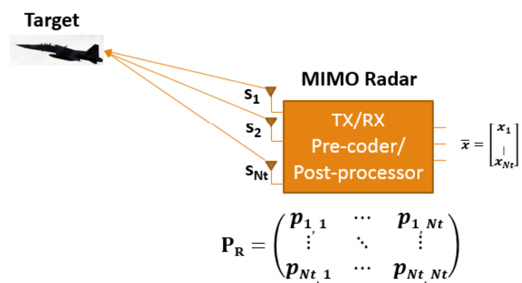

Fig. 3. MIMO radar model ($N_t = N_r$)

where, r_j is the received signal by antenna element j, i spans all transmit antennas, α accounts for attenuation that both transmitted signal and reflected echo suffer, w_j corresponds to the received AWGN noise of zeros mean and unity variance. Finally, $A_{ij}(\theta)$ corresponds to the phase shift that the transmitted signal suffers, starting from antenna i till it echoes back and is received by the antenna element j.

A_{ij} can be written as a product of two phase shift components $A_{ij}(\theta) = a_{i,t}(\theta).a_{t,j}(\theta)$, where both of components could be defined as follows: $a_{i,t}(\theta) = \exp(-jw_c\tau_{i,t}(\theta))$ and $a_{t,j}(\theta) = \exp(-jw_c\tau_{t,j}(\theta))$, where w_c is the operating angular frequency, $\tau_{i,t}$ is the time delay from the transmitting antenna i to the target, and $\tau_{t,j}$ is the time delay from the target to the receiving antenna j. These time delays can be derived as a function of $\{R_o, \theta_o, d, \phi\}$, and can be expressed simply by applying the law of cosines to the model as shown in Fig.(2).

The main purpose of presenting the previous model is to expose how radar performs. We are mainly interested in measuring the radar's ability to estimate the target's DOA angle. The main parameter that controls the MIMO radar performance is its transmission coherence matrix, defined as follows [6]:

$$R_s = \frac{1}{N_t} \cdot \sum_{n=1}^{N_t} \bar{s}[n]\bar{s}^*[n] \tag{4}$$

where the index n stands for the time frame index. We drop the time index in our analysis in this paper. Authors in [6] derive target DOA estimation error as a cramer rao bound (CRB) as follows:

$$CRB(\theta) = \frac{1}{2SNR}(N_t \dot{\mathbf{a_t}}^*(\theta)\mathbf{R_s}^T\dot{\mathbf{a_t}}(\theta) \\ +\mathbf{a_t}^*(\theta)R_s^T\mathbf{a_t}(\theta)||\dot{\mathbf{a_r}}(\theta)||^2 - \frac{N_t|\mathbf{a_t}^*(\theta)R_s^T\dot{\mathbf{a_t}}(\theta)|^2}{\mathbf{a_t}^*(\theta)R_s^T\mathbf{a_t}(\theta)})^{-1} \tag{5}$$

where SNR is the radar signal to noise ratio, $\mathbf{a_t}(\theta) = [a_{1,t}(\theta)a_{2,t}(\theta)\cdots a_{N_t,t}(\theta)]^T$, $\mathbf{a_r}(\theta) = [a_{t,1}(\theta)a_{t,2}(\theta)\cdots a_{t,N_r}(\theta)]^T$, $\dot{\mathbf{a_t}}(\theta)$ is simply the derivative of $\dot{\mathbf{a_t}}$ with respect to the angle θ.

Remark: It should be noted that strong radar's performance is satisfied when the its transmission coherence-matrix R_s is of a full rank (i.e. radar transmission is fully independent). This is guaranteed when R_s is the identity matrix and this is represented as:

$$Rs = \sum_{n=1}^{N_t} \bar{s}[n]\bar{s}^*[n] = P_R P_R^* = I_{N_t} \tag{6}$$

The configurations of P_R matrix controls R_s matrix, which controls the radar performance.

