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Verifiable conditions of \( \ell_1 \)-recovery of sparse signals with sign restrictions

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Abstract

We propose necessary and sufficient conditions for a sensing matrix to be “s-semigood” – to allow for exact \( \ell_1 \)-recovery of sparse signals with at most \( s \) nonzero entries under sign restrictions on part of the entries. We express the error bounds for imperfect \( \ell_1 \)-recovery in terms of the characteristics underlying these conditions. Furthermore, we demonstrate that these characteristics, although difficult to evaluate, lead to verifiable sufficient conditions for exact sparse \( \ell_1 \)-recovery and to efficiently computable upper bounds on those \( s \) for which a given sensing matrix is s-semigood. We concentrate on the properties of proposed verifiable sufficient conditions of s-semigoodness and describe their limits of performance.

1 Introduction

In this paper we address the recovery problem as follows: given an observation \( y \in \mathbb{R}^m \),

\[
y = Aw + e,
\]

(1)

where \( A \in \mathbb{R}^{m \times n} \) (in this context \( m < n \)), is a given matrix, \( e \in \mathbb{R}^m \) is the observation error, assess a sparse signal \( w \in \mathbb{R}^n \). We suppose that the a priori information about \( w \) amounts to the sign restrictions as follows: we are given the subsets \( P_+ \) and \( P_- \) of \( \{1, ..., n\} \), \( P_+ \cap P_- = \emptyset \), such that \( w_i \geq 0 \) for \( i \in P_+ \) and \( w_i \leq 0 \) for \( i \in P_- \).

A celebrated solution to the problem is given by the \( \ell_1 \)-recovery, which amounts to taking, as an estimate of \( w \), an optimal solution \( \hat{w} \) to the optimization problem

\[
\hat{w} \in \text{Argmin}_x \{ \|x\|_1 : \|Ax - y\| \leq \varepsilon, \ x_i \geq 0 \text{ for } i \in P_+, \ x_i \leq 0 \text{ for } i \in P_- \}
\]

(2)

(here \( \varepsilon \) is an a priori bound on the norm \( \|e\| \) of the observation disturbance, \( \|\cdot\| \) being some norm on \( \mathbb{R}^m \)). When no sign restrictions are imposed on \( w \) (i.e. \( P_+ = P_- = \emptyset \)), this problem reduces to the most commonly studied estimator in the existing Compressive Sensing theory. The central result in Compressive Sensing is that when signal \( w \) is \( s \)-sparse (i.e. has no more than \( s \) nonzero entries) and the matrix \( A \) possesses a certain well-defined property, then the \( \ell_1 \)-recovery \( \hat{w} \) is close to \( w \), provided the error bound \( \varepsilon \) is small. Our goal here is to specify efficiently the properties of a given sensing matrix \( A \) with respect to \( \ell_1 \)-recovery in the case when sign constraints are present.

To be more precise, let us consider the problem of noiseless recovery (there is no observation error, i.e. \( y = Aw \)). Let \( A \) be a given \( m \times n \) matrix. We are interested to answer the question:
Whether $A$ is such that whenever the true signal $w$ in (1) is $s$-sparse and satisfies the sign constraints $w_i \geq 0, i \in P_+, w_i \leq 0, i \in P_-$, the $\ell_1$-recovery

$$\hat{w} \in \operatorname{Argmin}_x \{ \|x\|_1 : Ax = y, x_i \geq 0 \text{ for } i \in P_+, x_i \leq 0 \text{ for } i \in P_- \}$$

reverses $w$ exactly.

If the answer is positive, we say that $A$ is $s$-semigood$^1$.

