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行動合作網通之無線訊號與訊息處理技術研究--子計畫二：合作型感知通訊之機會式傳輸技術

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計畫主持人：馮智豪

計畫參與人員：此計畫無其他參與人員

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中文摘要： 在多天線干擾通道傳輸多仰賴精確的通道資訊，但因往往缺乏精準的通道資訊，穩健傳輸設計也與誤匹配模型的保守程度息息相關。以往的誤匹配模型不是過於保守（確定模型），就是被其分布函數及其參數所誤（隨機模型）。為了解決此問題，本研究計畫中提出使用確定型結構性誤匹配模型(SMM)使用在多天線干擾通道穩健傳輸設計。不同於以往的誤匹配模型，SMM 善加利用多天線干擾通道之統計相關矩陣中隱含的稀疏特性。在感知無線環境中的前置編碼設計，在本研究計畫中，不論是理論分析或是實驗數據，均顯示使用 SMM 時，較多的傳輸功率被分配給干擾通道中的稀疏元素上，因此，相較於傳統範數球誤匹配模型，在通訊鏈有較佳的通訊品質。

中文關鍵詞： 干擾迴避，感知無線電，多天線系統，前置編碼，非完美通道

英文摘要： Transmission over MIMO interference channel often relies on the use of robust precoder due to a lack of accurate channel state information, with performance often depending on the conservativeness of the mismatch model. Previously proposed mismatch models either have been deemed too conservative (deterministic models) or are prone to error due to inaccuracy in the pdf and corresponding parameters (stochastic models). A deterministic mismatch model, called \emph{structural mismatch model}, or SMM, is proposed herein in attempt to alleviate these problems. Different from all previously deterministic models, the SMM exploits the inherent sparse characteristics of MIMO interference channel in the form of the statistical correlation matrix. In the context of precoder design for cognitive radio systems, it is shown analytically and by simulation that the SMM enables the transmitter to allocate more transmission power to the sparse elements of the interfering (SU-Tx to PU) link so that performance in the communicating (SU-Tx to SU-Rx) link is enhanced compared to conventional norm ball mismatch model (NBMM).

英文關鍵詞： Interference avoidance, cognitive radio, MIMO, precoder, imperfect channels

Structural Mismatch Model for Robust Transmission in MIMO-CR Network

Principal Investigator: *Carrson C. Fung*

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Abstract

Transmission over MIMO interference channel often relies on the use of robust precoder due to a lack of accurate channel state information, with performance often depending on the conservativeness of the mismatch model. Previously proposed mismatch models either have been deemed too conservative (deterministic models) or are prone to error due to inaccuracy in the pdf and corresponding parameters (stochastic models). A deterministic mismatch model, called *structural mismatch model*, or SMM, is proposed herein in attempt to alleviate these problems. Different from all previously deterministic models, the SMM exploits the inherent sparse characteristics of MIMO interference channel in the form of the statistical correlation matrix. In the context of precoder design for cognitive radio systems, it is shown analytically and by simulation that the SMM enables the transmitter to allocate more transmission power to the sparse elements of the interfering (SU-Tx to PU) link so that performance in the communicating (SU-Tx to SU-Rx) link is enhanced compared to conventional norm ball mismatch model (NBMM).

Keywords

Interference avoidance, cognitive radio, MIMO, precoder, imperfect channels

I. Introduction

Multiple antennas have recently been exploited to enable efficient transmission over interference channel in the presence of inaccurate channel state information (CSI). This inaccuracy exists in the channel state information (CSI) of both the communicating and interfering link due to lack of estimation accuracy and handshaking. The MIMO interference channel (MIMO-IC) model can be applied to model a cognitive radio system when secondary users (SUs) and primary users (PUs) are allowed to transmit simultaneously but the transmission of the SUs are oblivious to the PUs. This is accomplished by constraining the transmit power at the SU transmitter (SU-Tx) toward the PUs so that the interference toward the PUs is unnoticeable. In this case, the communicating link in the MIMO-IC models the channel between the SU-Tx and SU receiver (SU-Rx) while interfering link models the channel between the SU-Tx and PU. However, performance of such system is hindered by inaccurate CSI between the SU-Tx and the PU, as well as SU-Tx and SU-Rx, but the channel estimation error in the former will be greater thus more detrimental to system performance. Although optimal channel learning time has been derived to maximize the accuracy of the CSI, the accuracy will undoubtedly be limited by the use of blind channel estimators.

Stochastic and deterministic mismatch models to model mismatch between the actual and estimated CSI have been incorporated in transmitter [1], [3]–[6], [8], [9] and transceiver [2], [7] designs to guard against performance loss caused by channel estimation noise. The stochastic model attempts to model the mismatch in the form of confidence level. In [1], the mismatch terms associated with the communicating and interfering links are assumed to be independent and identically complex Gaussian distributed and the transmit power toward the PUs are bounded using a probabilistic constraint. In [2], only the 1^{st} and 2^{nd} order statistics about the mismatch terms are assumed known a priori and that the mean of the transmit power toward the PUs are bounded. However, using the stochastic model requires the knowledge of the distribution function, or the first and/or second-order statistics of function of the channel estimate. The optimality of the design will be affected if the assumed pdf and/or corresponding parameters are incorrect or inaccurately estimated.

In contrast, the deterministic mismatch, or worst-case performance, model assumes a priori knowledge about the maximum error bound and model the error using norm ball. This shall be known hereafter as norm ball mismatch model or NBMM, which can be generalized to an ellipsoid by assuming a priori knowledge about the directionality of the mismatch. In the context of cognitive radio, the deterministic mismatch model has been applied to a wide array of designs, from single SU and PU robust precoder design [3], [4], multiple SUs and PUs robust precoder design [5], [6], robust precoder design for multicast signal transmission [8], [9], to robust transceiver design [2], [7]. Unfortunately, the error bound, i.e. radius of the norm ball, that is assumed to bound the energy of the mismatch is often chosen arbitrarily, thus affecting optimality of the design. By assuming the channel coefficients and estimation noise are jointly Gaussian, a closed-form equation for the error bound was given in [10] in which estimation of the Gaussian parameters are required.

Although the above (conventional) stochastic and deterministic models can account for the channel estimation error in the communicating and interfering links, they are not designed specifically to take advantage of the potential offered by the MIMO-IC. A deterministic mismatch model called the *structural mismatch model*, or SMM, is proposed herein for precoder design at the SU-Tx. The proposed model allows the secondary transmitter to utilize higher transmit power without violating the interference constraint placed at the PUs, resulting in enhanced performance for the SUs. This is achievable because the additional transmit power have been “absorbed”, or allocated, to the sparse elements in the interfering channel. The design problem aims to maximize the minimum receive

SNR with an average or instantaneous interference constraint of the PU. Even though the single SU scenario is considered in this project, the proposed model does not preclude the inclusion of multiple SUs, in which problem formulation and methodology similar to the ones considered in [6] can be used.

The SMM deals with channel uncertainty by exploiting the structural property, which translates into sparsity, of the statistical correlation matrix of the channel between the SU-Tx and the PUs. The structural property refers to the diagonal elements of the spatial correlation matrix which always equal 1. The amount of sparsity which can be exploited for precoder design in cognitive radio systems to attain higher performance compared to the use of the NBMM will be shown analytically to be equal to the number of transmit antennas at the SU-Tx times the number of receive antennas at the PU, i.e. $n_T n_P$.

The system model and design metric for the precoder design are given in Sec. II, followed by a complete exposition of the SMM and formulation of the precoder design problem using it in Sec. III. Simulation results are presented in Sec. IV and the paper is concluded in Sec. V.