III. Problem Description and Challenges

The main goal we aim to satisfy in this work is to control the interference to make the coexistence between radar and the communication system successful, which will result in efficient spectrum usage. Nulling the interference completely in MIMO based systems can be achieved by zero forcing, as we will see in the next section. However, this interference nulling degrades the radar's performance. Radar becomes less accurate in estimating the target's DOA. This degradation can be improved by relaxing the interference nulling requirement. The question is if there is a flexible tool to relax this requirement in an efficient manner that guarantees the optimal harnessing of the available spectrum resources. The answer is yes.

A. Radar and Communication Coexistence Model

In this model we assume that the base-station and MIMO radar are sharing a common spectrum band. More precisely, the two systems transmit in the same spectrum band. We consider one aspect of the problem where the base-station operates normally and the MIMO radar adapts its operation in order to reduce the generated interference, as in Fig(4). The MIMO radar adaptively configures its pre-coder settings so that the interference seen by the base-station remains below a certain threshold.

The received interference seen by the base-station receiver is modeled mathematically as follows:

$$\bar{y}_{BR} = F_B H_{BR} P_R \bar{x}_R \tag{7}$$

where, $\bar{y}_{BR}$ is the interference vector generated by the radar and received by the base-station, F_B is the base-station post-processor matrix, H_{BR} is the MIMO channel matrix between the base-station and the radar. We assume that the H_{BR} is a block-fading reciprocal channel. Adding (7) to (1) results in:

$$\bar{y} = F_B(\bar{H}_{RX}\bar{z} + \bar{W}) + \underbrace{F_B H_{BR} P_R \bar{x}_R}_{\bar{y}_{BR}} \tag{8}$$

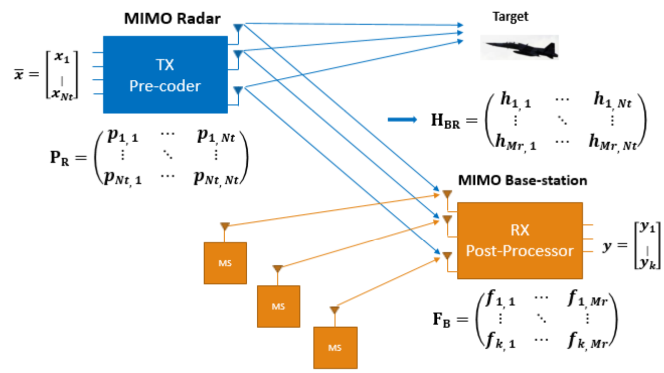

Fig. 4. Coexistence model

B. Associated Challenges

In order to control the generated interference y_{BR} in (8) we should first understand the main parameters that control interference y_{BR}. As we have seen in (8) the interference is a function of H_{BR}, F_B, P_R, and $\bar{x}_R$. We cannot control the generated interference using either of H_{BR}, F_B, or $\bar{x}_R$ due to the following challenges:

- H_{BR} is the channel matrix between the two coexistent systems and cannot be changed or modified since it is dependent on scatterers and terrains.
- F_B is the post-processor matrix that was configured previously to maintain a strong link between the base-station and its connected users. Modifying F_B would affect communication system performance. It should be noted also that the base-station would change F_B according to changes that happen to the H_{RX} channel matrix.
- $\bar{x}_R$ is the probing signal at the radar side and controls the amount of power transmitted by radar. Notice that by controlling $\bar{x}_R$ we can control the generated interference y_{BR}, but this will reduce the radar's capability to detect the target's range R_o. Hence, $\bar{x}_R$, as a control parameter should be avoided.

P_R is the only control parameter that we can configure to control the generated interference y_{BR}. Since H_{BR} and F_B are fixed parameters that are out of control, then P_R should be configured according to them. The main challenge is in configuring the radar pre-coder matrix P_R in a flexible and amenable manner so that the generated interference y_{BR} is equal to a certain threshold D, given certain H_{BR} and F_B matrices.

