Sparse Recovery from Combined Fusion Frame Measurements

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Abstract

Sparse representations have emerged as a powerful tool in signal and information processing, culminated by the success of new acquisition and processing techniques such as Compressed Sensing (CS). Fusion frames are very rich new signal representation methods that use collections of subspaces instead of vectors to represent signals. This work combines these exciting fields to introduce a new sparsity model for fusion frames. Signals that are sparse under the new model can be compressively sampled and uniquely reconstructed in ways similar to sparse signals using standard CS. The combination provides a promising new set of mathematical tools and signal models useful in a variety of applications. With the new model, a sparse signal has energy in very few of the subspaces of the fusion frame, although it does not need to be sparse within each of the subspaces it occupies. This sparsity model is captured using a mixed ℓ_1/ℓ_2 norm for fusion frames.

A signal sparse in a fusion frame can be sampled using very few random projections and exactly reconstructed using a convex optimization that minimizes this mixed ℓ_1/ℓ_2 norm. The provided sampling conditions generalize coherence and RIP conditions used in standard CS theory. It is demonstrated that they are sufficient to guarantee sparse recovery of any signal sparse in our model. Moreover, an average case analysis is provided using a probability model on the sparse signal that shows that under very mild conditions the probability of recovery failure decays exponentially with increasing dimension of the subspaces.

Index Terms

Compressed sensing, ℓ_1 minimization, $\ell_{1,2}$-minimization, sparse recovery, mutual coherence, fusion frames, random matrices.

I. Introduction

Compressed Sensing (CS) has recently emerged as a very powerful field in signal processing, enabling the acquisition of signals at rates much lower than previously thought possible [1], [2]. To achieve such performance, CS exploits the structure inherent in many naturally occurring and man-made signals. Specifically, CS uses classical signal representations and imposes a sparsity model on the signal of interest. The sparsity model, combined with

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randomized linear acquisition, guarantees that non-linear reconstruction can be used to efficiently and accurately recover the signal.

Fusion frames are recently emerged mathematical structures that can better capture the richness of the natural and man-made signals compared to classically used representations [3]. In particular, fusion frames generalize frame theory by using subspaces in the place of vectors as signal building blocks. Thus signals can be represented as linear combinations of components that lie in particular, and often overlapping, signal subspaces. Such a representation provides significant flexibility in representing signals of interest compared to classical frame representations.

In this paper we extend the concepts and methods of Compressed Sensing to fusion frames. In doing so we demonstrate that it is possible to recover signals from underdetermined measurements if the signals lie only in very few subspaces of the fusion frame. Our generalized model does not require that the signals are sparse within each subspace. The rich structure of the fusion frame framework allows us to characterize more complicated signal models than the standard sparse or compressible signals used in compressed sensing techniques.

We provide results using two worst-case analysis frameworks and an average-case one. Our worst-case analysis generalizes the notion of coherence to fusion frames and incorporates the restricted isometry property as a reconstruction condition. The two approaches provide complimentary intuition on the differences between standard sparsity models and sparsity in fusion frame models. Our understanding of the problem is further enhanced by the average case analysis. As we move from standard sparsity to fusion frame or other vector-based sparsity models, worst case analysis becomes increasingly pessimistic. The average case analysis provides a framework to discern which assumptions of the worst case model become irrelevant and which are critical. This paper complements and extends our work in [4].

In the remainder of this section we provide the motivation behind our work and describe some possible applications. Section II provides some background on Compressed Sensing and on fusion frames to serve as a quick reference for the fundamental concepts and our basic notation. In Section III we formulate the problem and establish the additional notation necessary in our development. We further explore the connections with existing research in the field, as well as possible extensions. In Section IV we prove recovery guarantees using the coherence properties of the sampling matrix. In Section V we prove similar guarantees using the restricted isometry properties (RIP) of the sampling matrix. Section VI presents an average case analysis of our methods which is more appropriate for typical usage scenarios. We conclude with a discussion of our results.

A. Motivation

As technology progresses, signals and computational sensing equipment becomes increasingly multidimensional. Sensors are being replaced by sensor arrays and samples are being replaced by multidimensional measurements. Yet, modern signal acquisition theory has not fully embraced the new computational sensing paradigm. Multidimensional measurements are often treated as collections of one-dimensional ones due to the mathematical simplicity of such treatment. This approach ignores the potential information and structure embedded in multidimensional signal and measurement models.

Our ultimate motivation is to provide a better understanding of more general mathematical objects, such as vector-valued data points [5]. Generalizing the notion of sparsity is part of such understanding. Towards that goal, we demonstrate that the generalization we present in this paper encompasses joint sparsity models [6], [7] as a special case. Furthermore, it is itself a special case of block-sparsity models [8], with significant additional structure that enhances existing results.

B. Applications

Although the development in this paper provides a general theoretical perspective, the principles and the methods we develop are widely applicable. In particular, the special case of joint (or simultaneous) sparsity has already been widely used in radar [9], sensor arrays [10], and MRI pulse design [11]. In these applications a mixed ℓ_1/ℓ_2 norm was used heuristically as a sparsity proxy. Part of our goals in this paper is to provide a solid theoretical understanding of such methods.

In addition, the richness of fusion frames allows the application of this work to other cases, such as target recognition and music segmentation. The goal in such applications is to identify, measure and track targets that are not well described by a single vector but by a whole subspace. In music segmentation, for example, each note is not characterized by a single frequency, but by the subspace spanned by the fundamental frequency of the instrument and its harmonics [12]. Furthermore, depending on the type of instrument in use, certain harmonics might or might not be present in the subspace. Similarly, in vehicle tracking and identification, the subspace of a vehicle's acoustic signature depends on the type of vehicle, its engine and its tires [13]. Note that in both applications, there might be some overlap in the subspaces which distinct instruments or vehicles occupy.

Fusion frames are quite suitable for such representations. The subspaces defined by each note and each instrument or each tracked vehicle generate a fusion frame for the whole space. Thus the fusion frame serves as a dictionary of targets to be acquired, tracked, and identified. The fusion frame structure further enables the use of sensor arrays to perform joint source identification and localization using far fewer measurements than a classical sampling framework.

We also envision fusion frames to play a key role in video acquisition, reconstruction and compression applications such as [14]. Nearby pixels in a video exhibit similar sparsity structure locally, but not globally. A block- or joint-sparsity model such as [6]–[8] is very constraining in such cases. On the other hand, subspace-based models for different parts of an image significantly improve the modeling ability compared to the standard compressed sensing model.

C. Notation

Throughout this paper $\|\mathbf{x}\|_p = \left(\sum_i x_i^p\right)^{1/p},\ p > 0$ denotes the standard ℓ_p norm. The operator norm of a matrix A from ℓ_p into ℓ_p is written as $\|A\|_{p\to p} = \max_{\|x\|_p \le 1} \|Ax\|_p$.

II. Background

A. Compressed Sensing

Compressed Sensing (CS) is a recently emerged field in signal processing that enables signal acquisition using very few measurements compared to the signal dimension, as long as the signal is sparse in some basis. It predicts that a signal $\mathbf{x} \in \mathbb{R}^N$ with only k non-zero coefficients can be recovered from only $n = \mathcal{O}(k \log(N/k))$ suitably chosen linear non-adaptive measurements, compactly represented using

$$\mathbf{y} = \mathbf{A}\mathbf{x}, \quad \mathbf{y} \in \mathbb{R}^n, \mathbf{A} \in \mathbb{R}^{n\times N}.$$

A necessary condition for exact signal recovery of all k-sparse $\mathbf{x}$ is that

$$\mathbf{A}\mathbf{z} \neq 0 \quad \text{ for all } \mathbf{z} \neq 0, \|\mathbf{z}\|_0 \leq 2k,$$

where the ℓ_0 'norm,' $\|\mathbf{x}\|_0$, counts the number of non-zero coefficients in $\mathbf{x}$. In this case, recovery is possible using the following combinatorial optimization,

$$\widehat{\mathbf{x}} = \text{argmin}_{\mathbf{x}\in\mathbb{R}^N} \|\mathbf{x}\|_0 \text{ subject to } \mathbf{y} = \mathbf{A}\mathbf{x}.$$

Unfortunately this is an NP-hard problem [15] in general, hence is infeasible.

Exact signal recovery using computationally tractable methods can be guaranteed if the coherence of the measurement matrix $\mathbf{A}$ is sufficiently small [5], [16]. The *coherence* of a matrix $\mathbf{A}$ with unit norm columns $\mathbf{a}_i$, $\|\mathbf{a}_i\|_2 = 1$, is defined as

$$\mu = \max_{i\neq j} |\langle \mathbf{a}_i, \mathbf{a}_j \rangle| \,.$$

Exact signal recovery is also guaranteed if $\mathbf{A}$ obeys a *restricted isometry property (RIP) of order* $2k$, i.e., if there exists a constant δ_{2k} such that for all $2k$-sparse signals $\mathbf{x}$

$$(1 - \delta_{2k})\|\mathbf{x}\|_2^2 \leq \|\mathbf{A}\mathbf{x}\|_2^2 \leq (1 + \delta_{2k})\|\mathbf{x}\|_2^2.$$

We note the relation $\delta_{2k} \leq (k-1)\mu$, which easily follows from Gershgorin's theorem. If the coherence of $\mathbf{A}$ is small or if $\mathbf{A}$ has a small RIP constant, then the following convex optimization program exactly recovers the signal from the measurement vector $\mathbf{y}$ [1],

$$\widehat{\mathbf{x}} = \text{argmin}_{\mathbf{x}\in\mathbb{R}^N} \|\mathbf{x}\|_1 \text{ subject to } \mathbf{y} = \mathbf{A}\mathbf{x}.$$

A surprising result is that random matrices with sufficient number of rows can achieve small coherence and small RIP constants with overwhelmingly high probability.