Notations: Upper (lower) bold face letters indicate matrices (column vectors). Superscript ^{H} denotes Hermitian, ^{T} denotes transposition. $[\mathbf{A}]_{ij}$ denotes the $(i,j)^{th}$ element of $\mathbf{A}$. $\mathbb{E}[\cdot]$ stands for statistical expectation of the entity inside the square bracket. $\mathbf{A} \succ 0$ and $\mathbf{A} \succeq 0$ mean $\mathbf{A}$ is a positive definite and positive semidefinite matrix, respectively. $\mathbf{I}_N$ denotes an $N \times N$ identity matrix. Denote $\mathbf{1}_{M\times N}$ and $\mathbf{1}_M$ as an $M \times N$ matrix and $M \times 1$ vector, respectively, containing 1 in all of their entries. $\otimes$ and $\circ$ denote the Kronecker and Hadamard product, respectively. $vec(\cdot)$ is the vectorization operator. $tr(\mathbf{A})$ denotes the trace of the matrix $\mathbf{A}$. $\|\cdot\|_2$ and $\|\cdot\|_F$ denote ℓ_2 and Frobenius norm, respectively. $\Re(\cdot)$ denotes the real part of the argument. $\mathcal{R}(\mathbf{A})$ denotes the column space of $\mathbf{A}$. $\mathbb{S}_n$ denotes a set of $n \times n$ Hermitian symmetric matrices. $\lambda_{\max}(\mathbf{A})$ denotes the maximum eigenvalue of matrix $\mathbf{A}$. $\mathbb{R}_+$/$\mathbb{R}_-$ denotes a set of positive/negative real number. $|\mathcal{S}|$ denotes the cardinality of the set $\mathcal{S}$

II. System Model and Design Metric

A. System Model

Herein a single SU transmitter and receiver equipped with multiple antenna is considered. All PUs have n_P antennas while the SU-Tx and SU-Rx have n_T and n_R antennas, respectively. The channel between SU-Tx and SU-Rx, the so-called communicating link, is denoted as $\mathbf{H} \in \mathbb{C}^{n_R \times n_T}$ and the channel between SU-Tx and the k^{th} PU, the so-called interfering link, is denoted as $\mathbf{G}_k \in \mathbb{C}^{n_P \times n_T}$. Orthogonal space-time code (OSTBC) is used to encode the data signal vector $\mathbf{s} \in \mathbb{C}^{B\times 1}$ at the SU-Tx containing 4-QAM modulated symbol with equal probability and equal power, i.e. $|s_i|^2 = 1$. Therefore, the received signal matrix at the SU-Rx is $\mathbf{Y} = \mathbf{HFC}+\mathbf{N} \in \mathbb{C}^{n_R\times T}$, where $\mathbf{F} \in \mathbb{C}^{n_T\times B}$ is the precoder matrix, $\mathbf{C} \in \mathbb{C}^{B\times T}$ is an orthogonal space-time codeword matrix such that $\mathbf{CC}^H = T\mathbf{I}_B$, with T denoting the number of symbols encoded in time and B denoting the number of data streams during T, and $\mathbf{N} \in \mathbb{C}^{n_R \times T}$ is the noise matrix containing zero-mean, independent Gaussian distributed samples with known variance σ_n^2. It is assumed that the noise is uncorrelated with the data signal. Finally, a maximum likelihood (ML) decoder is employed at the SU-Rx to recover an estimate of the data signal $\widehat{\mathbf{s}} \in \mathbb{C}^{B \times 1}$.

B. Design Metric

Given that OSTBC encoding and ML decoding are used, the reliability of the SU link is evaluated by the symbol error rate (SER), which is inversely proportional to the receive SNR [10]

$$\mathrm{SNR}\left(\mathbf{\Delta}_H\right) = \frac{T}{\sigma_n^2} \left\|\mathbf{HF}\right\|_F^2 = \frac{T}{\sigma_n^2} \left\|\left(\widehat{\mathbf{H}} + \mathbf{\Delta}_H\right)\mathbf{F}\right\|_F^2, \tag{1}$$

where $\widehat{\mathbf{H}}$ and $\mathbf{\Delta}_H$ denote the estimate and error (or mismatch) matrix of $\mathbf{H}$, respectively, such that $\mathbf{H} = \widehat{\mathbf{H}} + \mathbf{\Delta}_H$. σ_n^2 is the noise power. The proposed robust precoder is formulated by maximizing the minimum of $\mathrm{SNR}\left(\mathbf{\Delta}_H\right)$, denoted as $\mathrm{SNR}_{\min}$, given that the transmit power and interference constraints are not violated. $\mathrm{SNR}_{\min}$ is obtained by finding the "worst case" $\mathbf{\Delta}_H$, denoted as $\mathbf{\Delta}_H^{wst}$, where $\boldsymbol{\delta}_H^{wst} \triangleq vec\left(\mathbf{\Delta}_H^{wst}\right) \in \mathcal{H}$, so that $\mathrm{SNR}_{\min} = \mathrm{SNR}\left(\mathbf{\Delta}_H^{wst}\right)$ with $\mathcal{H}_E \triangleq \left\{\boldsymbol{\delta}_H \middle| \, \boldsymbol{\delta}_H^H \mathbf{B} \boldsymbol{\delta}_H \leq 1\right\}$. $\mathbf{B} \succ 0$ defines the shape and direction of an ellipsoid and it is used to bound $\mathbf{\Delta}_H$. Without a a priori knowledge of $\mathbf{\Delta}_H$, it is assumed that $\mathbf{B} = \frac{1}{\varepsilon_H^2}\mathbf{I}_{n_T n_R}$, implying that the uncertainty model degenerates back to a norm ball, and it is bounded as $\left\|\mathbf{\Delta}_H\right\|_F^2 \leq \varepsilon_H^2$. That is, $\mathbf{\Delta}_H \in \mathcal{H}_{NBMM} \triangleq \left\{\mathbf{\Delta}_H \middle| \left\|\mathbf{\Delta}_H\right\|_F^2 \leq \varepsilon_H^2\right\}$, where $\mathcal{H}_{NBMM}$ shall be referred to as the NBMM for $\mathbf{H}$ and it shall be used hereafter to bound the norm of $\mathbf{\Delta}_H$.

Since $\mathbf{G}_k$ will likely be estimated blindly as there is no handshaking between the SU and PUs, two uncertainty models are proposed hereafter to deal with the expected large degree of estimation error in $\mathbf{G}_k$. For improved aesthetic, without loss of generality, the subscript $_k$ in $\mathbf{G}_k$ and its associated mismatch matrix shall be ignored in the derivation in the following sections, and will only appear in the final problem formulation.

In the next section, the SMM will be introduced and it will be shown how the interference constraint is formulated using it. The constraint will be combined with the design metric described in this section to form the complete formulation of the precoder design. Comparison will be made with the design using the NBMM for the mismatch between $\mathbf{G}$ and its estimate.

III. Structural Mismatch Model (SMM) and Precoder Design

The Kronecker channel model [15] shall be adopted so that $\mathbf{G} = \mathbf{R}_{G,P}^{1/2}\mathbf{G}_w\mathbf{R}_{G,T}^{T/2} \in \mathbb{C}^{n_P \times n_T}$. $\mathbf{R}_{G,T} \in \mathbb{C}^{n_T \times n_T}$ and $\mathbf{R}_{G,P} \in \mathbb{C}^{n_P \times n_P}$ are spatial covariance matrix at the SU-Tx and PU, respectively. $\mathbf{R}_G \triangleq \mathbb{E}\left[vec(\mathbf{G})vec^H(\mathbf{G})\right] = \mathbf{R}_{G,T} \otimes \mathbf{R}_{G,P} \in \mathbb{C}^{n_T n_P \times n_T n_P}$ is the covariance matrix of channel matrix $\mathbf{G}$. The entries of $\mathbf{G}_w \in \mathbb{C}^{n_P \times n_T}$ are identical and independent complex Gaussian distributed with zero mean and unit variance. Hence, the average interference power toward the PU can be written as

$$\begin{aligned}\mathbb{E}\left[\|\mathbf{GF}\|_F^2\right] &= \mathbb{E}\left[\left\|\left(\mathbf{F}^T \otimes \mathbf{I}_{n_P}\right) vec(\mathbf{G})\right\|_2^2\right] \\ &= tr\left(\left((\mathbf{FF}^H)^T \otimes \mathbf{I}_{n_P}\right) \mathbf{R}_G\right).\end{aligned}$$

Let $\mathbf{R}_G = \widehat{\mathbf{R}}_G + \mathbf{\Delta}_R$, where $\widehat{\mathbf{R}}_G$ denotes the estimate of $\mathbf{R}_G$, and $\mathbf{\Delta}_R$ is its corresponding mismatch matrix. In the present scheme, the error power is upper bounded such that $\mathbf{\Delta}_R \in \mathcal{U}_R^s$, with

SMM :
$\mathcal{U}_R^s \triangleq \left\{ \mathbf{\Delta}_R \middle| \, \|\mathbf{\Delta}_R\|_F \leq \varepsilon_R, \mathbf{\Delta}_R^H = \mathbf{\Delta}_R, [\mathbf{\Delta}_R]_{ii} = 0, \forall i \right\}$

expressing the proposed SMM, since $[\mathbf{R}_G]_{ii} = 1, \forall i$ due to the use of the Kronecker model.