IV. Proposed Solutions

Controlling the generated interference y_{BR} could be approached as radar pre-coder design problem. There is literature that explains how to null the interference completely in the MIMO environment [7]. Other literature explains how to control the generated interference based on the subspace expansion method [8][9]. The latter method can control the generated interference y_{BR} according to a limited number of levels that are dependent on the number of singular values in the $F_B H_{BR}$ matrix product. In this work we propose a modified subspace expansion method that can control the generated interference according to any requested level. First we review the zero forcing

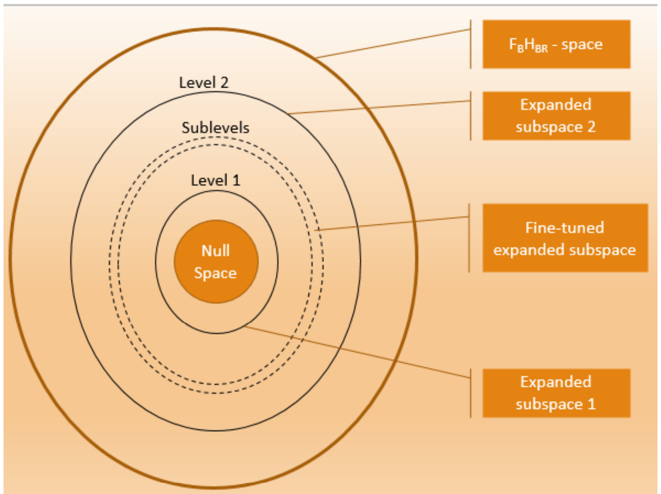

Fig. 5. Subspace expansion

and subspace expansion techniques, and then we explain the newly developed method.

A. Interference Nulling Using Zero Forcing

Canceling the generated interference y_{BR} completely could be achieved by configuring the pre-coder matrix to be a projection into the null-space of the F_BH_{BR} matrix product, as noted in section 2.5-6 in [10]. First, take the singular value decomposition (SVD) of the F_BH_{BR} matrix product as follows:

$$F_BH_{BR} = U\Sigma V^T \tag{9}$$

Next, partition the left and right matrices U and V^T in the last equation based on the number of singular values $\{\sigma_1, \cdots, \sigma_r\}$ in Σ as follows:

$$U\Sigma V^T = [U_r\tilde{U}_r]\begin{bmatrix} \sigma_1 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & \cdots & \sigma_r & \cdots & 0 \\ \vdots & \vdots & \cdots & 0 & \cdots & 0 \end{bmatrix}[V_r\tilde{V}_r]^T \tag{10}$$

The column vectors at $\tilde{V}_r$ are orthonormal bases that span the null space of the F_BH_{BR} matrix product. By using the columns in $\tilde{V}_r$ matrix, the pro-coder P_R matrix can be configured as a projection into the null space of F_BH_{BR} matrix product by using the following formula:

$$P_R = \tilde{V}_r(\tilde{V}_r^*\tilde{V}_r)^{-1}\tilde{V}_r^* \tag{11}$$

The pre-coder defined using the previous equation (11) generates zero interference y_B. This can be visualized graphically using Fig.(5). However, such interference cancellation results in changing the radar pre-coder matrix P_R, and this will affect the coherence matrix R_s, as in (6). This results in degraded radar performance, as we will see in simulation results section. To reduce these effects, the authors in [7][8] suggested a subspace expansion where the pre-coder matrix P_R is the projection on an expanded subspace. This expanded subspace contains the null-space of F_BH_{BR} matrix product, as we will discuss in the next subsection.