The Compressive Sensing theory provides several sufficient/necessary and sufficient conditions of $s$-semigoodness in two special cases: the one of nonnegative $w$, i.e. $P_+ = \{1, \ldots, n\}$, and the one when no sign constraints are imposed. In the former case, the founding paper of Donoho and Tanner [6] provides characterizations of $s$-semigoodness in terms of neighboring properties of the polytope $AS$, $S$ being the standard simplex $S = \{ x \in \mathbb{R}^n : x \geq 0, \sum_i x_i \leq 1 \}$. This paper contains also several important examples of $m \times n$ matrices which are $\lfloor \frac{m}{s} \rfloor$-semigood (here $\lfloor a \rfloor$ stands for the integer part of $a$) and demonstrates that various types of randomly generated matrices share this property with overwhelming probability. An equivalent characterization of $s$-semigoodness has been provided in this case by Zhang in [13], where it is shown that $A$ is $s$-semigood if and only if the kernel $\ker A$ is strictly half $s$-balanced, meaning that for any set $I \subset \{1, \ldots, n\}$ of cardinality $\leq s$ it holds

$$\sum_{i \in I} z_i < \sum_{i \notin I} |z_i| \text{ for any } z \in \ker A \text{ such that } z_i \leq 0, \text{ for all } i \notin I.$$ (4)

This necessary and sufficient condition for $s$-semigoodness can be compared to the condition for $s$-goodness of the matrix $A$, as it is given in [12]: $A$ is $s$-good if and only if $\ker A$ is strictly $s$-balanced, meaning that for any set $I \subset \{1, \ldots, n\}$ of cardinality $\leq s$ it holds

$$\sum_{i \in I} |z_i| < \sum_{i \notin I} |z_i| \text{ for any } z \in \ker A$$

(5)

(note that the sufficiency of this condition can be traced back to the discussion in Section 3 of [5]).

It should be mentioned that the characterizations (4), (5) and geometric characterizations of $s$-(semi)goodness of $A$ from [6, 7] share an important drawback – they seemingly cannot be verified in a computationally efficient way. To the best of our knowledge, the only computationally tractable techniques available in the “classical” theory of Compressive Sensing which allow to certify $s$-(semi)goodness of a given sensing matrix are those based on the mutual incoherence

$$\mu(A) = \max_{i \neq j} \frac{|A_i^T A_j|}{A_i^T A_i}$$

(6)

where $A_i$ are columns of $A$ (assumed to be nonzero). Clearly, the mutual incoherence can be easily computed even for large matrices. Unfortunately, it turns out that that the estimates of “level of (semi)goodness” of a sensing matrix based on mutual incoherence usually are too conservative, in particular, they are provably dominated by the verifiable Linear Programming-based sufficient conditions for $s$-goodness proposed in the companion paper [10] and based on Zhang’s characterization of $s$-goodness (5). Another verifiable sufficient condition for $s$-goodness, which uses the Semidefinite Relaxation, has been recently proposed in [4].

The contributions of this paper, which follow the approach developed in [10], are as follows.

$^1$We use the term “$s$-semigoodness” to comply with the terminology of the companion paper [10], where we used the name $s$-goodness to indicate that $\ell_1$-recovery as in (3) without the sign restrictions is exact.
• Taking Zhang’s characterizations of (semi)goodness (4), (5) as a starting point, we develop in Section 2 several equivalent necessary and sufficient conditions for $s$-semigoodness of a matrix $A$ in the case of general-type sign restrictions. Then in Section 3 we establish error bounds for inexact $\ell_1$-recovery (noisy observation (1), imprecise optimization in (2), nearly-sparse true signals); these bounds are expressed in the same terms as the necessary and sufficient conditions for $s$-semigoodness from Section 2. To the best of our knowledge, these bounds are new.

• We use the LP-relaxation technique, introduced in [10], to provide novel efficiently verifiable sufficient conditions for $s$-semigoodness of a matrix $A$; utilizing these conditions, one can build, in a computationally efficient manner, lower bounds on the “level of $s$-semigoodness of $A$”, that is, the largest $s = s_s(A)$ for which $A$ is $s$-semigood with respect to given $P_\pm$. Some properties of these verifiable conditions, same as limits of their performance, are studied in Sections 4, 5, where we provide also a computationally efficient scheme for upper bounding $s_s(A)$. In Section 6 we develop another efficiently computable lower bound for $s_s(A)$ by applying the Semidefinite Relaxation scheme, completely similar to the construction of [4] handling the “unsigned” case $P_\pm = \emptyset$.