A large body of literature extends these results to measurements of signals in the presence of noise, to signals that are not exactly sparse but compressible [1], to several types of measurement matrices [17]–[21] and to measurement models beyond simple sparsity [22].

B. Fusion Frames

Fusion frames are generalizations of frames that provide a richer description of signal spaces. A *fusion frame* for $\mathbb{R}^M$ is a collection of subspaces $\mathcal{W}_j \subseteq \mathbb{R}^M$ and associated weights v_j, compactly denoted using $(\mathcal{W}_j, v_j)_{j=1}^N$, that satisfies

$$A\|\mathbf{x}\|_2^2 \leq \sum_{j=1}^N v_j^2 \, \|\mathbf{P}_j \mathbf{x}\|_2^2 \leq B\|\mathbf{x}\|_2^2$$

for some universal fusion frame bounds $0 < A \leq B < \infty$ and for all $\mathbf{x} \in \mathbb{R}^M$, where $\mathbf{P}_j$ denotes the orthogonal projection onto the subspace $\mathcal{W}_j$. We use m_j to denote the dimension of the jth subspace $\mathcal{W}_j$, $j = 1, \dots, N$. A frame is a special case of a fusion frame in which all the subspaces $\mathcal{W}_j$ are one-dimensional (i.e., $m_j = 1,\ j = 1, \dots, N$), and the weights v_j are the norms of the frame vectors.

The generalization to fusion frames allows us to capture interactions between frame vectors to form specific subspaces that are not possible in classical frame theory. Similar to classical frame theory, we call the fusion frame *tight* if the frame bounds are equal, $A = B$. If the fusion frame has $v_j = 1,\ j = 1, \dots, N$, we call it a *unit-norm* fusion frame. In this paper, we will in fact restrict to the situation of unit-norm fusion frames, since the anticipated applications are only concerned with membership in the subspaces and do not necessitate a particular weighting.

Dependent on a fusion frame $(\mathcal{W}_j, v_j)_{j=1}^N$ we define the Hilbert space $\mathcal{H}$ as

$$\mathcal{H} = \{(\mathbf{x}_j)_{j=1}^N : \mathbf{x}_j \in \mathcal{W}_j \text{ for all } j = 1, \dots, N\} \subseteq \mathbb{R}^{M \times N}.$$

Finally, let $\mathbf{U}_j \in \mathbb{R}^{M \times m_j}$ be a known but otherwise arbitrary matrix, the columns of which form an orthonormal basis for $\mathcal{W}_j$, $j = 1, \dots, N$, that is $\mathbf{U}_j^T \mathbf{U}_j = \mathbf{I}_{m_j}$, where $\mathbf{I}_{m_j}$ is the $m_j \times m_j$ identity matrix, and $\mathbf{U}_j \mathbf{U}_j^T = \mathbf{P}_j$.

The *fusion frame mixed $\ell_{q,p}$ norm* is defined as

$$\left\|(\mathbf{x}_j)_{j=1}^N\right\|_{q,p} \equiv \left(\sum_{j=1}^N (v_j \|\mathbf{x}_j\|_q)^p \right)^{1/p}, \tag{1}$$

where $(v_j)_{j=1}^N$ are the fusion frame weights. When the parameter q of the norm is omitted, it is implied to be $q = 2$:

$$\left\|(\mathbf{x}_j)_{j=1}^N\right\|_{p} \equiv \left(\sum_{j=1}^N (v_j \|\mathbf{x}_j\|_2)^p \right)^{1/p}.$$

Furthermore, for a sequence $\mathbf{c} = (\mathbf{c}_j)_{j=1}^N$, $\mathbf{c}_j \in \mathbf{R}^{m_j}$, we similarly define the mixed norm

$$\|\mathbf{c}\|_{2,1} = \sum_{j=1}^N \|\mathbf{c}_j\|_2.$$

The ℓ_0–'norm' (which is actually not even a quasi-norm) is defined as

$$\|\mathbf{x}\|_0 = \#\{j : \mathbf{x}_j \neq 0\}.$$

We call a vector $\mathbf{x} \in \mathcal{H}$ *k-sparse*, if $\|\mathbf{x}\|_0 \leq k$.

III. Sparse Recovery of Fusion Frame Vectors

We now consider the following scenario. Let $\mathbf{x}^0 = (\mathbf{x}_j^0)_{j=1}^N \in \mathcal{H}$, and assume that we only observe n linear combinations of those vectors, i.e., there exist some scalars a_{ij} satisfying that $\|(a_{ij})_{i=1}^n\|_2 = 1$ for all $j = 1, \ldots, N$ such that we observe

$$\mathbf{y} = (\mathbf{y}_i)_{i=1}^n = \left(\sum_{j=1}^N a_{ij} \mathbf{x}_j^0 \right)_{i=1}^n \in \mathcal{K}, \tag{2}$$

where $\mathcal{K}$ denotes the Hilbert space

$$\mathcal{K} = \{(\mathbf{y}_i)_{i=1}^n : \mathbf{y}_i \in \mathbf{R}^M \text{ for all } i = 1, \ldots, n\}.$$

We first notice that (2) can be rewritten as

$$\mathbf{y} = \mathbf{A_I} \mathbf{x}^0, \quad \text{where } \mathbf{A_I} = (a_{ij} \mathbf{I}_M)_{1 \le i \le n,\, 1 \le j \le N},$$

i.e., $\mathbf{A_I}$ is the matrix consisting of the blocks $a_{ij}\mathbf{I}_M$.

We now wish to recover $\mathbf{x}^0$ from those measurements. If we impose conditions on the sparsity of $\mathbf{x}^0$, it is suggestive to consider the following minimization problem,

$$\hat{\mathbf{x}} = \text{argmin}_{\mathbf{x} \in \mathcal{H}} \|\mathbf{x}\|_0 \quad \text{subject to } \sum_{j=1}^N a_{ij} \mathbf{x}_j = \mathbf{y}_i \text{ for all } i = 1, \ldots, n.$$

Using the matrix $\mathbf{A_I}$, we can rewrite this optimization problem as

$$(P_0) \quad \hat{\mathbf{x}} = \text{argmin}_{\mathbf{x} \in \mathcal{H}} \|\mathbf{x}\|_0 \quad \text{subject to } \mathbf{A_I}\mathbf{x} = \mathbf{y}.$$

However, this problem is NP-hard [15] and, as proposed in numerous publications initiated by [23], we prefer to employ ℓ_1 minimization techniques. This leads to the investigation of the following minimization problem,

$$\hat{\mathbf{x}} = \text{argmin}_{\mathbf{x} \in \mathcal{H}} \|\mathbf{x}\|_1 \quad \text{subject to } \mathbf{A_I}\mathbf{x} = \mathbf{y}.$$

Since we minimize over all $\mathbf{x} = (\mathbf{x}_j)_{j=1}^N \in \mathcal{H}$ and certainly $\mathbf{P}_j \mathbf{x}_j = \mathbf{x}_j$ by definition, we can rewrite this minimization problem as

$$(\tilde{P}_1) \quad \hat{\mathbf{x}} = \text{argmin}_{\mathbf{x} \in \mathcal{H}} \|\mathbf{x}\|_1 \quad \text{subject to } \mathbf{A_P}\mathbf{x} = \mathbf{y},$$

where

$$\mathbf{A_P} = (a_{ij} \mathbf{P}_j)_{1 \le i \le n,\, 1 \le j \le N}. \tag{3}$$

Problem $(\tilde{P}_1)$ bears difficulties to implement since minimization runs over $\mathcal{H}$. Still, it is easy to see that $(\tilde{P}_1)$ is equivalent to the optimization problem

$$(P_1) \quad (\hat{\mathbf{c}}_j)_j = \text{argmin}_{\mathbf{c}_j \in \mathbb{R}^{m_j}} \|(\mathbf{U}_j \mathbf{c}_j)_{j=1}^N\|_1 \text{ subject to } \mathbf{A_I}(\mathbf{U}_j \mathbf{c}_j)_j = \mathbf{y}, \tag{4}$$

where then $\hat{\mathbf{x}} = (\mathbf{U}_j \hat{\mathbf{c}}_j)_{j=1}^N$. This particular form ensures that the minimizer lies in the collection of subspaces $(\mathcal{W}_j)_{j=1}^N$ while minimization is performed over $\mathbf{c}_j \in \mathbb{R}^{m_j}$, $j = 1, \ldots, N$, hence feasible.