B. Interference Control Using Subspace Expansion Based on Singular Values

In this method [8][9], the pre-coder matrix is defined as in (11), except that $\tilde{V}_r$ is constructed by augmenting additional columns from the adjacent V_r submatrix in (9), as follows:

$$\tilde{V}_r = \begin{bmatrix} \underbrace{v_{r-j}\cdots v_r}_{augmented\ col's} & \vdots\tilde{V}_r \end{bmatrix} \tag{12}$$

This violates projecting P_R into the null space of F_BH_{BR} matrix-product and generates more interference y_B. Each additional augmented column will contribute to one of the levels shown in Fig.(5). There are up to r control levels, where r is the number of singular values in the F_BH_{BR} matrix product. This pre-coder configuration enhances radar performance and generates more interference compared in the zero forcing method. In practice, base-station receivers can tolerate a certain level of interference y_B. This method is limited to the number of interference levels that can be achieved, which results in a sub-optimal interference control in the coexistence between radar and communication.

C. Interference Control Using Subspace Expansion Based on Polynomial Series

In this method, we design the pre-coder in a similar fashion as in the previous subsections, except that we apply the SVD to a polynomial series of the F_BH_{BR} matrix product. First, denote F_BH_{BR} as $\bar{H}_{eq} = F_BH_{BR}$ and define $\bar{H}_{poly}$ as follows:

$$\bar{H}_{poly} = \alpha_1(\bar{H}_{eq}).^{\beta_1} + \alpha_2(\bar{H}_{eq}).^{\beta_2} + \cdots + \alpha_n(\bar{H}_{eq}).^{\beta_n}$$
$$\bar{H}_{poly} = \begin{bmatrix} \alpha_1 h_{eq11}^{\beta_1} + \cdots + \alpha_n h_{eq11}^{\beta_n} & \cdots \\ \vdots & \ddots \end{bmatrix} \tag{13}$$

Next, decompose $\bar{H}_{poly}$ using SVD as follows:

$$\bar{H}_{poly} = [U_r\tilde{U}_r] \quad \Sigma \quad [V_r\tilde{V}_r]^T \tag{14}$$

$$\bar{H}_{poly} = [U_r\tilde{U}_r]\begin{bmatrix} \Sigma_r & \vdots & 0 \\ \cdots & \cdot & \cdots \\ 0 & \vdots & 0 \end{bmatrix}[V_r\tilde{V}_r]^T \tag{15}$$

Finally, construct the pre-coder matrix P_R as we did in (11):

$$P_R = \tilde{V}_r(\tilde{V}_r^*\tilde{V}_r)^{-1}\tilde{V}_r^* \tag{16}$$

It should be noted that polynomial coefficients $\alpha_i's$ and polynomial degrees $\beta_i's$ are the two main parameters that control the subspace expansion in Fig.(5) and hence these parameters control the generated interference.

V. Design Analysis

In this section we analyze the behavior of the polynomial-based subspace expansion method. It is important to understand how this method behaves for various polynomial coefficients $\alpha's$ and degrees $\beta's$ in order to select the format with lowest computational complexity. Every polynomial format has different capabilities in terms of controlling the generated interference. Let us first examine various polynomial format behaviors, compare their performances, and state the recommended format.

A. Polynomial Behavior and Format Selection

In order to investigate how various formats behave, we have simulated the received interference y_{BR} as a function of one coefficient α for various polynomial degrees $\beta's$. The interference received by the communication base-station can be quantified as a Frobenius norm $||\cdot||_F$ as follows [8]:

$$y_{BR} = ||F_B H_{BR} P_R||_F \tag{17}$$

Fig.(6) shows the behavior of some polynomial formats. We call these curves *interference profile curves*. We are interested in selecting a proper polynomial format that has not only a suitable range but also with low complexity. Considering the second order power and/or root is enough to match any interference threshold level, as in Fig.(8). Selecting $\{\beta = 1, 2\}$ results in a relatively low computational design that would save battery life and make this design suitable for mobile applications. The recommended polynomial format is:

$$\begin{gathered} H_{poly} = \alpha_1 H_{eq} + \alpha_2 (H_{eq}).^{\beta} \\ \alpha_{1,2} \in [-15, 15] \\ \beta = 2 \end{gathered} \tag{18}$$

These recommended values are based on statistical experiments through simulation. We have used an optimization tool for selecting the proper polynomial degrees $\beta's$ for various interference thresholds. The optimization tool, based on a mixed-integer genetic algorithm [12], selected $\beta = \{-1, 1, 2\}$ for more than 85 percent when compared with other polynomials. Fig.(7) shows one example of such analysis where we have run the optimization tool $5,000$ times for a certain interference level.