• It turns out that our verifiable sufficient conditions for $s$-semigoodness can be expressed in terms of specific properties of the linear recovery $\hat{w}^{\text{lin}} = Y^T y$ associated with an appropriate $m \times n$ matrix $Y$. In Section 7, we propose and justify a new Matching Pursuit algorithm associated with this linear recovery.

2 Necessary and sufficient conditions for $s$-semigoodness

Let $A$ be an $m \times n$ matrix, let $s$, $1 \leq s \leq m$, be an integer, and let $P_+, P_-$ and $P_n$ be a partition of $\{1, \ldots, n\}$ into three non-overlapping subsets. We say that $A$ is $s$-semigood, if for every vector $w$ with at most $s$ nonzero entries satisfying $w_i \geq 0$ for $i \in P_+$, and $w_i \leq 0$ for $i \in P_-$, $w$ is the unique optimal solution to the problem

$$\text{Opt} = \min_z \{ \| z \|_1 : Az = Aw, \ z_i \geq 0 \ \forall \ i \in P_+, \ z_i \leq 0 \ \forall \ i \in P_- \}.$$  

Our primary goals are to find necessary and sufficient and verifiable sufficient conditions for $A$ to be $s$-semigood.

Note that without loss of generality we may assume $P_- = \emptyset$. Indeed, by replacing the partition $P_+, P_-$, $P_n$ with the partition $\overline{P}_+ = P_+ \cup P_-, \overline{P}_- = \emptyset, \overline{P}_n = P_n$ and matrix $A$ with the matrix $\overline{A}$ obtained from $A$ by multiplying the columns with indices $i \in P_-$ by $-1$, $s$-semigoodness of $A$ with respect to the original sign restrictions given by $P_+, P_n$ is equivalent to the $s$-semigoodness of the new matrix $\overline{A}$ with respect to the new sign restrictions. By this reason, we assume from now on that $P_- = \emptyset$. Besides this, we assume without loss of generality that $P_+ = \{1, \ldots, p\}$ and $P_n = \{p+1, \ldots, n\}$ for some $p$. From now on, we denote by $\overline{P}_n$ the set of all signals satisfying the sign restrictions:

$$\overline{P}_n = \{ w \in \mathbb{R}^n : w_i \geq 0 \ \forall \ i \in P_+ \}.$$  

Note that since $P_- = \emptyset$, (7) simplifies to

$$\text{Opt} = \min_z \{ \| z \|_1 : Az = Aw, \ z_i \geq 0 \ \forall \ i \in P_+ \}.$$  

Let us fix a norm $\| \cdot \|$ on $\mathbb{R}^n$, and let $\| \cdot \|_s$ be the conjugate norm.

\[ \]
Proposition 2.1 Let $m,n,s$ and $P_+$ be given. The following six conditions on an $m \times n$ matrix $A$ are equivalent to each other:

(i) $A$ is $s$-semigood;

(ii) For every subset $J$ of $\{1,\ldots,n\}$ with $\text{Card}(J) \leq s$, and any $x \in \text{Ker}A \setminus \{0\}$ such that $x_i \leq 0$ for all $i \in P_+ \setminus J$ one has

$$\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_+} |x_i| < \sum_{i \notin J} |x_i|.$$

(iii) There exists $\xi \in (0,1)$ such that for every subset $J$ of $\{1,\ldots,n\}$ with $\text{Card}(J) \leq s$ and any $x \in \text{Ker}A$ such that $x_i \leq 0$ for all $i \in P_+ \setminus J$ one has

$$\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_+} |x_i| \leq \xi \sum_{i \notin J} |x_i|.$$