Finally, by rearranging (4), the optimization problems, invoking the ℓ_0-'norm' and ℓ_1-norm, can be rewritten using matrix-only notation as

$$(P_0) \quad \hat{\mathbf{c}} = \text{argmin}_{\mathbf{c}} \|\mathbf{c}\|_0 \text{ subject to } \mathbf{Y} = \mathbf{A}\mathbf{U}(\mathbf{c})$$

and

$$(P_1) \quad \hat{\mathbf{c}} = \text{argmin}_{\mathbf{c}} \|\mathbf{c}\|_{2,1} \text{ subject to } \mathbf{Y} = \mathbf{A}\mathbf{U}(\mathbf{c}),$$

in which

$$\mathbf{U}(\mathbf{c}) = \begin{pmatrix} \mathbf{c}_1^T \mathbf{U}_1^T \\ \hline \vdots \\ \hline \mathbf{c}_N^T \mathbf{U}_N^T \end{pmatrix} \in \mathbb{R}^{N \times M}, \ \mathbf{Y} = \begin{pmatrix} \mathbf{y}_1 \\ \hline \vdots \\ \hline \mathbf{y}_n \end{pmatrix} \in \mathbb{R}^{n \times M}, \mathbf{A} = (a_{ij}) \in \mathbb{R}^{n \times N}, \quad \mathbf{c}_j \in \mathbb{R}^{m_j}, \ \text{ and } \mathbf{y}_i \in \mathbb{R}^M.$$

Hereby, we additionally used that $\|\mathbf{U}_j \mathbf{c}_j\|_2 = \|\mathbf{c}_j\|_2$ by orthonormality of the columns of $\mathbf{U}_j$. We follow this notation for the remainder of the paper.

A. Extensions

Several extensions of this formulation and the work in this paper are possible, but beyond our scope. For example, the analysis we provide is on the exactly sparse, noiseless case. As with classical compressed sensing, it is possible to accommodate sampling in the presence of noise. It is also natural to consider the extension of this work to sampling signals that are not k-sparse in a fusion frame representation but can be very well approximated by such a representation. (However, see Section V-C.)

The richness of fusion frames also allows us to consider richer sampling matrices. Specifically, it is possible to consider sampling matrices with matrix entries, each operating on a different subspace of the fusion frame. Such extensions open the use of ℓ_1 methods to general vector-valued mathematical objects, to the general problem of sampling such objects [5], and to general model-based CS problems [22].

B. Relation with Previous Work

A special case of the problem above appears when all subspaces $(\mathcal{W}_j)_{j=1}^N$ are equal and also equal to the ambient space $\mathcal{W}_j = \mathbb{R}^M$ for all j. Thus, $\mathbf{P}_j = \mathbf{I}_M$ and the observation setup of Eq. (2) is identical to the matrix product

$$\mathbf{Y} = \mathbf{A}\mathbf{X}, \quad \text{where } \mathbf{X} = \begin{pmatrix} \mathbf{x}_1 \\ \hline \vdots \\ \hline \mathbf{x}_N \end{pmatrix} \in \mathbb{R}^{N \times M}.$$

This special case is the same as the well studied joint-sparsity setup of [6], [7], [24]–[26] in which a collection of M sparse vectors in $\mathbb{R}^N$ is observed through the same measurement matrix $\mathbf{A}$, and the recovery assumes that all the vectors have the same sparsity structure. The use of mixed ℓ_1/ℓ_2 optimization has been proposed and widely used in this case.

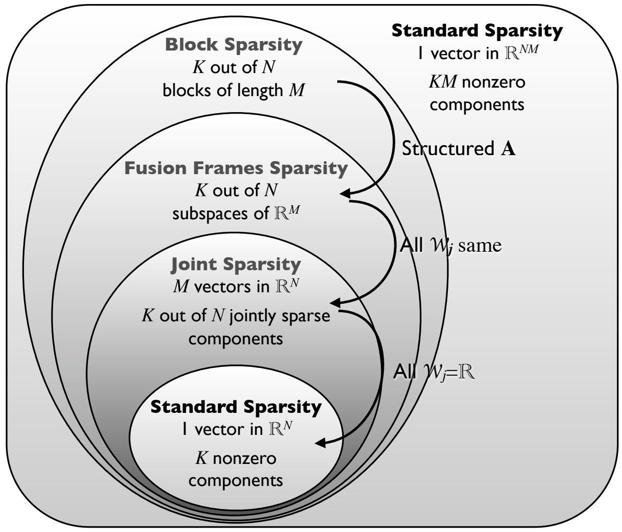

Fig. 1. Hierarchy of Sparsity Models

Our formulation is a special case of the bock sparsity problem [8], where we impose a particular structure on the measurement matrix $\mathbf{A}$. This relationship is already known for the joint sparsity model, which is also a special case of block sparsity. In other words, the fusion frames formulation we examine here specializes block sparsity problems and generalizes joint sparsity ones. As we discussed in the introduction, fusion frames provide significant structure to enhance the existing block-sparsity results, especially in the form of the fusion coherence, which we discuss in the next section.

We would also like to note that the hierarchy of such sparsity problems depends on their dimension. For example, a joint sparsity problem with $M = 1$ becomes the standard sparsity model. In that sense, joint sparsity models generalize standard sparsity models. The hierarchy of sparsity models is illustrated in the venn diagram of Fig. 1.

IV. Sparse Recovery Using Coherence Bounds

In this section we derive conditions on $\mathbf{c}^0$ and $\mathbf{A}$ so that $\mathbf{c}^0$ is the unique solution of (P_0) as well as of (P_1). Our approach generalizes the notion of *coherence*, a commonly used measure of morphological difference between the vectors of a measuring matrix. An excellent survey of the role of coherence in sparse representations can be found in [5].

A. Fusion Coherence

First, we require some analog of mutual coherence. In particular, we need to consider an adaptation of this notion to our more complicated situation involving the *angles* between the subspaces generated by the bases $\mathbf{U}_j$, $j = 1, \ldots, N$. In other words, here we face the problem of recovery of *vector-valued* (instead of scalar-valued) components. This leads to the following definition.

Definition 4.1: The *fusion coherence* of a matrix $\mathbf{A} \in \mathbf{R}^{n\times N}$ with normalized 'columns' $(\mathbf{a}_j = \mathbf{a}_{\cdot,j})_{j=1}^N$ and a fusion frame $(\mathcal{W}_j)_{j=1}^N$ for $\mathbf{R}^M$ is given by

$$\mu_f = \mu_f(\mathbf{A}, (\mathcal{W}_j)_{j=1}^N) = \max_{j\neq k} \left[|\langle \mathbf{a}_j, \mathbf{a}_k\rangle| \cdot \|\mathbf{P}_j\mathbf{P}_k\|_2 \right],$$

where $\mathbf{P}_j$ denotes the orthogonal projection onto $\mathcal{W}_j$, $j = 1, \ldots, N$.

Since the $\mathbf{P}_j$'s are projection matrices, we can also rewrite the definition of fusion coherence as

$$\mu_f = \max_{j\neq k} \left[|\langle \mathbf{a}_j, \mathbf{a}_k\rangle| \cdot |\lambda_{\max}(\mathbf{P}_j\mathbf{P}_k)|^{1/2} \right]$$

with $\lambda_{\max}$ denoting the largest eigenvalue, simply due to the fact that the eigenvalues of $\mathbf{P}_k\mathbf{P}_j\mathbf{P}_k$ and $\mathbf{P}_j\mathbf{P}_k$ coincide. Let us also remark that $|\lambda_{\max}(\mathbf{P}_j\mathbf{P}_k)|^{1/2}$ equals the largest absolute value of the cosines of the principle angles between $\mathcal{W}_j$ and $\mathcal{W}_k$.

B. Fusion Coherence and Sparse Recovery

We first formulate the main result of this section using the new notions previously developed.

Theorem 4.2: Let $\mathbf{A} \in \mathbf{R}^{n\times N}$ with normalized columns $(\mathbf{a}_j)_{j=1}^N$, let $(\mathcal{W}_j)_{j=1}^N$ be a fusion frame in $\mathbf{R}^M$, and let $\mathbf{Y} \in \mathbf{R}^{n\times M}$. If there exists a solution $\mathbf{c}^0$ of the system $\mathbf{A}\mathbf{U}(\mathbf{c}) = \mathbf{Y}$ satisfying

$$\|\mathbf{c}^0\|_0 < \frac{1}{2}(1 + \mu_f^{-1}), \tag{5}$$

then this solution is the unique solution of (P_0) as well as of (P_1).

Before we continue with the proof, let us for a moment consider the following special cases of this theorem.

a) Case $M = 1$: In this case the projection matrices equal 1, and hence the problem reduces to the classical recovery problem $\mathbf{A}\mathbf{x} = \mathbf{y}$ with $\mathbf{x} \in \mathbf{R}^N$ and $\mathbf{y} \in \mathbf{R}^n$. Thus our result reduces to the result obtained in [27], and the fusion coherence coincides with the commonly used mutual coherence, i.e., $\mu_f = \max_{j\neq k} |\langle \mathbf{a}_j, \mathbf{a}_k\rangle|$.

b) Case $\mathcal{W}_j = \mathbf{R}^M$ for all j: In this case the problem becomes the standard joint sparsity recovery. We recover a matrix $\mathbf{X}^0 \in \mathbb{R}^{N\times M}$ with few non-zero rows from knowledge of $\mathbf{A}\mathbf{X}^0 \in \mathbf{R}^{n\times M}$, without any constraints on the structure of each row of $\mathbf{X}^0$ (the general case has the constraint that $\mathbf{X}^0$ is required to be of the form $\mathbf{U}(\mathbf{c}^0)$). Again fusion coherence coincides with the commonly used mutual coherence, i.e., $\mu_f = \max_{j\neq k} |\langle \mathbf{a}_j, \mathbf{a}_k\rangle|$.

c) Case $\mathcal{W}_j \perp \mathcal{W}_k$ for all j, k: In this case the fusion coherence becomes 0. And this is also the correct answer, since in this case there exists precisely one solution of the system $\mathbf{A}\mathbf{U}(\mathbf{c}) = \mathbf{Y}$ for a given $\mathbf{Y}$. Hence the condition (5) becomes meaningless.

d) General Case: In the general case we can consider two scenarios: either we are given the subspaces $(\mathcal{W}_j)_j$ or we are given the measuring matrix $\mathbf{A}$. In the first situation we face the task of choosing the measuring matrix such that μ_f is as small as possible. Intuitively, we would choose the vectors $(\mathbf{a}_j)_j$ so that a pair $(\mathbf{a}_j, \mathbf{a}_k)$ has a large angle if the associated two subspaces $(\mathcal{W}_j, \mathcal{W}_k)$ have a small angle, hence balancing the two factors and try to reduce the maximum. In the second situation, we can use a similar strategy now designing the subspaces $(\mathcal{W}_j)_j$ accordingly.