Notice that $\mathcal{U}_R^s$ is different from the traditional NBMM defined as $\mathcal{U}_R^b \triangleq \left\{ \mathbf{\Delta}_R \middle| \, \|\mathbf{\Delta}_R\|_F \leq \varepsilon_R, \mathbf{\Delta}_R^H = \mathbf{\Delta}_R \right\}$[1], where the structural property of $\mathbf{R}_G$, i.e. $[\mathbf{R}_G]_{ii} = 1, \forall i$, is not exploited.

Ignoring $\frac{T}{\sigma_n^2}$ in (1) and let $\mathbf{\Delta}_H \in \mathcal{H}$ and $\mathbf{\Delta}_R \in \mathcal{U}_R^s$, the precoder $\mathbf{F}$ can be computed by solving

$$\begin{aligned}&\max_{\mathbf{F}} \min_{\mathbf{\Delta}_H \in \mathcal{H}} \left\| \left(\widehat{\mathbf{H}} + \mathbf{\Delta}_H\right) \mathbf{F} \right\|_F^2 \\ &s.t.\ tr\left(\left(\left(\mathbf{FF}^H\right)^T \otimes \mathbf{I}_{n_P}\right)\left(\widehat{\mathbf{R}}_G + \mathbf{\Delta}_R\right)\right) \leq Q_{th}, \\ &\mathbf{\Delta}_R \in \mathcal{U}_R^s, \quad tr\left(\mathbf{FF}^H\right) \leq P_{th},\end{aligned} \tag{2}$$

where P_{th} and Q_{th} are the maximum transmit power of the SU-Tx brought about by $\mathbf{F}$ and the interference constraint threshold of the PU, respectively. Denote $\mathbf{Q} \triangleq \mathbf{FF}^H$ and $\widetilde{\mathbf{Q}}_P \triangleq \mathbf{Q}^T \otimes \mathbf{I}_{n_P}$, (2) can be rewritten as

$$\begin{aligned}&\max_{\mathbf{Q}} \min_{\mathbf{\Delta}_H \in \mathcal{H}} tr\left(\left(\widehat{\mathbf{H}} + \mathbf{\Delta}_H\right) \mathbf{Q} \left(\widehat{\mathbf{H}} + \mathbf{\Delta}_H\right)\right) \\ &s.t.\ tr\left(\widetilde{\mathbf{Q}}_P \left(\widehat{\mathbf{R}}_G + \mathbf{\Delta}_R\right)\right) \leq Q_{th}, \mathbf{\Delta}_R \in \mathcal{U}_R^s, \\ &tr\left(\mathbf{Q}\right) \leq P_{th}, rank(\mathbf{Q}) = B, \widetilde{\mathbf{Q}}_P = \mathbf{Q}^T \otimes \mathbf{I}_{n_P}.\end{aligned} \tag{3}$$

The use of $\mathcal{U}_R^s$ allows the precoder to maintain high link reliability for a continuum of *all* possible channel covariance mismatches given by $\mathcal{U}_R^s$ instead of providing such performance for only a fixed channel covariance matrix. However, the existence of infinite number of constraints also makes finding the solution impossible. Fortunately, the problem can be bypassed by finding an upper bound for $tr\left(\widetilde{\mathbf{Q}}_P \left(\widehat{\mathbf{R}}_G + \mathbf{\Delta}_R\right)\right)$ of which $\mathbf{\Delta}_R \in \mathcal{U}_R^s$. The result of this bound using $\mathcal{U}_R^b$ and $\mathcal{U}_R^s$ is stated

[1]The only difference between the NBMM for $\mathbf{H}$, $\mathcal{H}_{NBMM}$, and $\mathcal{U}_R^b$, is the symmetry condition for $\mathbf{\Delta}_R$. This is of course needed because the latter mismatch model is applied to the mismatch matrix associated with a Hermitian matrix. Since the symmetry condition does not affect the performance of the model, hence, $\mathcal{H}$ and $\mathcal{U}_R^b$ shall both be referred to as NBMM even though they are mathematically different. The confusion should be clarified from the context.

in Theorem 1, which is called the Power Allocation exploiting Sparsity Theorem-SMM, or PAST-SMM. This name is used because as the theorem will show, more transmit power can be used when $\mathbf{\Delta}_R \in \mathcal{U}_R^s$ is employed (compared to $\mathcal{U}_R^b$) as part of the precoder design for cognitive radio systems because more transmit power can be allocated to the interfering channel without exceeding Q_{th}.

Theorem 1: Power Allocation exploiting Sparsity Theorem-SMM (PAST-SMM): An upper bound for $tr\left(\widetilde{\mathbf{Q}}_P\left(\widehat{\mathbf{R}}_G + \mathbf{\Delta}_R\right)\right)$ using

(i) the NBMM defined as $\mathcal{U}_R^b$ is

$$\begin{aligned} &\max_{\mathbf{\Delta}_R \in \mathcal{U}_R^b} tr\left(\widetilde{\mathbf{Q}}_P\left(\widehat{\mathbf{R}}_G + \mathbf{\Delta}_R\right)\right) \\ &\qquad = tr\left(\widetilde{\mathbf{Q}}_P \widehat{\mathbf{R}}_G\right) + \varepsilon_R \left\|\widetilde{\mathbf{Q}}_P\right\|_F, \end{aligned} \tag{4}$$

and using

(ii) the SMM defined as $\mathcal{U}_R^s$ is

$$\begin{aligned} &\max_{\mathbf{\Delta}_R \in \mathcal{U}_R^s} tr\left(\widetilde{\mathbf{Q}}_P\left(\widehat{\mathbf{R}}_G + \mathbf{\Delta}_R\right)\right) \\ &\qquad = tr\left(\widetilde{\mathbf{Q}}_P \widehat{\mathbf{R}}_G\right) + \varepsilon_R \left\|\bar{\mathbf{I}}_{n_T n_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F, \end{aligned} \tag{5}$$

where $\bar{\mathbf{I}}_{n_T n_P} \triangleq \mathbf{1}_{n_T n_P \times n_T n_P} - \mathbf{I}_{n_T n_P}$.

The amount of sparsity in the SMM that can be exploited by precoder design for performance improvement equals $n_T n_P$.

Proof: The proof of the PAST-SMM is shown in Appendix A. ■

The result of the PAST-SMM allows for reduction in symbol error rate compared to the use of the NBMM in [6]. Numerical result corroborating this claim is shown in Sec. IV.

Therefore, employing semidefinite relaxation [11], in which the rank constraint (3) is removed so that (3) becomes

$$\begin{aligned} &\max_{\mathbf{Q}} \min_{\mathbf{\Delta}_H \in \mathcal{H}} tr\left(\left(\widehat{\mathbf{H}} + \mathbf{\Delta}_H\right)\mathbf{Q}\left(\widehat{\mathbf{H}} + \mathbf{\Delta}_H\right)\right) \\ &s.t.\ tr\left(\widetilde{\mathbf{Q}}_P \widehat{\mathbf{R}}_G\right) + \varepsilon_R \left\|\bar{\mathbf{I}}_{n_T n_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F \le Q_{th}, \\ &tr\left(\mathbf{Q}\right) \le P_{th}, \widetilde{\mathbf{Q}}_P = \mathbf{Q}^T \otimes \mathbf{I}_{n_P}. \end{aligned} \tag{6}$$

After the optimal solution for (6) is obtained, the randomization procedure proposed in [8], [14] can be used to find a precoder matrix, denoted as $\mathbf{F}^{opt}$, which is of rank B. Specifically, `randA` method is used, in which $\mathbf{F}^{opt} = \mathbf{U}_Q \mathbf{\Lambda}_Q^{1/2} \mathbf{E}$, from $\mathbf{Q} = \mathbf{U}_Q \mathbf{\Lambda}_Q \mathbf{U}_Q^H$, where $[\mathbf{E}]_{ij} = e^{j\theta_{ij}}$ and θ_{ij} are independent identical uniform distributed on $[0, 2\pi)$. There is no guarantee, however, that $\mathbf{F}^{opt}$ will be the same as the solution of (3), but (6) is easier to solve. Two methods are used hereafter to solve the minimization problem stated in (6).