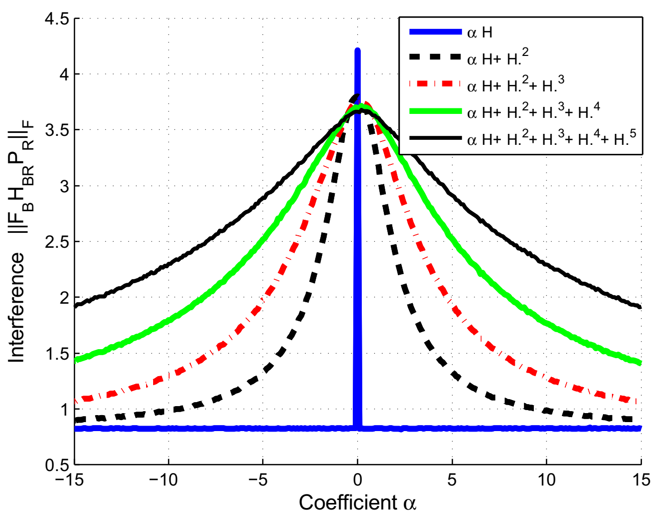

Fig. 6. Interference for various polynomial formats

B. Pre-coder Design Algorithm for Interference Control

We have showed various polynomial behaviors and the recommended polynomial formats. Now, we will illustrate how this polynomial-based method could be used to control the generated interference in the radar side. To control generated interference we first formulate the pre-coder design as an optimization problem where we optimize the α and β values that result in the desired interference

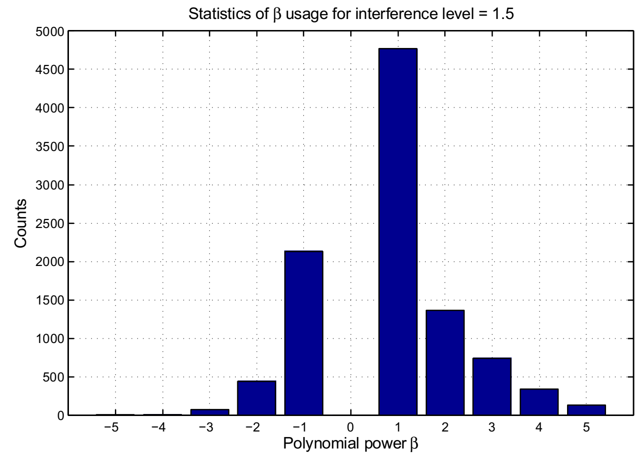

Fig. 7. Statistics for selecting β degrees for interference level $= 1.5$

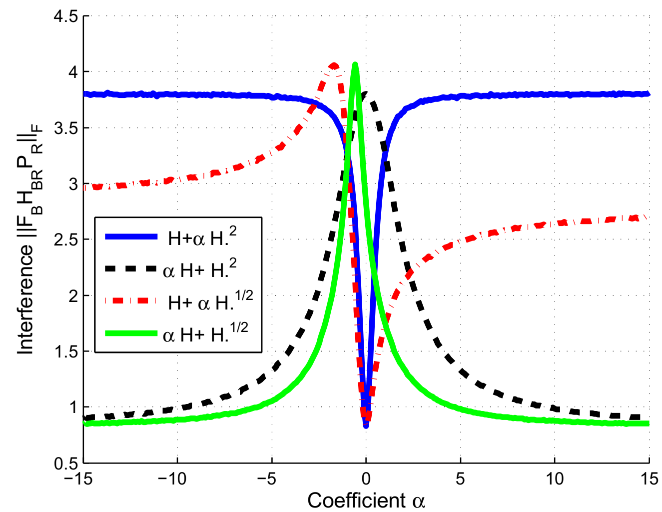

Fig. 8. Interference for polynomial with degrees $\beta = \{2, 1/2\}$

threshold D, as follows:

$$\underbrace{arg}_{\alpha's,\beta's} \min |D - ||F_B H_{BR} P_R||_F| \tag{19}$$

where, $\alpha's$ and $\beta's$ are embedded in P_R as described in (13)-(16). The problem in (19) above is a multi-variable non-linear optimization problem. Algorithms can be researched to solve this problem. Algorithm 1 shows how a radar pre-coder can be configured recursively to constrain its generated interference according to a maximum allowed interference threshold, D.

VI. Simulation Results

Here we show two main results that prove the ability of the proposed method to work as a flexible tool that trades off radar and communication system performance. Main simulation parameters are posted in Table 1.

Algorithm 1 MIMO pre-coder design algorithm

procedure ITERATIVE INTERFERENCE CONTROL
Inputs: D, $H_{eq} = F_B H_{BR}$
Outputs: P_R
Decide design objective(s): Control generated interference.
Select polynomial format: $H_{poly} = \alpha_1 H_{eq} + \alpha_2 (H_{eq}).^{\beta}$
Optimize parameters $\alpha_1,\ \alpha_2,\ \beta$
$* \underbrace{arg}_{\alpha_{1,2},\beta} \min |D - ||F_B H_{BR} P_R||_F|$
Design pre-coder $\mathbf{P}_R$
$\quad H_{poly} = \left[U_r \vdots \tilde{U}_r\right] \Sigma \left[V_r \vdots \tilde{V}_r\right]$ (SVD)
$\quad P_R = \tilde{V}_r(\tilde{V}_r^* \tilde{V}_r)^{-1} \tilde{V}_r^*$ (Projection)
Channel changes
$\quad$ loop to Inputs

A. Communication System Performance

The performance of a communication system is evaluated based on the received interference that is quantified as a frobenious norm $||F_B H_{BR} P_R||_F$. Fig(9) shows that changing the polynomial coefficient α controls the interference seen by the communication system. The y-axis represents the interference seen by the base-station. The x-axis represents the degree of freedom DoF in the communication system side. Recall that DoF relates to the MIMO channel between users and the cellular base-station.

TABLE I. SIMULATION PARAMETERS

Simulation Parameter	
Channel Type	Block-fading
Base-station MIMO M_tx M_r	$8x8$
MIMO radar N_tx N_r	$8x8$
Target Angle θ_o	30^o
Radar MIMO antenna array orientation ϕ	45^o
Radar antenna separation d	$3/4 * \lambda$
Target Range R_o	$10\ km$
Radar SNR	$20\ db$
frequency f_c	$3.5\ GHz$