(iv) There exist $\xi \in (0,1)$ and $\theta \in [1,\infty)$ such that $A$ satisfies the condition $\text{SG}_s(\xi,\theta)$ as follows: for every $x \in \text{Ker}A$ and every subset $J$ of $\{1,\ldots,n\}$ with $\text{Card}(J) \leq s$, one has

$$\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_+} |x_i| \leq \xi \left( \sum_{i \in P_+ \setminus J} |x_i| + \sum_{i \in P_+ \setminus J} \psi(x_i) \right), \quad \psi(t) = \max[-t, \theta t],$$

or equivalently: for all $x \in \text{Ker}A$,

$$\Theta(x) := \max_{J \subseteq \{1,\ldots,n\}, \text{Card}(J) \leq s} \left[ \sum_{i \in J \cap P_+} \max((1-\xi)x_i, (1+\theta \xi)x_i) + \sum_{i \in J \cap P_+} (1+\xi)|x_i| \right] \leq \Psi(x).$$

(v) There exist $\xi \in (0,1)$, $\theta \in [1,\infty)$ and $\beta \in [0,\infty)$ such that $A$ satisfies the condition $\text{SG}_{s,\beta}(\xi,\theta)$ as follows: for every $x \in \mathbb{R}^n$ and every subset $J$ of $\{1,\ldots,n\}$ with $\text{Card}(J) \leq s$, one has

$$\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_+} |x_i| \leq \beta \|Ax\| + \xi \left( \sum_{i \in P_+ \setminus J} |x_i| + \sum_{i \in P_+ \setminus J} \psi(x_i) \right), \quad \psi(t) = \max[-t, \theta t].$$

(vi) There exist $\xi \in (0,1)$ and $\beta \in [0,\infty)$ such that $A$ satisfies the condition $\text{SG}_{s,\beta}(\xi)$ as follows: for every $J \subseteq \{1,\ldots,n\}$ with $\text{Card}(J) \leq s$ and any $x \in \mathbb{R}^n$ such that $x_i \leq 0$ for all $i \in P_+ \setminus J$, one has

$$\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_+} |x_i| \leq \beta \|Ax\| + \xi \sum_{i \notin J} |x_i|.$$

We provide the proof of Proposition 2.1 in Appendix A.

As we have already mentioned in Introduction, when $P_n = \emptyset$ or $P_+ = \emptyset$, the characterizations (i)–(iv) of $s$-semigoodness are not completely new. For instance, when $P_n = \emptyset$, a necessary and sufficient condition for $s$-semigoodness of $A$ in the form (ii) has been established in [13] (compare (ii) to the definition (4) of half $s$-balancedness of $\text{Ker}A$). On the other hand, the equivalent formulation of this characterization in terms of conditions $\text{SG}_{s,\beta}(\xi,\theta)$ and $\text{SG}_{s,\beta}(\xi)$ seems to be new. It appears that the same conditions allow to control the error of $\ell_1$-recovery in the case when the vector $w \in \mathbb{R}^n$ is not $s$-sparse and the problem (7) is not solved to exact optimality.
3 Error bounds for imperfect $\ell_1$-recovery

We have seen that the conditions provided in Proposition 2.1 are responsible for $s$-semigoodness of a sensing matrix $A$, that is, for the precise $\ell_1$-recovery of a signal $w \in \mathcal{P}_n$ in the “ideal case” when the signal $w$ is $s$-sparse, there is no measurement error and the optimization problem (7) is solved to exact optimality. In this section, we will show that these quantities also control the error of $\ell_1$-recovery in the case when the signal vector $w \in \mathcal{P}_n$ is not exactly $s$-sparse, there is an observation noise and problem (7) is not solved to exact optimality. The error bound is as follows:

**Proposition 3.1** Let $w \in \mathcal{P}_n$ be such that $\|w-w^s\|_1 \leq \mu$, where $w^s$ is the vector obtained from $w$ by replacing all but the $s$ largest in magnitude entries in $w$ with zeros, let $y$ be such that $\|Aw-y\| \leq \varepsilon$, and let, finally, $x$ be an approximate solution to the optimization problem

$$\text{Opt} = \min \{ \|z\|_1 : \|Az-y\| \leq \varepsilon, \ z_i \geq 0 \ \forall i \in P_+ \},$$

such that $\|x\|_1 \leq \text{Opt} + \nu$ and $\|Ax-y\| \leq \delta$.