1) Lower Bound (LB) Method: Instead of directly solving for the solution of the minimization problem

$$\min_{\boldsymbol{\Delta}_H \in \mathcal{H}} tr\left(\left(\widehat{\mathbf{H}} + \boldsymbol{\Delta}_H\right) \mathbf{Q} \left(\widehat{\mathbf{H}} + \boldsymbol{\Delta}_H\right)\right),$$

it is possible to find its lower bound and substitute it into (6). The following theorem will ease the derivation of the lower bound [3].

Theorem 2: Receive signal is lower bounded by

$$tr\left(\left(\widehat{\mathbf{H}} + \boldsymbol{\Delta}_H\right) \mathbf{Q} \left(\widehat{\mathbf{H}} + \boldsymbol{\Delta}_H\right)\right) \geq tr\left(\mathbf{QA}\right),$$

where $\mathbf{A} \triangleq \widehat{\mathbf{H}}^H \widehat{\mathbf{H}} + \left(\varepsilon_H^2 - 2\varepsilon_H \left\|\widehat{\mathbf{H}}\right\|_F\right) \mathbf{I}_{n_T}$. Equality holds iff

$$\begin{aligned}
\boldsymbol{\Delta}_H &= -k\mathbf{H}, \\
rank\left(\widehat{\mathbf{H}}\right) &= rank\left(\boldsymbol{\Delta}_H\right) = rank\left(\mathbf{F}\right) = 1, \text{ and} \\
\mathcal{R}\left(\widehat{\mathbf{H}}^T\right) &= \mathcal{R}\left(\boldsymbol{\Delta}_H^T\right) = \mathcal{R}\left(\mathbf{F}\right).
\end{aligned}$$

Proof: The proof is given in Appendix B. ■

However, the first condition is difficult to achieve as $\mathbf{H}$ is supposedly unknown. The second and third condition cannot be attained without severely diminishing the design freedom of the precoder. Even if the first condition is satisfied, the solution obtained will still be suboptimal.

Therefore, including PU index k, (6) can be rewritten as

$$\boxed{\begin{aligned}
&\mathbf{LB+SMM}: \\
&\max_{\mathbf{Q}} tr(\mathbf{QA}) \\
&\quad s.t.\ tr\left(\widetilde{\mathbf{Q}}_P \widehat{\mathbf{R}}_{G,k}\right) + \varepsilon_R \left\|\bar{\mathbf{I}}_{n_T n_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F \leq Q_{th}, \forall k \\
&\qquad tr\left(\mathbf{Q}\right) \leq P_{th}, \widetilde{\mathbf{Q}}_P = \mathbf{Q}^T \otimes \mathbf{I}_{n_P},
\end{aligned}} \tag{7}$$

which is a convex SDP.

2) S-Procedure (SP) Method: By hypograph equivalence [13], (6) can be rewritten as

$$\begin{aligned}
&\max_{\mathbf{Q},\gamma} \gamma \\
&\quad s.t.\ tr((\widehat{\mathbf{H}} + \boldsymbol{\Delta}_H)\mathbf{Q}(\widehat{\mathbf{H}} + \boldsymbol{\Delta}_H)^H) \geq \gamma, \forall \boldsymbol{\Delta}_H \in \mathcal{H}, \\
&\qquad tr\left(\widetilde{\mathbf{Q}}_P \widehat{\mathbf{R}}_G\right) + \varepsilon_R \left\|\bar{\mathbf{I}}_{n_T n_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F \leq Q_{th}, \\
&\qquad tr\left(\mathbf{Q}\right) \leq P_{th}, \widetilde{\mathbf{Q}}_P = \mathbf{Q}^T \otimes \mathbf{I}_{n_P}.
\end{aligned} \tag{8}$$

Define $\widehat{\mathbf{h}} \triangleq vec(\widehat{\mathbf{H}})$, $\boldsymbol{\delta}_H \triangleq vec\left(\boldsymbol{\Delta}_H\right)$, and $\widetilde{\mathbf{Q}}_R \triangleq \mathbf{Q}^T \otimes \mathbf{I}_{n_R}$. Using the fact that $tr\left(\mathbf{XAX}^H\right) = \mathbf{x}^H\left(\mathbf{A}^T \otimes \mathbf{I}_m\right)\mathbf{x}$, where $\mathbf{X} \in \mathbb{C}^{m\times n}, \mathbf{A} \in \mathbb{S}_n$ and vector $\mathbf{x} \triangleq vec(\mathbf{X})$, the receive signal power can be expressed as

$$
\begin{aligned}
& tr\left(\left(\widehat{\mathbf{H}}+\boldsymbol{\Delta}_H\right)\mathbf{Q}\left(\widehat{\mathbf{H}}+\boldsymbol{\Delta}_H\right)^H\right) \\
&\qquad = \left(\widehat{\mathbf{h}}+\boldsymbol{\delta}_H\right)^H\left(\mathbf{Q}^T\otimes\mathbf{I}_{n_R}\right)\left(\widehat{\mathbf{h}}+\boldsymbol{\delta}_H\right) \\
&\qquad = \boldsymbol{\delta}_H^H\widetilde{\mathbf{Q}}_R\boldsymbol{\delta}_H + 2\Re\left(\widehat{\mathbf{h}}^H\widetilde{\mathbf{Q}}_R\boldsymbol{\delta}_H\right) + \widehat{\mathbf{h}}^H\widetilde{\mathbf{Q}}_R\widehat{\mathbf{h}}.
\end{aligned}
$$

The first constraint, which contains infinite number of constraints, can be replaced by a linear matrix inequality (LMI) via S-lemma [13].

Theorem 3: (**S-Lemma**): For $\mathbf{A}_i \in \mathbb{S}_n$, and $c_i \in \mathbb{R}$, where $i \in \{0,1\}$, and $\mathbf{b} \in \mathbb{C}^n$. Suppose Slater condition holds, i.e., $\exists\tilde{\mathbf{x}} \in \mathbb{C}^n$ such that $\tilde{\mathbf{x}}^H\mathbf{A}_1\tilde{\mathbf{x}} + c_1 > 0$, then the following two statement are equivalent:

(i) $\mathbf{x}^H\mathbf{A}_0\mathbf{x} + 2\Re\left(\mathbf{b}^H\mathbf{x}\right) + c_0 \geq 0,\ \forall \mathbf{x}^H\mathbf{A}_1\mathbf{x} + c_1 \geq 0.$

(ii) $\exists\alpha \geq 0$ such that

$$
\begin{bmatrix} \mathbf{A}_0 - \alpha\mathbf{A}_1 & \mathbf{b} \\ \mathbf{b}^H & c_0 - \alpha c_1 \end{bmatrix} \succeq 0.
$$

Let $\mathbf{x} = \boldsymbol{\delta}_H$, $\mathbf{A}_0 = \widetilde{\mathbf{Q}}_R$, $\mathbf{A}_1 = -\mathbf{B}$, $\mathbf{b} = \widetilde{\mathbf{Q}}_R\widehat{\mathbf{h}}$, $c_0 = \widehat{\mathbf{h}}^H\widetilde{\mathbf{Q}}_R\widehat{\mathbf{h}} - \gamma$, and $c_1 = 1$. Including the PU index $_k$, (8) is equivalent to the convex SDP

$$
\boxed{
\begin{aligned}
& \mathbf{SP+SMM}: \\
& \max_{\mathbf{Q},\gamma,\alpha\geq 0}\ \gamma \\
& \quad s.t. \begin{bmatrix} \widetilde{\mathbf{Q}}_R + \alpha\mathbf{B} & \widetilde{\mathbf{Q}}_R\widehat{\mathbf{h}} \\ \widehat{\mathbf{h}}^H\widetilde{\mathbf{Q}}_R & \widehat{\mathbf{h}}^H\widetilde{\mathbf{Q}}_R\widehat{\mathbf{h}} - \alpha - \gamma \end{bmatrix} \succeq 0, \\
& \qquad tr\left(\widetilde{\mathbf{Q}}_P\widehat{\mathbf{R}}_{G,k}\right) + \varepsilon_R\left\|\bar{\mathbf{I}}_{n_T n_P}\circ\widetilde{\mathbf{Q}}_P\right\|_F \leq Q_{th}, \forall k \\
& \qquad tr\left(\mathbf{Q}\right) \leq P_{th}, \\
& \qquad \widetilde{\mathbf{Q}}_R = \mathbf{Q}^T\otimes\mathbf{I}_{n_R}, \widetilde{\mathbf{Q}}_P = \mathbf{Q}^T\otimes\mathbf{I}_{n_P}.
\end{aligned}
}
\tag{9}
$$