C. Proof of Theorem 4.2

Before proceeding with the proof of Theorem 4.2, we introduce the fusion null space property as a useful tool, which generalizes the notion of null space property from the standard compressed sensing setup [28]. This notion will also be useful later to prove recovery bounds using the *fusion restricted isometry constants*.

Definition 4.3: Denote $\mathcal{N} = \{\mathbf{h} = (\mathbf{h}_j)_{j=1}^N : \mathbf{h}_j \in \mathbf{R}^{m_j}, \mathbf{AU}(\mathbf{h}) = 0\}$. The pair $(\mathbf{A}, (\mathcal{W}_j)_{j=1}^N)$, with a matrix $\mathbf{A} \in \mathbf{R}^{n \times N}$ and a fusion frame $(\mathcal{W}_j)_{j=1}^N$ is said to satisfy the *fusion null space property* if

$$\|\mathbf{h}_S\|_{2,1} < \frac{1}{2}\|\mathbf{h}\|_{2,1} \quad \text{for all } \mathbf{h} \in \mathcal{N} \setminus \{0\},$$

for all support sets $S \subset \{1, \ldots, N\}$ of cardinality at most k. Here $\mathbf{h}_S$ denotes the vector which coincides with $\mathbf{h}$ on the index set S and is zero outside S.

Lemma 4.4: Let $\mathbf{A} \in \mathbf{R}^{n \times N}$ and $(\mathcal{W}_j)_{j=1}^N$ be a fusion frame. Then all $\mathbf{c} = (\mathbf{c}_j)_{j=1}^N$, $\mathbf{c}_j \in \mathbf{R}^{m_j}$, with $\|\mathbf{c}\|_0 \le k$ are the unique solution to (P_1) with $\mathbf{Y} = \mathbf{AU}(\mathbf{c})$ if and only if $(\mathbf{A}, (\mathcal{W}_j)_{j=1}^N)$ satisfies the fusion null space property of order k.

Proof: Assume first that the fusion null space property holds. Let $\mathbf{c}^0$ be a vector with $\|\mathbf{c}^0\|_0 \le k$, and let $\mathbf{c}^1$ be an arbitrary solution of the system $\mathbf{AU}(\mathbf{c}) = \mathbf{Y}$, and set

$$\mathbf{h} = \mathbf{c}^0 - \mathbf{c}^1.$$

We obtain

$$\|\mathbf{c}^0\|_{2,1} - \|\mathbf{c}^1\|_{2,1} = \|\mathbf{c}^0_{S^c}\|_{2,1} + \|\mathbf{c}^0_S\|_{2,1} - \|\mathbf{c}^1_S\|_{2,1} \ge \|\mathbf{h}_{S^c}\|_{2,1} - \|\mathbf{h}_S\|_{2,1}.$$

This term is greater than zero for any $\mathbf{h} \neq 0$ provided that

$$\|\mathbf{h}_{S^c}\|_{2,1} > \|\mathbf{h}_S\|_{2,1} \tag{6}$$

or, in other words,

$$\tfrac{1}{2}\|\mathbf{h}\|_{2,1} > \|\mathbf{h}_S\|_{2,1}, \tag{7}$$

which is ensured by the fusion null space property.

Conversely, assume that all vectors $\mathbf{c}$ with $\|\mathbf{c}\|_0 \le k$ are recovered using (P_1). Then, for any $\mathbf{h} \in \mathcal{N} \setminus \{0\}$ and any $S \subset \{1, \ldots, N\}$ with $|S| \le k$, the k-sparse vector $\mathbf{h}_S$ is the unique minimizer of $\|\mathbf{c}\|_{2,1}$ subject to $\mathbf{Ac} = \mathbf{Ah}_S$. Further, observe that $\mathbf{A}(-\mathbf{h}_{S^c}) = \mathbf{A}(\mathbf{h}_S)$ and $-\mathbf{h}_{S^c} \neq \mathbf{h}_S$, since $\mathbf{h} \in \mathcal{N} \setminus \{0\}$. Therefore, $\|\mathbf{h}_S\|_{2,1} < \|\mathbf{h}_{S^c}\|_{2,1}$, which is equivalent to the fusion null space property because $\mathbf{h}$ was arbitrary. ■

For the proof of Theorem 4.2 we first derive a reformulation of the equation $\mathbf{AU}(\mathbf{c}) = \mathbf{Y}$. For this, let $\mathbf{P}_j$ denote the orthogonal projection onto $\mathcal{W}_j$ for each $j = 1, \ldots, N$, set $\mathbf{A}_\mathbf{P}$ as in (3) and define the map $\varphi_k : \mathbf{R}^{k \times M} \to \mathbf{R}^{kM}$, $k \ge 1$ by

$$\varphi_k(\mathbf{Z}) = \varphi_k \begin{pmatrix} \mathbf{z}_1 \\ \hline \vdots \\ \hline \mathbf{z}_k \end{pmatrix} = (\mathbf{z}_1 \ldots \mathbf{z}_k)^T, \text{ i.e., the concatenation of the rows.}$$

Then it is easy to see that

$$\mathbf{A}\mathbf{U}(\mathbf{c}) = \mathbf{Y} \quad \Leftrightarrow \quad \mathbf{A}_{\mathbf{P}}\varphi_N(\mathbf{U}(\mathbf{c})) = \varphi_n(\mathbf{Y}). \tag{8}$$

We now split the proof of Theorem 4.2 into two lemmas, and wish to remark that many parts are closely inspired by the techniques employed in [27], [29].

We first show that $\mathbf{c}^0$ satisfying (5) is the *unique* solution of (P_1).

Lemma 4.5: If there exists a solution $\mathbf{U}(\mathbf{c}^0) \in \mathbb{R}^{N\times M}$ of the system $\mathbf{A}\mathbf{U}(\mathbf{c}) = \mathbf{Y}$ with $\mathbf{c}^0$ satisfying (5), then $\mathbf{c}^0$ is the unique solution of (P_1).

Proof: We aim at showing that the condition on the fusion coherence implies the fusion null space property. To this end, let $\mathbf{h} \in \mathcal{N} \setminus \{0\}$, i.e., $\mathbf{A}\mathbf{U}(\mathbf{h}) = 0$. By using the reformulation (8), it follows that

$$\mathbf{A}_{\mathbf{P}}\varphi_N(\mathbf{U}(\mathbf{h})) = 0.$$

This implies that

$$\mathbf{A}_{\mathbf{P}}^*\mathbf{A}_{\mathbf{P}}\varphi_N(\mathbf{U}(\mathbf{h})) = 0.$$

Defining $\mathbf{a}_j$ by $\mathbf{a}_j = (a_{ij})_i$ for each j, the previous equality can be computed to be

$$(\langle \mathbf{a}_j, \mathbf{a}_k\rangle \mathbf{P}_j\mathbf{P}_k)_{jk}\varphi_N(\mathbf{U}(\mathbf{h})) = 0.$$

Recall that we have required the vectors $\mathbf{a}_j$ to be normalized. Hence, for each j,

$$\mathbf{U}_j\mathbf{h}_j = -\sum_{k\neq j} \langle \mathbf{a}_j, \mathbf{a}_k\rangle \mathbf{P}_j\mathbf{P}_k\mathbf{U}_k\mathbf{h}_k.$$

Since $\|\mathbf{U}_j\mathbf{h}_j\|_2 = \|\mathbf{h}_j\|_2$ for any j, this gives

$$\|\mathbf{h}_j\|_2 \le \sum_{k\neq j} |\langle \mathbf{a}_j, \mathbf{a}_k\rangle| \cdot \|\mathbf{P}_j\mathbf{P}_k\|_2\|\mathbf{h}_k\|_2 \le \mu_f(\|\mathbf{h}\|_{2,1} - \|\mathbf{h}_j\|_2),$$

which implies

$$\|\mathbf{h}_j\|_2 \le (1+\mu_f^{-1})^{-1}\|\mathbf{h}\|_{2,1}.$$

Thus, we have

$$\|\mathbf{h}_S\|_{2,1} \le \#(S)\cdot(1+\mu_f^{-1})^{-1}\|\mathbf{h}\|_{2,1} = \|\mathbf{c}^0\|_0\cdot(1+\mu_f^{-1})^{-1}\|\mathbf{h}\|_{2,1}.$$

Concluding, (5) and the fusion null space property show that $\mathbf{h}$ satisfies (7) unless $\mathbf{h} = 0$, which implies that $\mathbf{c}^0$ is the unique minimizer of (P_1) as claimed. ■

Using Lemma 4.5 it is easy to show the following lemma.