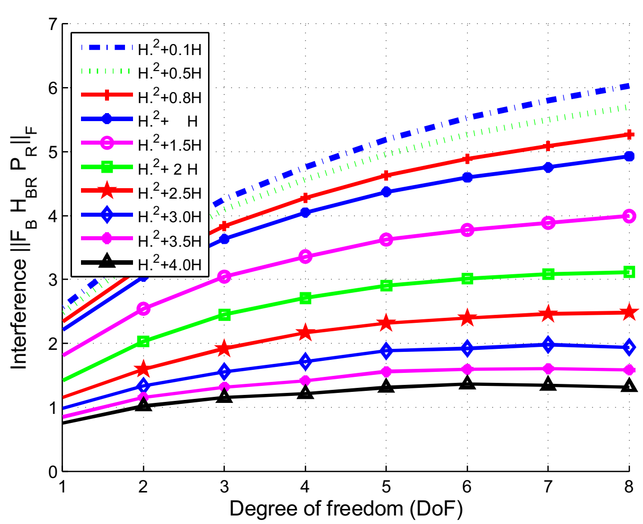

Fig. 9. Received interference by communication base-station

B. Radar Performance Results

Radar performance is quantified in terms of its ability to estimate a target's DOA. Fig.(10) shows how changing the polynomial coefficient α, would affect the accuracy in estimating target's DOA. The y-axis represents the target's DOA estimation error quantified by the CRB, defined in (5). The x-axis represents the DoF in the communication system side. The lowest estimation error occurs when the radar-coherence matrix R_s is an identity matrix, as explained in (6). The horizontal black line represents the lowest estimation error. As radar coexists with communication system, its estimation error increases as shown in the same figure. The polynomials investigated in Fig.(10) are the same as those shown in Fig.(9). Increasing the polynomial coefficient α, would reduce the generated interference, but increase the target's DOA estimation error.

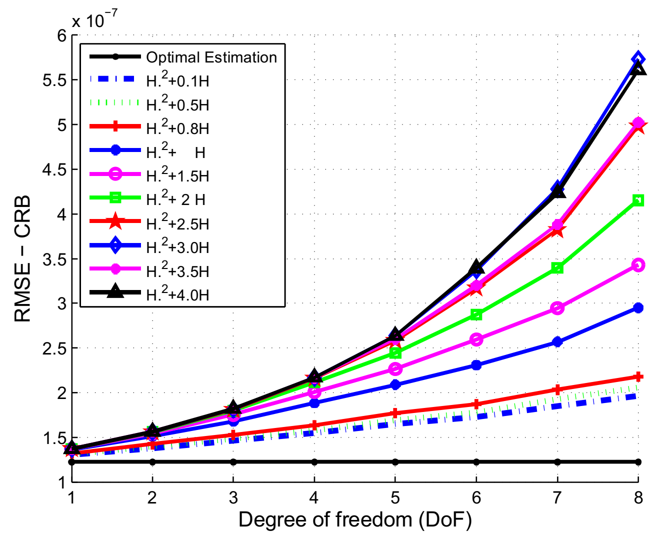

Fig. 10. Target's angle estimation error

C. Interference Control is Difficult in Co-existence Problems

Results of the last two subsections indicate that the proposed polynomial method is a flexible method that matches any interference level, as well as any target's DOA estimation error. This method could be helpful as an underlying tool that serves any upper-layer entity that determines the the maximum allowed interference thresholds in a coexistence scenario. This proposed method optimizes the available resources and ensures that radar's operation is sub-optimized under the given constraints. The previous upper-layer entity could run a game-theoretic based mechanism that addresses the maximum interference threshold. The power of this method is in the fine resolution control parameters it provides (i.e. $\alpha' s,\ \beta' s$).

VII. DISCUSSION

In this section there are illustrations showing how the developed interference control method can be useful tool in any MIMO based system. First, we present a general platform and describe its main parts and how they interact with each other. Next, we describe some future research that can be applied to the polynomial method

A. The General Platform

The interference control method proposed in this paper can be used as a general adaptive control method that works with any MIMO system. The only difficulty is to re-formulate the optimization problem stated in (19) to match the requested objective(s). The space and subspace expansion illustrated in Fig.(5) could be considered depending on the nature of the system and the operational design objectives.

In Fig.(11) we propose a general platform for optimal pre-coder design that satisfies multi-operational objectives in MIMO-based systems. The platform consists of three main components: the intelligent controller, the multi-objective optimization tool, and recommended polynomial formats data base (experience DB). The platform has two inputs: the feedback coming from the environment and the recommended operational objectives provided by the decision machine. The final platform output is the pre-coder (or) post-processor configurations P.