1. Let $A$ satisfy the condition $\text{SG}_{s,\beta}(\xi, \theta)$ with certain $\xi \in (0,1)$, $\beta \in [0,\infty)$ and $\theta \in [1,\infty)$. Then

$$\|x-w\|_1 \leq \frac{1+\xi}{1-\xi} \nu + \frac{2(1+\xi\theta)}{1-\xi} \mu + \frac{2\beta}{1-\xi}(\varepsilon + \delta).$$

(10)

2. Let $A$ satisfy condition $\text{SG}_{s,\beta}(\xi)$ with certain $\xi \in (0,1)$ and $\beta \in [0,\infty)$. Then

$$\|x-w\|_1 \leq \frac{1+\xi}{1-\xi} \nu + \frac{2(1+\beta\alpha)}{1-\xi} \mu + \frac{2\beta}{1-\xi}(\varepsilon + \delta).$$

(11)

where $\alpha$ stands for the maximum of $\| \cdot \|$-norms of the columns in $A$.

**Proof.** Let $I$ be the support of $w^s$, $\bar{I}$ be the complement of $I$ in $\{1,...,n\}$, and let $z = w-x$. We denote $I_+ = \{ i \in I : z_i \geq 0 \}$, $I_+ = \{ i \in \bar{I} : z_i \geq 0 \}$, and $I_- = I \setminus I_+$, $\bar{I}_- = \bar{I} \setminus I_+$. Observe that $w$ is a feasible solution to (9), so that

$$\|x\|_1 \leq \|w\|_1 + \nu.$$  

(12)

Obviously, $|x_i| - |w_i| \geq -|z_i|$ and $|x_i| - |w_i| \geq |z_i| - 2|w_i|$. Now using $x_i, w_i \geq 0 \ \forall i \in P_+$, and $z_i \geq 0 \ \forall i \in I_+$, we get

$$\nu \geq \sum_i (|x_i| - |w_i|) \quad \text{[by (12)]}$$

$$\geq \sum_{i \in I_+} (x_i - w_i) + \sum_{i \in I_-} (x_i - w_i) + \sum_{i \in I_+} (x_i - w_i) + \sum_{i \in I_+} (x_i - w_i)$$

$$+ \sum_{i \in P_+} (|x_i| - |w_i|)$$

$$\geq - \sum_{i \in I_+} z_i + \sum_{i \in I_-} |z_i| + \sum_{i \in I_+} |z_i| - \sum_{i \in I_+} w_i$$

$$- \sum_{i \in I_-} |z_i| + \sum_{i \in \bar{I}_+} (|z_i| - 2|w_i|),$$

or, equivalently,

$$\sum_{i \in I_+} |z_i| + \sum_{i \in I_-} |z_i| + \sum_{i \in \bar{I}_+} |z_i| \leq \nu + \sum_{i \in I_+} z_i + \sum_{i \in I_-} |z_i| + \sum_{i \in I_+} w_i + 2 \sum_{i \in \bar{I}_+} |w_i|.$$  

(13)
On the other hand, we have

$$\|Az\| = \|Aw - Ax\| \leq \|Aw - y\| + \|Ax - y\| \leq \varepsilon + \delta. \quad (14)$$