It will be shown in Sec. IV that precoders designed using the proposed SMM, via the lower bound method (7) and the SP method (9), outperform over those designed using the NBMM defined as $\mathcal{U}_R^b$. As alluded earlier, this is because higher transmit power can be used without violating the interference constraint due to the existence of the sparse elements in $\left\|\bar{\mathbf{I}}_{n_T n_P}\circ\widetilde{\mathbf{Q}}_P\right\|_F$ induced by $\mathcal{U}_R^s$.

IV. SIMULATIONS

All simulations employ 4-QAM modulation. One PU is considered hereafter. Simulation results using the SMM are generated using 2×2 Alamouti OSTBC, with $B = 2$, $T = 2$, $n_T = 4$, and $n_R = 2$. Without loss of generality, n_P is assumed to be 1. The channel matrix between the

SU-Tx and PU degenerates to a vector $\mathbf{G} = \mathbf{g}^T = \mathbf{g}_w^T \mathbf{R}_{G,T}^{T/2} \in \mathbb{C}^{1 \times n_T}$. The average interference becomes $\mathbb{E}\left[\|\mathbf{GF}\|_F^2\right] = tr\left(\mathbf{FF}^H \mathbf{R}_{G,T}\right)$. The antennas are aligned in an uniform linear array with half wavelength antenna spacing. The spatial correlation matrix $\mathbf{R}_{G,T}$ is generated according to [15], where the mean angle of departure (AoD) is $65°$, and the angular spread (AS) is $25°$. The entries of $\mathbf{H}$ are independent and identically complex Gaussian distributed, with zero mean and unit variance. Uncertainty level ε_H and ε_R have been normalized to have values in the interval $[0, 1]$. The transmit power threshold P_{th} is set to 10 and interference threshold Q_{th} is set to 0.1.

To establish the efficacy of the proposed SMM based precoder design, the robust precoders designed from (7) and (9) are also compared with one designed using the norm ball constraint as stated in $\mathcal{U}_R^b$. Hence, four different cases are compared: LB method with norm ball constraint, LB method with the SMM (see (7)), S-procedure (SP) method with norm ball constraint, and SP method with the SMM (see (9)).

Fig. 1 shows the CDF curve of the receive signal power $\|\mathbf{HF}\|^2$. It is clear that the proposed SMM design enables the SU-Rx to receive higher signal power than the NBMM based methods by about 1.5 dB on average. It is shown in the figure that using the SP method with the SMM outperforms the channel and covariance constraints based designs proposed in [6] by about 5 and 10 dB, respectively, when the instantaneous interference threshold in [6] is $I_{th} = 0.01$ or -20 dB. This is again due to the existence of $\left\|\bar{\mathbf{I}}_{n_T n_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F$ in (9) which allows for more transmit power to be used without exceeding Q_{th}. This is verified in Fig. 2 which shows higher transmit power $tr(\mathbf{Q})$ are consistently achieved using the SP method with structural constraint than all other methods. This increase in receive SNR translates directly into gain in SER as shown in Fig. 3 where the SP and LB methods with the SMM are able to outperform their NBMM counterparts by 1 and 2 dB, respectively, at SER = 10^{-2}.

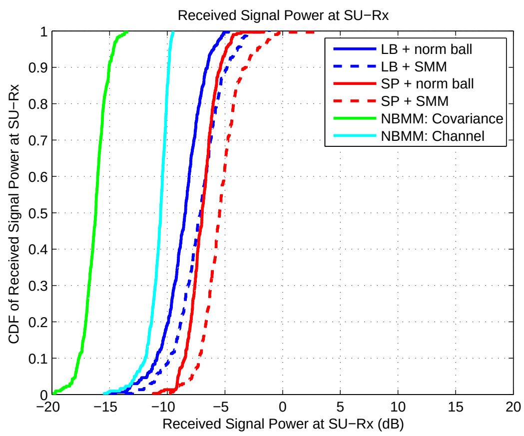

Fig. 1. CDF curve of receive signal power $\|\mathbf{HF}\|^2$ at the SU-Rx. $\varepsilon_H = 0.1$ and $\varepsilon_R = 0.3$. NBMM herein stands for the method proposed in [6].

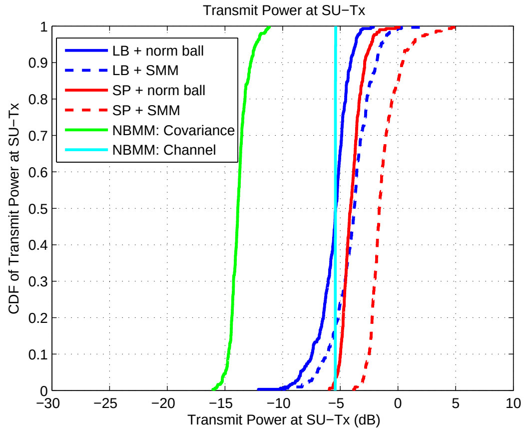

Fig. 2. CDF curve of transmit power $tr(\mathbf{Q})$. NBMM herein stands for the method proposed in [6].

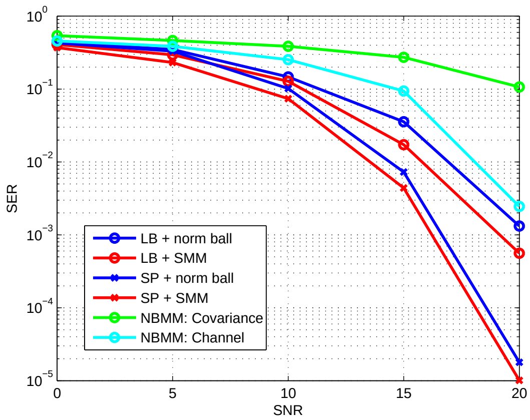

Fig. 3. SER versus SNR performance comparison. $\varepsilon_H = 0.1$ and $\varepsilon_R = 0.3$. NBMM herein stands for the method proposed in [6].

Figures 4 and 5 show the instantaneous interference power toward the PU and the average interference power toward the PU from the SU-Tx, respectively. The instantaneous interference power is defined as $\|\mathbf{GF}\|_F^2$, and the average interference power is defined as $\mathbb{E}\left[\|\mathbf{GF}\|_F^2\right] = tr\left(\mathbf{FF}^H\mathbf{R}_{G,T}\right)$. From the figures, it is clear that the PU experiences a lower level of interference from the SU-Tx when the NBMM is used. This is understandable as the higher interference power experienced at the PU in the SMM based systems translates into higher receive power at the SU-Rx. Even though higher average interference power is experienced by the PU when the proposed model is used, the average interference constraint is not violated, i.e. $Pr(\text{average instantaneous power } \leq -10\text{dB}) \approx 1$, as the average interference power constraint is used as part of the proposed design. However, since the instantaneous interference power is not used as a constraint in both the NBMM and SMM based designs, hence, it is possible for both methods to experience instantaneous interference power exceeding -20 dB ($I_{th} = 0.01$).