Lemma 4.6: If there exists a solution $\mathbf{U}(\mathbf{c}^0) \in \mathbb{R}^{N\times M}$ of the system $\mathbf{A}\mathbf{U}(\mathbf{c}) = \mathbf{Y}$ with $\mathbf{c}^0$ satisfying (5), then $\mathbf{c}^0$ is the unique solution of (P_0).

Proof: Assume $\mathbf{c}^0$ satisfies (5) and $\mathbf{A}\mathbf{U}(\mathbf{c}^0) = \mathbf{Y}$. Then, by Lemma 4.5, it is the unique solution of (P_1). Assume there is a $\tilde{\mathbf{c}}$ satisfying $\mathbf{A}\mathbf{U}(\tilde{\mathbf{c}}) = \mathbf{Y}$ such that $\|\tilde{\mathbf{c}}\|_0 \le \|\mathbf{c}^0\|_0$. Then $\tilde{\mathbf{c}}$ also satisfies (5) and again by Lemma 4.5 $\tilde{\mathbf{c}}$ is also the unique solution to (P_1). But this means that $\tilde{\mathbf{c}} = \mathbf{c}^0$ and $\mathbf{c}^0$ is the unique solution to (P_0). ■

We observe that Theorem 4.2 now follows immediately from Lemmas 4.5 and 4.6.

V. Sparse Recovery Using the Restricted Isometry Property

In this section we consider an alternative condition for sparse recovery using the restricted isometry property (RIP) of the sampling matrix.

A. The Fusion Restricted Isometry Property (FRIP)

The RIP property on the sampling matrix, first introduced in [1], complements the mutual coherence conditions. We introduce the following generalization for the fusion frame setup.

Definition 5.1: Let $\mathbf{A} \in \mathbb{R}^{n \times N}$ and $(\mathcal{W}_j)_{j=1}^N$ be a fusion frame for $\mathbb{R}^M$. Recall the matrix $\mathbf{A_P}$ defined in (3). The *fusion restricted isometry constant* δ_k is the smallest constant such that

$$(1-\delta_k)\|\mathbf{z}\|_2^2 \le \|\mathbf{A_P z}\|_2^2 \le (1+\delta_k)\|\mathbf{z}\|_2^2$$

for all $\mathbf{z} = (\mathbf{z}_1, \mathbf{z}_2, \ldots, \mathbf{z}_N) \in \mathbf{R}^{MN}$, $\mathbf{z}_j \in \mathbf{R}^M$, of sparsity $\|\mathbf{z}\|_0 \le k$.
Informally, we say that $(\mathbf{A}, (\mathcal{W}_j)_{j=1}^N)$ satisfies the *fusion restricted isometry property* (FRIP) if δ_k is small for reasonably large k. Note that we obtain the classical definition of the RIP of $\mathbf{A}$ if $M = 1$ and all the subspaces $\mathcal{W}_j$ have dimension 1.

Theorem 5.2: Let $(\mathbf{A}, (\mathcal{W}_j)_{j=1}^N)$ with fusion frame restricted isometry constant $\delta_{2k} < 1/3$. Then (P_1) recovers all k-sparse $\mathbf{c}$ from $\mathbf{Y} = \mathbf{AU}(\mathbf{c})$.

Proof: The proof proceeds analogously to the one of Theorem 2.6 in [21], that is, we establish the fusion null space property. The claim will then follow from Lemma 4.4.

Let us first note that

$$|\langle \mathbf{A_P u}, \mathbf{A_P v}\rangle| \le \delta_k \|\mathbf{u}\|_2 \|\mathbf{v}\|_2$$

for all $\mathbf{u} = (\mathbf{u}_1, \ldots, \mathbf{u}_N), \mathbf{v} = (\mathbf{v}_1, \ldots, \mathbf{v}_N) \in \mathbf{R}^{MN}$, $\mathbf{u}_j, \mathbf{v}_j \in \mathbf{R}^M$, with $\operatorname{supp}\mathbf{u} = \{j : \mathbf{u}_j \neq 0\} \cap \operatorname{supp}\mathbf{v} = \emptyset$ and $\|\mathbf{u}\|_0 + \|\mathbf{v}\|_0 \le k$. This statement follows completely analogously to the proof of Proposition 2.5(c) in [30], see also [28], [31].

Now let $\mathbf{h} \in \mathcal{N} = \{\mathbf{h} : \mathbf{AU}(\mathbf{h}) = 0\}$ be given. Using the reformulation (8), it follows that

$$\mathbf{A_P}\varphi_N(\mathbf{U}(\mathbf{h})) = 0.$$

In order to show the fusion null space property it is enough to consider an index set S_0 of size k of largest components $\|\mathbf{h}_j\|_2$, i.e., $\|\mathbf{h}_j\|_2 \ge \|\mathbf{h}_i\|_2$ for all $j \in S_0$, $i \in S_0^c = \{1, \ldots, N\} \setminus S_0$. We partition S_0^c into index sets $S_1, S_2, \ldots$ of size k (except possibly the last one), such that S_1 is an index set of largest components in S_0^c, S_2 is an index set of largest components in $(S_0 \cup S_0)^c$, etc. Let $\mathbf{h}_{S_i}$ be the vector that coincides with $\mathbf{h}$ on S_i and is set to zero outside. In view of $\mathbf{h} \in \mathcal{N}$ we have $\mathbf{AU}(\mathbf{h}_{S_0}) = \mathbf{AU}(-\mathbf{h}_{S_1} - \mathbf{h}_{S_2} - \cdots)$. Now set $\mathbf{z} = \varphi_N(\mathbf{U}(\mathbf{h}))$ and $\mathbf{z}_{S_i} = \varphi_N(\mathbf{U}(\mathbf{h}_{S_i}))$. It follows that $\mathbf{A_P}(\mathbf{z}_{S_0}) = \mathbf{A_P}(-\sum_{i\ge 1} \mathbf{z}_{S_i})$. By definition of the FRIP we obtain

$$\begin{aligned}
\|\mathbf{h}_{S_0}\|_2^2 &= \|\mathbf{z}_{S_0}\|_2^2 \le \frac{1}{1-\delta_k}\|\mathbf{A_P z}_{S_0}\|_2^2 = \frac{1}{1-\delta_k}\Big\langle \mathbf{A_P z}_{S_0}, \mathbf{A_P}\big(-\sum_{i\ge1}\mathbf{z}_{S_i}\big)\Big\rangle \\
&\le \frac{1}{1-\delta_k}\sum_{i\ge1}|\langle \mathbf{A_P z}_{S_0}, \mathbf{A_P}(-\mathbf{z}_{S_i})\rangle| \le \frac{\delta_{2k}}{1-\delta_k}\|\mathbf{z}_{S_0}\|_2 \cdot \sum_{i\ge1}\|\mathbf{z}_{S_i}\|_2.
\end{aligned}$$

Using that $\delta_k \leq \delta_{2k}$ and dividing by $\|\mathbf{z}_{S_0}\|_2$ yields

$$\|\mathbf{z}_{S_0}\|_2 \leq \frac{\delta_{2k}}{1-\delta_{2k}} \sum_{i\geq 1} \|\mathbf{z}_{S_i}\|_2.$$

By construction of the sets S_i we have $\|\mathbf{z}_j\|_2 \leq \frac{1}{k}\sum_{\ell \in S_{i-1}} \|\mathbf{z}_\ell\|_2$ for all $j \in S_i$, hence,

$$\|\mathbf{z}_{S_i}\|_2 = \big(\sum_{j\in S_i} \|\mathbf{z}_j\|_2^2\big)^{1/2} \leq \frac{1}{\sqrt{k}}\|\mathbf{z}_{S_{i-1}}\|_{2,1}.$$

The Cauchy-Schwarz inequality yields

$$\|\mathbf{h}_{S_0}\|_{2,1} \leq \sqrt{k}\|\mathbf{h}_{S_0}\|_2 \leq \frac{\delta_{2k}}{1-\delta_{2k}} \sum_{i\geq 1} \|\mathbf{z}_{S_{i-1}}\|_{2,1} \leq \frac{\delta_{2k}}{1-\delta_{2k}} (\|\mathbf{z}_{S_0}\|_{2,1} + \|\mathbf{z}_{S_0^c}\|_{2,1}) < \frac{1}{2}\|\mathbf{h}\|_{2,1},$$

where we used the assumption $\delta_{2k} < 1/3$. Hence, the fusion null space property follows. ∎

B. The classical RIP implies FRIP

Our next proposition relates the classical RIP with our newly introduced FRIP. Let us note, however, that it does not take into account any properties of the fusion frame, so it is sub-optimal—especially if the subspaces of the fusion frame are orthogonal or almost orthogonal.