Then by condition $SG_{s,\beta}(\xi, \theta)$ with $(I_+ \cap P_+) \cup (I \cap P_n)$ in the role of $J$, we get

$$\sum_{i \in I_+ \cap P_+} z_i + \sum_{i \in I \cap P_n} |z_i| \leq \beta \|Az\| + \xi \left[ \sum_{i \in I \cap P_n} \theta \right] \left[ \sum_{i \in (I \cap P_n) \cup (I_+ \cap P_+)} \psi(z_i) \right]$$

$$\kappa \leq \beta \|Az\| + \xi \left[ \sum_{i \in I \cap P_n} \theta \right] \left[ \sum_{i \in (I \cap P_n) \cup (I_+ \cap P_+)} \psi(z_i) \right]$$

Let us derive a bound on $\tau(\theta)$. Now (13) implies, independently of whether $SG_{s,\beta}(\xi, \theta)$ is or is not true, the first inequality in the following chain:

$$\tau(\theta) \leq \nu + \sum_{i \in I_+ \cap P_+} z_i + \sum_{i \in I \cap P_n} \theta \left[ \sum_{i \in (I \cap P_n) \cup (I_+ \cap P_+)} \psi(z_i) \right]$$

$$\leq \nu + \kappa + (1 + \theta) \sum_{i \in I_+ \cap P_+} w_i + 2 \sum_{i \in I \cap P_n} \theta \left[ \sum_{i \in (I \cap P_n) \cup (I_+ \cap P_+)} \psi(z_i) \right]$$

$$\leq \nu + \kappa + (1 + \theta) \mu, \quad \text{[since } w_i \geq z_i \text{ for } i \in P_+]$$

and, in particular,

$$\tau(1) = \sum_{i \in I_+ \cap P_+} z_i + \sum_{i \in I \cap P_n} \theta \left[ \sum_{i \in (I \cap P_n) \cup (I_+ \cap P_+)} \psi(z_i) \right] \leq \nu + \kappa + 2\mu. \quad (17)$$

Combining (14), (15) and (16), we obtain

$$\kappa \leq \beta(\varepsilon + \delta) + \xi [\nu + \kappa + (1 + \theta) \mu],$$

whence

$$\kappa = \sum_{i \in I_+ \cap P_+} z_i + \sum_{i \in I \cap P_n} \theta \left[ \sum_{i \in (I \cap P_n) \cup (I_+ \cap P_+)} \psi(z_i) \right] \leq \beta(\varepsilon + \delta) + \xi [\nu + (\theta + 1) \mu] \frac{1}{1 - \xi}.$$

Summing up the latter inequality and (17), we obtain

$$\|z\|_1 = \sum_{i \in I \cap P_n} |z_i| + \sum_{i \in I_+ \cap P_+} \left[ \sum_{i \in I \cap P_n} |z_i| + \sum_{i \in I_+ \cap P_+} \theta \left[ \sum_{i \in (I \cap P_n) \cup (I_+ \cap P_+)} \psi(z_i) \right] \right] \leq \nu + 2\mu + 2\kappa$$

$$\leq \nu + 2\mu + \frac{2\beta(\varepsilon + \delta) + 2\xi [\nu + (\theta + 1) \mu]}{1 - \xi}$$

$$= \frac{1 + \xi}{1 - \xi} \nu + \frac{2(1 + \xi \theta)}{1 - \xi} \mu + \frac{2\beta}{1 - \xi} (\varepsilon + \delta),$$

which is (10).

To show (11) observe that increasing $\varepsilon$ to $\varepsilon' = \varepsilon + \alpha \mu$, we can think that the true signal underlying the observation $y$ is $w^\varepsilon$ rather than $w$; note that (12) implies that

$$\|x\|_1 \leq \|w^\varepsilon\|_1 + \nu', \quad \nu' = \nu + \mu. \quad (18)$$
We can now repeat the reasoning which follows (12), with (18) in the role of (12), $w^*$ in the role of $w, \varepsilon'$ in the role of $\varepsilon$ and 0 in the role of $\mu$, thus arriving at the following analogy of the bound (10):