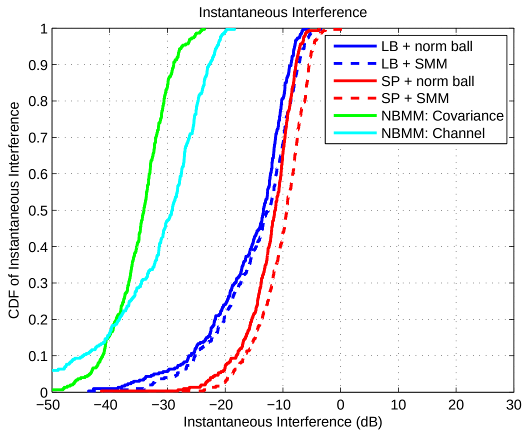

Fig. 4. CDF curve of instantaneous interference power $\|\mathbf{GF}\|_F$ toward PU. $\varepsilon_H = 0.1$ and $\varepsilon_R = 0.3$. NBMM herein stands for the method proposed in [6].

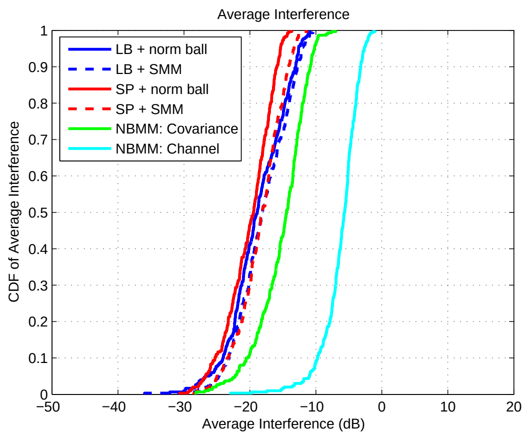

Fig. 5. CDF curve of the average interference power toward the PU, in terms of $tr\left(\mathbf{FF}^H\mathbf{R}_{G,T}\right)$. $\varepsilon_H = 0.1$ and $\varepsilon_R = 0.3$. NBMM herein stands for the method proposed in [6].

V. Conclusion

A mismatch model called the structural mismatch model, or SMM, is proposed for robust interference channel transmission when CSI in the communicating and interfering links is inaccurate. The results were presented in the context of a cognitive radio system in which the SU-Tx is allowed to transmit simultaneously with the PU, but without causing noticeable interference at the PUs. It has been shown that precoder design using the SMM can outperform its NBMM counterpart by

2 dB in terms of transmit power and SER, by successfully trading off the interference power, but without violating the average interference power constraint. Analysis has been included to highlight the deficiency of the lower bound method. It has been shown analytically in the PAST-SMM that the performance gain of the SMM comes from allocation of the transmit power to the sparse elements in the interfering link, where this sparsity is brought forth by exploiting the structural property of the statistical correlation matrix of the channel in the SMM. It was also proven that the amount of sparsity available to be exploited by the SMM for precoder design equals $n_T n_P$.

APPENDIX A
PAST-SMM

(i) Since $\widetilde{\mathbf{Q}}_P$ is Hermitian symmetric, according to the Cauchy-Schwarz inequality, $tr\left(\widetilde{\mathbf{Q}}_P\boldsymbol{\Delta}_R\right) \leq \left\|\widetilde{\mathbf{Q}}_P\right\|_F \|\boldsymbol{\Delta}_R\|_F$. Equality holds iff $\boldsymbol{\Delta}_R$ and $\widetilde{\mathbf{Q}}_P$ are linear dependent, i.e., $\boldsymbol{\Delta}_R = k\widetilde{\mathbf{Q}}_P$. In addition, since $\|\boldsymbol{\Delta}_R\|_F \leq \varepsilon_R$, maximum of $tr\left(\widetilde{\mathbf{Q}}_P\boldsymbol{\Delta}_R\right)$ occurs at $k = \varepsilon_R / \left\|\widetilde{\mathbf{Q}}_P\right\|_F$. Therefore, $\max_{\boldsymbol{\Delta}_R \in \mathcal{U}_R^b} tr\left(\widetilde{\mathbf{Q}}_P\boldsymbol{\Delta}_R\right) = \varepsilon_R \left\|\widetilde{\mathbf{Q}}_P\right\|_F$. Substituting this into the left-hand side of (4) would equal to the right-hand side of (4).

(ii) Denote $\mathbf{A}^u$ and $\mathbf{A}^\ell$ as the strictly upper and lower triangular portion of matrix $\mathbf{A}$, respectively. Also denote $\mathbf{A}^d$ as diagonal portion of $\mathbf{A}$. Note that

$$tr\left(\widetilde{\mathbf{Q}}_P\boldsymbol{\Delta}_R\right) = tr\left(\widetilde{\mathbf{Q}}_P^u\boldsymbol{\Delta}_R^\ell\right) + tr\left(\widetilde{\mathbf{Q}}_P^\ell\boldsymbol{\Delta}_R^u\right) + tr\left(\widetilde{\mathbf{Q}}_P^d\boldsymbol{\Delta}_R^d\right) = tr\left(\widetilde{\mathbf{Q}}_P^u\boldsymbol{\Delta}_R^\ell\right) + tr\left(\widetilde{\mathbf{Q}}_P^\ell\boldsymbol{\Delta}_R^u\right). \tag{10}$$

$tr\left(\widetilde{\mathbf{Q}}_P^d\boldsymbol{\Delta}_R^d\right)$ vanishes because $[\boldsymbol{\Delta}_R]_{ii} = 0$. Due to Hermitian symmetry of $\widetilde{\mathbf{Q}}_P$, $\widetilde{\mathbf{Q}}_P^u = (\widetilde{\mathbf{Q}}_P^\ell)^H$, thus

$$tr\left(\widetilde{\mathbf{Q}}_P^u\boldsymbol{\Delta}_R^\ell\right) + tr\left(\widetilde{\mathbf{Q}}_P^\ell\boldsymbol{\Delta}_R^u\right) = tr\left(\left(\widetilde{\mathbf{Q}}_P^\ell\right)^H\boldsymbol{\Delta}_R^\ell\right) + tr\left(\left(\widetilde{\mathbf{Q}}_P^u\right)^H\boldsymbol{\Delta}_R^u\right). \tag{11}$$

In $\mathcal{U}_R^s$, $\boldsymbol{\Delta}_R$ is also Hermitian symmetric, i.e., $\boldsymbol{\Delta}_R^u = \left(\boldsymbol{\Delta}_R^\ell\right)^H$, implies $\|\boldsymbol{\Delta}_R^u\|_F^2 = \left\|\boldsymbol{\Delta}_R^\ell\right\|_F^2 = \|\boldsymbol{\Delta}_R\|_F^2/2 \leq \varepsilon_R^2/2$. Applying the Cauchy-Schwarz inequality,

$$tr\left(\left(\widetilde{\mathbf{Q}}_P^\ell\right)^H\boldsymbol{\Delta}_R^\ell\right) \leq \left\|\widetilde{\mathbf{Q}}_P^\ell\right\|_F\left\|\boldsymbol{\Delta}_R^\ell\right\|_F. \tag{12}$$

Equality holds iff $\boldsymbol{\Delta}_R^\ell$ and $\widetilde{\mathbf{Q}}_P^\ell$ are linear dependent, i.e., $\boldsymbol{\Delta}_R^\ell = k_\ell\widetilde{\mathbf{Q}}_P^\ell$. Furthermore, since $\left\|\boldsymbol{\Delta}_R^\ell\right\| \leq \varepsilon_R/\sqrt{2}$, the maximum occurs at $k_\ell = \varepsilon_R \Big/ \left(\sqrt{2}\left\|\widetilde{\mathbf{Q}}_P^\ell\right\|_F\right)$ and

$$tr\left(\left(\widetilde{\mathbf{Q}}_P^\ell\right)^H\boldsymbol{\Delta}_R^\ell\right) \leq \varepsilon_R\left\|\widetilde{\mathbf{Q}}_P^\ell\right\|_F \Big/ \sqrt{2}.$$

Since $\left\|\widetilde{\mathbf{Q}}_P^\ell\right\|_F^2 + \left\|\widetilde{\mathbf{Q}}_P^u\right\|_F^2 = \left\|\bar{\mathbf{I}}_{n_Tn_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F^2$ and $\left\|\widetilde{\mathbf{Q}}_P^\ell\right\|_F = \left\|\widetilde{\mathbf{Q}}_P^u\right\|_F$, it is clear that $\left\|\widetilde{\mathbf{Q}}_P^\ell\right\|_F = \left\|\bar{\mathbf{I}}_{n_Tn_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F \Big/ \sqrt{2}$ so that

$$tr\left(\left(\widetilde{\mathbf{Q}}_P^\ell\right)^H\boldsymbol{\Delta}_R^\ell\right) \leq \frac{\varepsilon_R\left\|\bar{\mathbf{I}}_{n_Tn_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F}{2}. \tag{13}$$

Similarly,

$$tr\left(\left(\widetilde{\mathbf{Q}}_P^u\right)^H \mathbf{\Delta}_R^u\right) \leq \frac{\varepsilon_R \left\|\bar{\mathbf{I}}_{n_T n_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F}{2}. \tag{14}$$

Substituting (13) and (14) into (10), it can be concluded that

$$\max_{\mathbf{\Delta}_R \in \mathcal{U}_R^s} tr\left(\widetilde{\mathbf{Q}}_P \mathbf{\Delta}_R\right) = \varepsilon_R \left\|\bar{\mathbf{I}}_{n_T n_P} \circ \widetilde{\mathbf{Q}}_P\right\|_F. \tag{15}$$

Substituting (15) into (5), the second part of the proof is complete.