Proposition 5.3: Let $\mathbf{A} \in \mathbf{R}^{n\times N}$ with classical restricted isometry constant $\tilde{\delta}_k$, that is,

$$(1-\tilde{\delta}_k)\|y\|_2^2 \leq \|\mathbf{A}y\|_2^2 \leq (1+\tilde{\delta}_k)\|y\|_2^2$$

for all k-sparse $y \in \mathbf{R}^N$. Let $(\mathcal{W}_j)_{j=1}^N$ be an arbitrary fusion frame for $\mathbf{R}^M$. Then the fusion restricted isometry constant δ_k of $(\mathbf{A}, (\mathcal{W})_{j=1}^N)$ satisfies $\delta_k \leq \tilde{\delta}_k$.

Proof: Let $\mathbf{c}$ satisfy $\|\mathbf{c}\|_0 \leq k$, and denote the columns of the matrix $\mathbf{U}(\mathbf{c})$ by $\mathbf{u}_1, \ldots, \mathbf{u}_M$. The condition $\|\mathbf{c}\|_0 \leq k$ implies that each $\mathbf{u}_i$ is k-sparse. Since $\mathbf{A}$ satisfies the RIP of order k with constant δ_k, we obtain

$$\|\mathbf{AU}(\mathbf{c})\|_{2,2}^2 = \sum_{i=1}^M \|\mathbf{A}\mathbf{u}_i\|_2^2 \leq (1+\delta_k)\sum_{i=1}^M \|\mathbf{u}_i\|_2^2 = (1+\delta_k)\|\mathbf{U}(\mathbf{c})\|_{2,2}^2 = (1+\delta_k)\|\mathbf{c}\|_{2,2}^2$$

as well as

$$\|\mathbf{AU}(\mathbf{c})\|_{2,2}^2 = \sum_{i=1}^M \|\mathbf{A}\mathbf{u}_i\|_2^2 \geq (1-\delta_k)\sum_{i=1}^M \|\mathbf{u}_i\|_2^2 = (1-\delta_k)\|\mathbf{U}(\mathbf{c})\|_{2,2}^2 = (1-\delta_k)\|\mathbf{c}\|_{2,2}^2.$$

This proves the proposition because $\mathbf{AU}(\mathbf{c}) = \mathbf{A}_{\mathbf{P}}\mathbf{U}(\mathbf{c})$. ∎

C. Additional Remarks

Of course, it is possible to extend this proof in a similar manner to [1], [31]–[33] such that we can accommodate measurement noise and signals that are well approximated by sparse fusion frame representation. We state the analog of the main theorem of [31] without proof.

Theorem 5.4: Assume that the fusion restricted isometry constant δ_{2k} of $(\mathbf{A}, (\mathcal{W}_j)_{j=1}^N)$ satisfies

$$\delta_{2k} < \Delta := \sqrt{2} - 1 \approx 0.4142.$$

For $\mathbf{x} \in \mathcal{H}$, let noisy measurements $\mathbf{Y} = \mathbf{A}\mathbf{x} + \eta$ be given with $\|\eta\|_2 \leq \epsilon$. Let $\mathbf{c}^{\#}$ be the solution of the convex optimization problem

$$\min \|\mathbf{c}\|_{2,1} \quad \text{subject to} \quad \|\mathbf{A}\mathbf{U}(\mathbf{c}) - \mathbf{Y}\|_2 \leq \eta,$$

and set $\mathbf{x}^{\#} = \mathbf{U}(\mathbf{c}^{\#})$. Then

$$\|\mathbf{x} - \mathbf{x}^{\#}\|_{\mathcal{H}} \leq C_1 \eta + C_2 \frac{\|\mathbf{x}^k - \mathbf{x}\|_{\mathcal{H}}}{\sqrt{k}}$$

where $\mathbf{x}_k$ is obtained from $\mathbf{x}$ be setting to zero all components except the k largest in norm. The constants $C_1, C_2 > 0$ only depend on δ_{2k} (or rather on $\Delta - \delta_{2k}$).

VI. Average Case Analysis

In this section we study the effect of the dimension of subspaces of the considered fusion frame on recoverability of a vector $\mathbf{x} \in \mathcal{H}$. Intuitively, it seems that the higher the dimension, the 'easier' the recovery via the ℓ_1 minimization problem [26] should be. However, it turns out that this intuition only holds true if we consider an average case analysis, averaging over the vectors to be recovered. Adding dimensions can be interpreted as adding more channels to a joint sparsity problem, which is known to not improve recoverability in the worst case [26].

A. *General Recovery Condition*

We start our analysis by deriving a recovery condition which the reader might want to compare with [34], [35]. Given a matrix $\mathbf{X} \in \mathbb{R}^{N \times M}$, we let $\mathrm{sgn}(\mathbf{X}) \in \mathbb{R}^{N \times M}$ denote the matrix which is generated from $\mathbf{X}$ by normalizing each entry X_{ji} by the norm of the corresponding row $\mathbf{X}_{j,\cdot}$. More precisely,

$$\mathrm{sgn}(\mathbf{X})_{ji} = \begin{cases} \frac{X_{ji}}{\|\mathbf{X}_{j,\cdot}\|_2} & : \quad \|\mathbf{X}_{j,\cdot}\|_2 \neq 0, \\ 0 & : \quad \|\mathbf{X}_{j,\cdot}\|_2 = 0. \end{cases}$$

Column vectors are defined similarly by $\mathbf{X}_{\cdot,i}$.

Under a certain condition on A, which is dependent on the support of the solution, we derive the result below on unique recovery. To phrase it, let $(\mathcal{W}_j)_{j=1}^N$ be a fusion frame with associated orthogonal bases $(\mathbf{U}_j)_{j=1}^N$ and orthogonal projections $(\mathbf{P}_j)_{j=1}^N$, and recall the definition of the notion $\mathbf{U}(\mathbf{c})$ in Section III. Then, for some support set $S = \{j_1, \ldots, j_{|S|}\} \subseteq \{1, \ldots, N\}$ of $\mathbf{U}(\mathbf{c})$, we let

$$\mathbf{A}_S = (\mathbf{A}_{\cdot,j_1} \cdots \mathbf{A}_{\cdot,j_{|S|}}) \in \mathbb{R}^{n \times |S|}$$

and

$$\mathbf{U}(\mathbf{c})_S = \begin{pmatrix} \mathbf{c}_{j_1}^T \mathbf{U}_{j_1}^T \\ \hline \vdots \\ \hline \mathbf{c}_{j_{|S|}}^T \mathbf{U}_{j_{|S|}}^T \end{pmatrix} \in \mathbb{R}^{|S| \times M}.$$

Before stating the theorem, we wish to remark that its proof uses similar ideas as the analog proof in [26]. We however state all details for the convenience of the reader.

Theorem 6.1: Retaining the notions from the beginning of this section, we let $\mathbf{c}_j \in \mathbb{R}^{m_j}$, $j = 1\ldots,N$ with $S = \mathrm{supp}(\mathbf{c}) = \{j : \mathbf{c}_j \neq 0\}$. If $\mathbf{A}_S$ is non-singular and there exists a matrix $\mathbf{H} \in \mathbb{R}^{n\times M}$ such that

$$\mathbf{A}_S^T\mathbf{H} = \mathrm{sgn}(\mathbf{U}(\mathbf{c})_S) \tag{9}$$

and

$$\|\mathbf{H}^T\mathbf{A}_{\cdot,j}\|_2 < 1 \quad \text{for all } j \notin S, \tag{10}$$

then $\mathbf{U}(\mathbf{c})$ is the unique solution of (P_1).

Proof: Let $\mathbf{c}_j \in \mathbb{R}^{m_j}$, $j = 1\ldots,N$ be a solution of $\mathbf{Y} = \mathbf{AU}(\mathbf{c})$, set $S = \mathrm{supp}(\mathbf{U}(\mathbf{c}))$, and suppose $\mathbf{A}_S$ is non-singular and the hypotheses (9) and (10) are satisfied for some matrix $\mathbf{H} \in \mathbb{R}^{n\times M}$. Let $\mathbf{c}'_j \in \mathbb{R}^{m_j}$, $j = 1\ldots,N$ with $\mathbf{c}'_{j_0} \neq \mathbf{c}_{j_0}$ for some j_0 be a different set of coefficient vectors which satisfies $\mathbf{Y} = \mathbf{AU}(\mathbf{c}')$. To prove our result we aim to establish that

$$\|\mathbf{c}\|_{2,1} < \|\mathbf{c}'\|_{2,1}. \tag{11}$$

We first observe that

$$\|\mathbf{c}\|_{2,1} = \|\mathbf{U}(\mathbf{c})\|_{2,1} = \|\mathbf{U}(\mathbf{c})_S\|_{2,1} = \mathrm{tr}\left[\mathrm{sgn}(\mathbf{U}(\mathbf{c})_S)(\mathbf{U}(\mathbf{c})_S)^T\right].$$

Set $S' = \mathrm{supp}(\mathbf{U}(\mathbf{c}'))$, apply (9), and exploit properties of the trace,

$$\|\mathbf{c}\|_{2,1} = \mathrm{tr}\left[\mathbf{A}_S^T\mathbf{H}(\mathbf{U}(\mathbf{c})_S)^T\right] = \mathrm{tr}\left[(\mathbf{AU}(\mathbf{c}))^T\mathbf{H}\right] = \mathrm{tr}\left[(\mathbf{AU}(\mathbf{c}'))^T\mathbf{H}\right] = \mathrm{tr}\left[(\mathbf{AU}(\mathbf{c}'_S))^T\mathbf{H}\right] + \mathrm{tr}\left[(\mathbf{AU}(\mathbf{c}'_{S^c}))^T\mathbf{H}\right]. \tag{12}$$