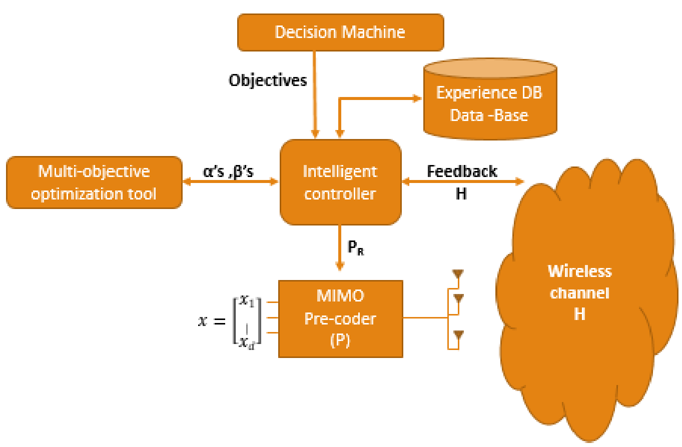

Fig. 11. General platform for adaptive pre-coder design

This platform works as follows. The intelligent controller receives decisions from the decision machine about recommended operational objectives, such as: the maximum allowed interference threshold. Next, the intelligent controller examines the channel status H and compares that with the previous experience, and selects the proper polynomial format from its polynomial formats data base. Finally, the intelligent controller uses the multi-objective optimization tool to find the proper control parameters $\alpha' s$, $\beta' s$, and accordingly constructs the pre-coder configurations P, as noted in (13)-(16).

In the coexistence problem between MIMO radar and a communication system, blocks in Fig.(11) operate as follows:

- The decision machine could be the module that runs a game-theoretic based mechanism that coordinates the operation between the radar and the communication system. The decision machine passes down the recommended operational objectives to the intelligent controller. These objectives could be the maximum tolerable interference threshold in (17), or the maximum tolerable target's DOA estimation error, as defined in (5).
- The experience DB contains the recommended polynomial formats for the desired operational objectives.
- The multi-objective optimization tool optimizes the $\alpha' s$ and $\beta' s$ values.
- The intelligent controller is the core unit that coordinates everything. It receives feedback from the MIMO channel H and configures the radar pre-coder accordingly.

B. Recommendations and Further Research

As we have described, the proposed interference control method using a polynomial based subspace expansion can be a general control method that achieves multiple objectives. We have proved the effectiveness of the proposed method using simulation results with one objective only and we are currently working to provide a mathematical-based proof. The following are some proposed ideas for developing this method:

1) Hardware implementation and other applications: The proposed method will be applied to other applications and its efficiency will be evaluated as a general control method for MIMO based systems. Also, we are planning to implement the proposed method using a proper MIMO hardware platform.

2) Reducing complexity: There is room for enhancing the proposed method in terms of the associated computational complexity. There could be simpler ways to obtain the orthonormal bases vectors, as obtained in (15). There also could be simpler ways to apply the projection defined in (16).

3) Optimization and searching method: The optimization noted here is based on a mixed-integer genetic algorithm. There could be better optimization tools that require less computation. Shapes and characteristics of the objective profile curves shown in Fig.(6) and (8) could be helpful in selecting better optimization tools.

4) Massive MIMO and 5G: Massive MIMO is expected to be one of the main trends in future 5G networks [11]. The general platform proposed in Fig.(11) could be a primary candidate to achieve multiple objectives. The proposed platform could be modified to be compatible with the 5G requirements.

5) MIMO radar with multiple objectives: The proposed platform in Fig.(11) could be deployed in MIMO radar to obtain an adaptive optimal radar design that achieves multiple objectives. For example, at a certain operational time a target's information, such as Doppler speed, could be more important than DOA and range. Radar tunes its pre-coder based on the requested target information. The proposed platform could be a flexible tool to translate these radar operations into practice.

VIII. Conclusion

We have presented a new interference control method for MIMO based systems. The proposed method controls the generated interference between two systems working on the same frequency band. It controls the generated interference in a flexible manner, and it is based on subspace expansion. The subspace expansion is achieved by considering a polynomial series of the channel matrix between the two coexistent systems. This method could be a useful tool in spectrum sharing between radar and communication systems. The proposed polynomial method could be enhanced and is still under development and research.

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