Comparing (4) and (5) in Theorem 1, and interpreting the result by incorporating these equations into (2), the existence of $\left\|\bar{\mathbf{I}}_{n_T n_P} \circ \mathbf{Q}\right\|$ removes all the diagonal terms in $\mathbf{Q}$, which allows the corresponding elements of $\mathbf{Q}$ more room to increase when the worst-case SNR is maximized without causing any constraint violation. This can be interpreted as allowing more transmit power to be used as they are "absorbed" by, or allocated to, the zeros in $\left\|\bar{\mathbf{I}}_{n_T n_P} \circ \mathbf{Q}\right\|$. Hence, the amount of power allocated to the interfering link equals $n_T n_P$. Note that this result is similar to the water-filling solution in which the coefficients of $\mathbf{Q}$ serve as the bottom of the subchannel of the effective channel $\mathbf{GF}$, which is similar to the role the inverse eigenmode coefficients played in the water-filling solution. Hence, (15) suggests that the use of the SMM allows the removal of some of the coefficients in $\mathbf{Q}$, resulting in higher transmit power utilization.

APPENDIX B
LINEAR BOUND THEOREM

Corollary 1: For $\mathbf{A} \in \mathbb{C}^{m\times n}$ and $\mathbf{B} \in \mathbb{C}^{n\times p}$, then $\|\mathbf{AB}\|_F \leq \|\mathbf{A}\|_F \|\mathbf{B}\|_F$. Equality is attained iff $rank(\mathbf{A}) = rank(\mathbf{B}) = 1$ and $\mathcal{R}(\mathbf{A}^T) = \mathcal{R}(\mathbf{B})$.

Proof: Since

$$\|\mathbf{AB}\|_F^2 = \sum_{i,j} \left|\mathbf{a}_i'^H \mathbf{b}_j\right|^2 \leq \sum_i \sum_j \|\mathbf{a}_i'\|_2^2 \|\mathbf{b}_j\|_2^2 = \|\mathbf{A}\|_F^2 \|\mathbf{B}\|_F^2,$$

where $(\mathbf{a}_i')^H = [a_{i1} \cdots a_{in}]$ is the i^{th} row of matrix $\mathbf{A}$ and $\mathbf{b}_j$ is j^{th} column of $\mathbf{B}$. From the Cauchy-Schwarz inequality, equality is attained when $\mathbf{a}_i' = k\mathbf{b}_j \forall i,j$, implying that $\mathbf{a}_i'$ and $\mathbf{b}_j$ are linear dependent $\forall i,j$. In other words, $rank(\mathbf{A}) = rank(\mathbf{B}) = 1$ and $\mathcal{R}(\mathbf{A}^T) = \mathcal{R}(\mathbf{B})$. ■

Lemma 1 (Reverse triangle inequality): For $\mathbf{A},\mathbf{B} \in \mathbb{C}^{n\times m}$, $\|\mathbf{A}+\mathbf{B}\|_F \geq \left|\, \|\mathbf{A}\|_F - \|\mathbf{B}\|_F \,\right|$. Equality holds if $\mathbf{A} = k\mathbf{B}$, where $k \in \mathbb{R}_-$.

Proof:

$$\begin{aligned}\|\mathbf{A}+\mathbf{B}\|_F^2 &= \|\mathbf{A}\|_F^2 + 2\Re\left\{tr\left(\mathbf{B}^H\mathbf{A}\right)\right\} + \|\mathbf{B}\|_F^2 \geq \|\mathbf{A}\|_F^2 - 2\left|tr\left(\mathbf{B}^H\mathbf{A}\right)\right| + \|\mathbf{B}\|_F^2 \\ &\geq \|\mathbf{A}\|_F^2 - 2\|\mathbf{A}\|_F\|\mathbf{B}\|_F + \|\mathbf{B}\|_F^2 = (\|\mathbf{A}\|_F - \|\mathbf{B}\|_F)^2\end{aligned}$$

The first inequality is true because $-|z| \leq \Re(z),\ \forall z \in \mathbb{C}$ and the second inequality is true due to the Cauchy-Schwarz inequality. In addition, for the equality condition of both these inequalities to be true, it requires that $\mathbf{A} = k\mathbf{B}$ and $k \in \mathbb{R}_{-}$. ■

Using the reverse triangular inequality, it follows that

$$\left\|\left(\widehat{\mathbf{H}} + \mathbf{\Delta}_H\right)\mathbf{F}\right\|_F^2 = \left\|\widehat{\mathbf{H}}\mathbf{F} + \mathbf{\Delta}_H\mathbf{F}\right\|_F^2 \geq \left(\left\|\widehat{\mathbf{H}}\mathbf{F}\right\|_F - \left\|\mathbf{\Delta}_H\mathbf{F}\right\|_F\right)^2, \tag{16}$$

where the equality will hold iff $\mathbf{\Delta}_H = -k\mathbf{H}$ and $k \in \mathbb{R}_{+}$. Using Corollary 1 and the fact that $\mathbf{B} = \frac{1}{\varepsilon_H^2}\mathbf{I}_{n_T n_R}$,

$$\left\|\mathbf{\Delta}_H\mathbf{F}\right\|_F \leq \left\|\mathbf{\Delta}_H\right\|_F \left\|\mathbf{F}\right\|_F \leq \varepsilon_H \left\|\mathbf{F}\right\|_F, \tag{17}$$

where the first equality will hold by **Corollary 1** iff $rank\left(\mathbf{\Delta}_H\right) = rank\left(\mathbf{F}\right) = 1$ and $\mathcal{R}\left(\mathbf{\Delta}_H^T\right) = \mathcal{R}\left(\mathbf{F}\right)$. Substituting (17) into (16) and expanding, (16) becomes $\left(\left\|\widehat{\mathbf{H}}\mathbf{F}\right\|_F - \left\|\mathbf{\Delta}_H\mathbf{F}\right\|_F\right)^2 \geq \left\|\widehat{\mathbf{H}}\mathbf{F}\right\|_F^2 + \varepsilon_H^2\left\|\mathbf{F}\right\|_F^2 - 2\varepsilon_H\left\|\widehat{\mathbf{H}}\mathbf{F}\right\|_F\left\|\mathbf{F}\right\|_F$ Noting that $\left\|\widehat{\mathbf{H}}\mathbf{F}\right\|_F \leq \left\|\widehat{\mathbf{H}}\right\|_F\left\|\mathbf{F}\right\|_F$, then the above becomes

$$\begin{aligned} &\left\|\widehat{\mathbf{H}}\mathbf{F}\right\|_F^2 + \varepsilon_H^2\left\|\mathbf{F}\right\|_F^2 - 2\varepsilon_H\left\|\widehat{\mathbf{H}}\mathbf{F}\right\|_F\left\|\mathbf{F}\right\|_F \geq \left\|\widehat{\mathbf{H}}\mathbf{F}\right\|_F^2 + \left(\varepsilon_H^2 - 2\varepsilon_H\left\|\widehat{\mathbf{H}}\right\|_F\right)\left\|\mathbf{F}\right\|_F^2 \\ &= tr\left(\mathbf{F}\mathbf{F}^H\left(\widehat{\mathbf{H}}^H\widehat{\mathbf{H}} + \left(\varepsilon_H^2 - 2\varepsilon_H\left\|\widehat{\mathbf{H}}\right\|_F\right)\mathbf{I}_{n_T}\right)\right). \end{aligned} \tag{18}$$