Now use the Cauchy-Schwarz inequality to obtain

$$\begin{aligned}\|\mathbf{c}\|_{2,1} &\leq \sum_{j\in S}\|(\mathbf{U}(\mathbf{c}')_S)_{j,\cdot}\|_2\|(\mathbf{H}^T\mathbf{A}_S)_{\cdot,j}\|_2 + \sum_{j\in S^c}\|(\mathbf{U}(\mathbf{c}')_{S^c})_{j,\cdot}\|_2\|(\mathbf{H}^T\mathbf{A}_{S^c})_{\cdot,j}\|_2\\ &\leq \max_{j\in S}\|(\mathbf{H}^T\mathbf{A}_S)_{\cdot,j}\|_2\|\mathbf{c}'_S\|_{2,1} + \max_{j\in S^c}\|(\mathbf{H}^T\mathbf{A}_{S^c})_{\cdot,j}\|_2\|\mathbf{c}'_{S^c}\|_{2,1} < \|\mathbf{c}'_S\|_{2,1} + \|\mathbf{c}'_{S^c}\|_{2,1} = \|\mathbf{c}\|_{2,1}.\end{aligned}$$

The strict inequality follows from $\|\mathbf{c}_{S^c}\|_1 > 0$, which is true because otherwise $\mathbf{c}$ would be supported on S. The equality $\mathbf{AU}(\mathbf{c}) = \mathbf{AU}(\mathbf{c}')$ would then be in contradiction to the injectivity of $\mathbf{A}_S$ (recall that $\mathbf{c} \neq \mathbf{c}'$). This concludes the proof. ■

The matrix $\mathbf{H}$ exploited in Theorem 6.1 might be chosen as

$$\mathbf{H} = (\mathbf{A}_S^\dagger)^T\mathrm{sgn}(\mathbf{U}(\mathbf{c})_S)$$

to satisfy (9). This particular choice will in fact be instrumental for the average case result we are aiming for. For now, we obtain the following result as a corollary from Theorem 6.1.

Corollary 6.2: Retaining the notions from the beginning of this section, we let $\mathbf{c}_j \in \mathbb{R}^{m_j}$, $j = 1\ldots,N$ with $S = \mathrm{supp}(\mathbf{U}(\mathbf{c}))$. If $\mathbf{A}_S$ is non-singular and

$$\|\mathrm{sgn}(\mathbf{U}(\mathbf{c})_S)^T\mathbf{A}_S^\dagger\mathbf{A}_{\cdot,j}\|_2 < 1 \quad \text{for all } j \notin S, \tag{13}$$

then $\mathbf{U}(\mathbf{c})$ is the unique solution of (P_1).

B. Probability Model

To derive a result in the average case, we require a probability model on the k-sparse $\mathbf{U}(\mathbf{c})$, more precisely, on the associated vectors $\mathbf{c}_j \in \mathbb{R}^{m_j}$, $j = 1 \dots, N$. From now on, we assume that the dimensions of all subspaces are the same, i.e., that

$$m = m_j \quad \text{for all } j = 1 \dots, N.$$

Inspired by the probability model in [26], we will assume that on the k-element support set $S = \text{supp}(\mathbf{U}(\mathbf{c})) = \{j_1, \dots, j_k\}$ the entries of each vector $\mathbf{c}_j$ are independent and follow a normal distribution,

$$\mathbf{U}(\mathbf{c})_S = \begin{pmatrix} \mathbf{X}_1^T \mathbf{U}_{j_1}^T \\ \hline \vdots \\ \hline \mathbf{X}_k^T \mathbf{U}_{j_k}^T \end{pmatrix} \in \mathbb{R}^{k \times M}, \tag{14}$$

where $\mathbf{X} = (\mathbf{X}_1^T \dots \mathbf{X}_k^T)^T \in \mathbb{R}^{Nm}$ is a Gaussian random vector, i.e., all entries are independent standard normal random variables.

For later use, we will introduce the matrices $\tilde{\mathbf{U}}_j \in \mathbb{R}^{M \times Nm}$ defined by

$$\tilde{\mathbf{U}}_j = (\mathbf{0}_{M \times m} | \cdots | \mathbf{0}_{M \times m} | \mathbf{U}_j | \mathbf{0}_{M \times m} | \cdots | \mathbf{0}_{M \times m}),$$

where $\mathbf{U}_j$ is the jth block. For some $\mathbf{b} = (b_1, \dots, b_k)^T \in \mathbb{R}^k$, we can then write $\mathbf{U}(\mathbf{c})_S^T \mathbf{b}$ as

$$\sum_{\ell=1}^{k} b_\ell \tilde{\mathbf{U}}_{j_\ell} \mathbf{X} \in \mathbb{R}^M. \tag{15}$$

C. Average Case Recovery for Fusion Frames

Our main result shows that the failure probability for recovering $\mathbf{U}(\mathbf{c})$ decays exponentially fast with growing dimension m of the subspaces. Interestingly, the quantity θ involved in the estimate is again dependent on the 'angles' between subspaces and is of the flavor of the fusion coherence from Section IV.

Theorem 6.3: Let $S \subseteq \{1, \dots, N\}$ be a set of cardinality k and suppose that $\mathbf{A} \in \mathbb{R}^{n \times N}$ satisfies

$$\|\mathbf{A}_S^\dagger \mathbf{A}_{\cdot,j}\|_2 \le \alpha < 1 \quad \text{for all } j \notin S. \tag{16}$$

Let $(\mathcal{W}_j)_{j=1}^N$ be a fusion frame with associated orthogonal bases $(\mathbf{U}_j)_{j=1}^N$ and orthogonal projections $(\mathbf{P}_j)_{j=1}^N$, and let $\mathbf{Y} \in \mathbf{R}^{n \times M}$. Further, let $\mathbf{c}_j \in \mathbb{R}^{m_j}$, $j = 1 \dots, N$ with $S = \text{supp}(\mathbf{U}(\mathbf{c}))$ such that the coefficients on S are given by (14), and let θ be defined by

$$\theta = 1 + \max_i \sum_{j \neq i} \lambda_{\max} (\mathbf{P}_i \mathbf{P}_j)^{1/2}.$$

Choose $\delta \in (0, 1 - \alpha^2)$. Then with probability at least

$$1 - (N-k) \exp\left(-\frac{(\sqrt{1-\delta} - \alpha)^2}{2\alpha^2 \theta} m\right) - k \exp\left(-\frac{\delta^2}{4} m\right)$$

the minimization problem (P_1) recovers $\mathbf{U}(\mathbf{c})$ from $\mathbf{Y} = \mathbf{A}\mathbf{U}(\mathbf{c})$. In particular, the failure probability can be estimated by

$$N \exp\left(-\left(\max_{\delta\in(0,1-\alpha^2)} \min\left\{\frac{(\sqrt{1-\delta}-\alpha)^2}{2\alpha^2\theta}, \frac{\delta^2}{4}\right\}\right) m\right).$$

Let us note that [26] provides several mild conditions that imply (16).

The proof of the above result is developed in several steps. A key ingredient is a concentration of measure result: If f is a Lipschitz function on $\mathbb{R}^K$ with Lipschitz constant L, i.e., $|f(x) - f(y)| \le L\|x-y\|_2$ for all $x, y \in \mathbb{R}^K$, and $\mathbf{X}$ is a K-dimensional vector of independent standard normal random variables then [36, eq. (2.35)]

$$\mathbb{P}(|f(X) - \mathbb{E}f(X)| \ge u) \le 2e^{-u^2/(2L^2)} \quad \text{for all } u > 0. \tag{17}$$

Our first lemma investigates the properties of a function related to (15) that are needed to apply the above inequality.

Lemma 6.4: Let $\mathbf{b} = (b_1, \dots, b_k)^T \in \mathbb{R}^k$ and $S = \{j_1, \dots, j_k\} \subseteq \{1, \dots, N\}$. Define the function f by

$$f(\mathbf{X}) = \|\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell}\mathbf{X}\|_2, \quad \mathbf{X} \in \mathbf{R}^{Nm}.$$

Then the following holds.

(i) f is Lipschitz with constant $\|\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell}\|_{2\to 2}$.

(ii) For a standard Gaussian vector $\mathbf{X} \in \mathbb{R}^{Nm}$ we have $\mathbb{E}[f(\mathbf{X})] \le \sqrt{m}\|\mathbf{b}\|_2$.