It should be noted the equality conditions in (16), (17), and (18) will hold iff

$$\begin{aligned} \mathbf{\Delta}_H &= -k\mathbf{H}, \\ rank\left(\widehat{\mathbf{H}}\right) &= rank\left(\mathbf{\Delta}_H\right) = rank\left(\mathbf{F}\right) = 1, \text{ and} \\ \mathcal{R}\left(\widehat{\mathbf{H}}^T\right) &= \mathcal{R}\left(\mathbf{\Delta}_H^T\right) = \mathcal{R}\left(\mathbf{F}\right). \end{aligned}$$

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國科會補助專題研究計畫項下出席國際學術會議心得報告

日期：101 年 09 月 01 日

計畫編號	NSC 101-2219-E-009-019		
計畫名稱	合作型感知通訊之機會式傳輸技術		
出國人員姓名	張傑堯	服務機構及職稱	Dept. of Electronics Engineering, NCTU, Ph. D. Candidate
會議時間	Aug. 5~8, 2012	會議地點	Ann Arbor, USA.
會議名稱	(中文) IEEE 統計訊號處理會義 (英文) IEEE Statistical Signal Processing Workshop		
發表論文題目	(中文) 在干擾通道上使用 SEMM 方法之穩健傳輸 (英文) Robust Interference Channel Transmission Using Sparsity Enhanced Mismatch Model		

一、參加會議經過

SSP is a biannual all-poster workshop. However, there are totally 6 plenary talks provided in this SSP workshop. The first one is “Xampling at the Rate of Innovation: Correlations, Nonlinearities, and Bounds” by Prof. Yonina Eldar. “Xampling” is the term related to sampling at a rate which is lower than Nyquist rate. Then, prof. Robert Ghris introduced the topic of “Topology Signal Processing”. These two talks are the 2 plenary talks for the first day. For the second day, Prof. Robert Nowak provided a talk entitle as “Adaptive Sensing and Active Learning.” Machine learning is a hot topic recently, and the active learning method can dramatically reduce the number of labeled training examples needed to design good classifiers. In the afternoon, prof. Persi Diaconis from Stanford University, who is a former magician, introduced the talk as “Adding Numbers and Determinental Point Processes.”On the last day, Prof. Yoram Bresler introduced the topic of “The invention of Compressive Sensing and Recent Results,” which is especially applied to spectrum blind sampling and image compression. Finally, Prof. Randy Moses shared his results entitled as “Radar Signal Processing.” can dramatically reduce the number of labeled training examples needed to design good classifiers.
I am able to present my work on the last day.

二、與會心得

SSP workshop is an all poster workshop, which I can have close contact and interaction with numerous worldwide scholars and researchers. Through all these interaction, I have learn a lot of thing and been inspired some thought which can be applied on my own research problem. Even though I am working the communication and signal processing, through all poster session, I can view signal processing applied on various application, such as military radar, medical usage, and image. In signal processing field, machine learning and compressive sensing attract massive attraction. Almost every sessions are related to “learning” and “compressive.”

三、考察參觀活動(無是項活動者略) Activities (skipped if none)

四、建議 Recommendation

Although this workshop is not the flagship conference of the signal processing society, but it has attracted top-notched researcher to attend. Due to the poster presentation nature of the conference, it allows for close interaction among the attendees. Thus, as a student, I highly recommend this workshop to other students.

五、攜回資料名稱及內容

Proceedings CD, bag

六、其他 Others

國科會補助計畫衍生研發成果推廣資料表

日期:2013/07/30

<table>
<tr><td rowspan="3">國科會補助計畫</td><td>計畫名稱: 子計畫二：合作型感知通訊之機會式傳輸技術</td></tr>
<tr><td>計畫主持人: 馮智豪</td></tr>
<tr><td>計畫編號: 101-2219-E-009-019-　　學門領域: 接取技術(網通國家型)</td></tr>
<tr><td colspan="2">無研發成果推廣資料</td></tr>
</table>

101年度專題研究計畫研究成果彙整表

<table>
<tr><td colspan="3">計畫主持人：馮智豪</td><td colspan="5">計畫編號：101-2219-E-009-019-</td></tr>
<tr><td colspan="8">計畫名稱：行動合作網通之無線訊號與訊息處理技術研究--子計畫二：合作型感知通訊之機會式傳輸技術</td></tr>
<tr><td colspan="3" rowspan="2">成果項目</td><td colspan="3">量化</td><td rowspan="2">單位</td><td rowspan="2">備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）</td></tr>
<tr><td>實際已達成數（被接受或已發表）</td><td>預期總達成數(含實際已達成數)</td><td>本計畫實際貢獻百分比</td></tr>
<tr><td rowspan="14">國內</td><td rowspan="4">論文著作</td><td>期刊論文</td><td>0</td><td>0</td><td>100%</td><td rowspan="3">篇</td><td></td></tr>
<tr><td>研究報告/技術報告</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td>研討會論文</td><td>1</td><td>0</td><td>100%</td><td>Best presentation award at the 2013 Taiwan Spring School on Information Theory and Communications</td></tr>
<tr><td>專書</td><td>0</td><td>0</td><td>100%</td><td></td><td></td></tr>
<tr><td rowspan="2">專利</td><td>申請中件數</td><td>0</td><td>0</td><td>100%</td><td rowspan="2">件</td><td></td></tr>
<tr><td>已獲得件數</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td rowspan="2">技術移轉</td><td>件數</td><td>0</td><td>0</td><td>100%</td><td>件</td><td></td></tr>
<tr><td>權利金</td><td>0</td><td>0</td><td>100%</td><td>千元</td><td></td></tr>
<tr><td rowspan="4">參與計畫人力（本國籍）</td><td>碩士生</td><td>0</td><td>0</td><td>100%</td><td rowspan="4">人次</td><td></td></tr>
<tr><td>博士生</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td>博士後研究員</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td>專任助理</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td rowspan="8">國外</td><td rowspan="4">論文著作</td><td>期刊論文</td><td>0</td><td>1</td><td>70%</td><td rowspan="3">篇</td><td>under review at the IEEE Trans. on Vehicular Technology</td></tr>
<tr><td>研究報告/技術報告</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td>研討會論文</td><td>1</td><td>0</td><td>30%</td><td>IEEE Statistical Signal Processing Workshop</td></tr>
<tr><td>專書</td><td>0</td><td>0</td><td>100%</td><td>章/本</td><td></td></tr>
<tr><td rowspan="2">專利</td><td>申請中件數</td><td>0</td><td>0</td><td>100%</td><td rowspan="2">件</td><td></td></tr>
<tr><td>已獲得件數</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td rowspan="2">技術移轉</td><td>件數</td><td>0</td><td>0</td><td>100%</td><td>件</td><td></td></tr>
<tr><td>權利金</td><td>0</td><td>0</td><td>100%</td><td>千元</td><td></td></tr>
</table>

	參與計畫人力（外國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)		N/A					

	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□未達成目標（請說明，以 100 字為限）

　　□實驗失敗

　　□因故實驗中斷

　　□其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：■已發表 □未發表之文稿 □撰寫中 □無

專利：□已獲得 □申請中 ■無

技轉：□已技轉 □洽談中 ■無

其他：（以 100 字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

Transmission over MIMO interference channel often relies on the use of robust precoder due to a lack of accurate channel state information, with performance often depending on the conservativeness of the mismatch model. Previously proposed mismatch models either have been deemed too conservative (deterministic models) or are prone to error due to inaccuracy in the pdf and corresponding parameters (stochastic models). A deterministic mismatch model, called \emph{structural mismatch model}, or SMM, is proposed herein in attempt to alleviate these problems. Different from all previously deterministic models, the SMM exploits the inherent sparse characteristics of MIMO interference channel in the form of the statistical correlation matrix. In the context of precoder design for cognitive radio systems, it is shown analytically and by simulation that the SMM enables the transmitter to allocate more transmission power to the sparse elements of the interfering (SU-Tx to PU) link so that performance in the communicating (SU-Tx to SU-Rx) link is enhanced compared to conventional norm ball mismatch model (NBMM).