Proof: The claim in (i) follows immediately from

$$|f(\mathbf{X}) - f(\mathbf{Y})| = \left|\|\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell}\mathbf{X}\|_2 - \|\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell}\mathbf{Y}\|_2\right|$$

$$\le \quad \|\left(\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell}\right)(\mathbf{X}-\mathbf{Y})\|_2 \le \|\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell}\|_{2\to 2}\|\mathbf{X}-\mathbf{Y}\|_2.$$

It remains to prove (ii). Obviously,

$$(\mathbb{E}f(\mathbf{X}))^2 \le \mathbb{E}[f(\mathbf{X})^2] = \mathbb{E}\left[\sum_{i=1}^M \left|\sum_{\ell=1}^k b_\ell(\tilde{\mathbf{U}}_{j_\ell}\mathbf{X})_i\right|^2\right] = \sum_{i=1}^M \sum_{\ell,\ell'=1}^k b_\ell b_{\ell'} \mathbb{E}[(\tilde{\mathbf{U}}_{j_\ell}\mathbf{X})_i(\tilde{\mathbf{U}}_{j_{\ell'}}\mathbf{X})_i].$$

Invoking the conditions on $\mathbf{X}$,

$$\mathbb{E}[f(\mathbf{X})]^2 \le \sum_{i=1}^M \sum_{\ell=1}^k b_\ell^2 \mathbb{E}[(\tilde{\mathbf{U}}_{j_\ell}\mathbf{X})_i]^2 = \sum_{\ell=1}^k b_\ell^2 \|\tilde{\mathbf{U}}_{j_\ell}\|_F^2 = m\|\mathbf{b}\|_2^2.$$

■

Next we estimate the Lipschitz constant of the function f in the previous lemma.

Lemma 6.5: Let $\mathbf{b} = (b_1, \dots, b_k)^T \in \mathbb{R}^k$ and $S = \{j_1, \dots, j_k\} \subseteq \{1, \dots, N\}$. Then

$$\|\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell}\|_{2\to 2} \le \|\mathbf{b}\|_\infty \sqrt{1 + \max_{i\in S} \sum_{j\in S, j\ne i} \lambda_{\max}(\mathbf{P}_i\mathbf{P}_j)^{1/2}}.$$

Proof: First observe that

$$\|\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell}\|_{2\to 2} = \|(\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell})^T(\sum_{\ell=1}^k b_\ell \tilde{\mathbf{U}}_{j_\ell})\|_{2\to 2}^{1/2} = \|\sum_{\ell,\ell'=1}^k b_\ell b_{\ell'} \tilde{\mathbf{U}}_{j_\ell}^T \tilde{\mathbf{U}}_{j_{\ell'}}\|_{2\to 2}^{1/2}.$$

Since

$$\| \sum_{\ell,\ell'=1}^{k} b_\ell b_{\ell'} \tilde{\mathbf{U}}_{j_\ell}^T \tilde{\mathbf{U}}_{j_{\ell'}} \|_{2\to 2} \le \|\mathbf{b}\|_\infty^2 \|(\mathbf{U}_i^T \mathbf{U}_j)_{i,j\in S}\|_{2\to 2},$$

it follows that

$$\| \sum_{\ell=1}^{k} b_\ell \tilde{\mathbf{U}}_{j_\ell} \|_{2\to 2} \le \|\mathbf{b}\|_\infty \|(\mathbf{U}_i^T \mathbf{U}_j)_{i,j\in S}\|_{2\to 2}^{1/2}. \tag{18}$$

Next,

$$\|(\mathbf{U}_i^T \mathbf{U}_j)_{i,j\in S}\|_{2\to 2} \le \max_{i\in S} \sum_{j\in S} \|\mathbf{U}_i^T \mathbf{U}_j\|_{2\to 2} = 1 + \max_{i\in S} \sum_{j\in S, j\neq i} \|\mathbf{U}_i^T \mathbf{U}_j\|_{2\to 2}. \tag{19}$$

By definition of the orthogonal projections $\mathbf{P}_i$,

$$\|\mathbf{U}_i^T \mathbf{U}_j\|_{2\to 2} = \|(\mathbf{U}_i^T \mathbf{U}_j)^T \mathbf{U}_i^T \mathbf{U}_j\|_{2\to 2}^{1/2} = \|\mathbf{U}_i^T \mathbf{U}_j \mathbf{U}_j^T \mathbf{U}_i\|_{2\to 2}^{1/2} = \|\mathbf{P}_i \mathbf{P}_j\|_{2\to 2}^{1/2} = \lambda_{\max}(\mathbf{P}_i \mathbf{P}_j)^{1/2}.$$

Combining with (19),

$$\|(\mathbf{U}_i^T \mathbf{U}_j)_{i,j\in S}\|_{2\to 2} \le 1 + \max_{i\in S} \sum_{j\in S, j\neq i} \lambda_{\max}(\mathbf{P}_i \mathbf{P}_j)^{1/2}. \tag{20}$$

The lemma now follows from (18), (19), and (20). ■

Now we have collected all ingredients to prove our main result.

D. *Proof of Theorem 6.3*

Denote $\mathbf{b}^{(j)} = (b_1^{(j)}, \ldots, b_k^{(j)})^T = \mathbf{A}_S^\dagger \mathbf{A}_{\cdot,j} \in \mathbb{R}^k$ for all $j \notin S$ and choose $\delta \in (0, 1-\alpha^2)$. By Corollary 6.2, the probability that the minimization problem (P_1) fails to recover $\mathbf{U}(\mathbf{c})$ from $\mathbf{Y} = \mathbf{A}\mathbf{U}(\mathbf{c})$ can be estimated as

$$\begin{aligned}
&\mathbb{P}\left(\max_{j\notin S} \|\mathrm{sgn}(\mathbf{U}(\mathbf{c})_S)^T \mathbf{b}^{(j)}\|_2 > 1\right) = \mathbb{P}\left(\max_{j\notin S} \| \sum_{\ell=1}^{k} b_\ell^{(j)} \|U_{j_\ell} \mathbf{X}_\ell\|_2^{-1} \tilde{\mathbf{U}}_{j_\ell} \mathbf{X}\|_2 > 1\right)\\
\le\ & \mathbb{P}\left(\max_{j\notin S} \| \sum_{\ell=1}^{k} b_\ell^{(j)} \tilde{\mathbf{U}}_{j_\ell} \mathbf{X}\|_2 > \sqrt{(1-\delta)m}\right) + \mathbb{P}\left(\max_{\ell=1,\ldots,k} \|U_{j_\ell} \mathbf{X}_\ell\|_2 < \sqrt{(1-\delta)m}\right)\\
\le\ & \sum_{j\notin S} \mathbb{P}\left(\| \sum_{\ell=1}^{k} b_\ell^{(j)} \tilde{\mathbf{U}}_{j_\ell} \mathbf{X}\|_2 > \sqrt{(1-\delta)m}\right) + \sum_{\ell=1}^{k} \mathbb{P}\left(\|\mathbf{X}_\ell\|_2^2 \le (1-\delta)m\right).
\end{aligned}$$

Since X_ℓ is a standard Gaussian vector in $\mathbb{R}^m$ [37, Corollary 3] gives

$$\mathbb{P}\left(\|\mathbf{X}_\ell\|_2^2 \le (1-\delta)m\right) \le \exp(-\delta^2 m/4).$$

Furthermore, the concentration inequality (17) combined with Lemmas 6.4 and Lemma 6.5 yields

$$\begin{aligned}
&\mathbb{P}\left(\| \sum_{\ell=1}^{k} b_\ell^{(j)} \tilde{\mathbf{U}}_{j_\ell} \mathbf{X}\|_2 > \sqrt{(1-\delta)m}\right)\\
=\ & \mathbb{P}\left(\| \sum_{\ell=1}^{k} b_\ell^{(j)} \tilde{\mathbf{U}}_{j_\ell} \mathbf{X}\|_2 > \|b^{(j)}\|_2 \sqrt{m} + (\sqrt{1-\delta} - \|b^{(j)}\|_2)\sqrt{m}\right)\\
\le\ & \exp\left(-\frac{(\sqrt{1-\delta} - \|b^{(j)}\|_2)^2 m}{2\|b^{(j)}\|_\infty^2 \theta}\right) \le \exp\left(-\frac{(\sqrt{1-\delta} - \|b^{(j)}\|_2)^2 m}{2\|b^{(j)}\|_2^2 \theta}\right)\\
\le\ & \exp\left(-\frac{(\sqrt{1-\delta} - \alpha)^2 m}{2\alpha^2 \theta}\right).
\end{aligned}$$

Combining the above estimates yields the statement of the Theorem.

VII. Conclusions and Discussion

The main contribution in this paper is the generalization of standard Compressed Sensing results for sparse signals to signals that have a sparse fusion frame representation. As we demonstrated, the results generalize to fusion frames in a very nice and easy to apply way, using the mixed ℓ_0/ℓ_1 norm.

A key result in our work shows that the structure in fusion frames provides additional information that can be exploited in the measurement process. Specifically, our definition of fusion coherence demonstrates the importance of prior knowledge about the signal structure. Indeed, if we know that the signal lies in subspaces with very little overlap (i.e., where $\|\mathbf{P}_j\mathbf{P}_k\|_2$ is small in Definition 4.1) we can relax the requirement on the coherence of the corresponding vectors in the sampling matrix (i.e., $|\langle \mathbf{a}_j, \mathbf{a}_k\rangle|$ in the same definition) and maintain a low fusion coherence. This behavior emerges from the inherent structure of fusion frames.

The emergence of this behavior is evident both in the guarantees provided by the fusion coherence, and in our average case analysis. Unfortunately, our analysis of this property currently has not been incorporated in a tight approach to satisfying the Fusion RIP property, as described in Section V. While an extension of such analysis for the RIP guarantees is desirable, it is still an open problem.

Our average case analysis also demonstrates that as the sparsity structure of the problem becomes more intricate, the worst case analysis can become too pessimistic for many practical cases. The average case analysis provides reassurance that typical behavior is as expected; significantly better compared to the worst case. Our results corroborate and extend similar findings for the special case of joint sparsity in [26].

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