$$\|x - w^*\|_1 \leq \frac{1 + \xi}{1 - \xi} \nu' + \frac{2\beta}{1 - \xi}(\varepsilon' + \delta),$$

whence

$$\|x - w\|_1 \leq \frac{1 + \xi}{1 - \xi} \nu' + \frac{2\beta}{1 - \xi}(\varepsilon' + \delta) + \mu,$$

which is nothing but (11). □

4 Verifiable conditions for $s$-semigoodness

We are about to demonstrate that among the conditions listed in Proposition 2.1, $\text{SG}_{s,\beta}(\xi, \theta)$ leads to efficiently computable “nontrivial” lower and upper bounds.

4.1 Verifiable sufficient conditions for $s$-semigoodness by LP-relaxation

Let

$$\mathcal{U}_s = \{ u \in \mathbb{R}^n : \|u\|_1 \leq s, \|u\|_\infty \leq 1 \} ,$$

so that $\mathcal{U}_s$ is the convex hull of all $\{-1, 0, 1\}$ vectors with at most $s$ nonzero entries, and for $x \in \mathbb{R}^n$, let $\|x\|_{s,1}$ be the sum of the $s$ largest in magnitude entries in $x$, or equivalently,

$$\|x\|_{s,1} = \max_{u \in \mathcal{U}_s} u^T x.$$

Let

$$(D_\theta[x])_i = \begin{cases} [1 + \theta \xi] \max|x_i, 0|, & i \in P_+ \\ (1 + \xi)|x_i|, & i \not\in P_+ \end{cases} ,$$

and

$$\Phi(x) = \|D_\theta[x]\|_{s,1}.$$  

Suppose $\xi \in [0, 1), \theta \in [1, \infty)$ and $\rho, \sigma \in [0, \infty)$ are given. Consider the following condition on an $m \times n$ matrix $A$:

**VSG$_s(\xi, \theta, \rho, \sigma)$:** There exists $m \times n$ matrix $Y = [y_1, \ldots, y_n]$ and a vector $v \in \mathbb{R}^m$ such that

$$\begin{align*}
\Phi(-C_i[Y, A]) + (A^T v)_i &\leq \xi, \ 1 \leq i \leq n \quad (a) \\
\Phi(C_i[Y, A]) - (A^T v)_i &\leq \xi, \ i \not\in P_+ \quad (b) \\
\Phi(C_i[Y, A]) - (A^T v)_i &\leq \theta \xi, \ i \in P_+ \quad (c) \\
\|y_i\|_* &\leq \sigma, \ 1 \leq i \leq n \quad (d) \\
\|v\|_* &\leq \rho \quad (e)
\end{align*}$$

where $C_i[Y, A]$ is the $i$-th column of the matrix $I - Y^T A$.

Observe that this condition is verifiable, since (19) is a system of explicit convex constraints on $Y$ and $v$.

**Proposition 4.1** Let $A$ satisfy VSG$_s(\xi, \theta, \rho, \sigma)$ with some $\xi \in [0, 1), \theta \in [1, \infty), \text{ and } \rho, \sigma \in [0, \infty)$. Then $A$ satisfies $\text{SG}_{s,\beta}(\xi, \theta)$ with

$$\beta = \rho + \sigma \max_{k_+, k_n} \left\{ k_+(1 + \theta \xi) + k_n(1 + \xi) : \begin{array}{l}
0 \leq k_+ \leq \text{Card}(P_+) \\
0 \leq k_n \leq \text{Card}(P_n) \\
k_+ + k_n \leq s
\end{array} \right\} \leq \rho + \sigma s(1 + \theta \xi).$$

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Proof. Let $A$ satisfy $\mathbf{VSG}_s(\xi, \theta, \rho, \sigma)$, and let $Y = \{y_1, \ldots, y_n\}$ and $\nu$ satisfy (19). Let, further, $I \subset \{1, \ldots, n\}$ be such that $\text{Card}(I) \leq s$, and let $x \in \mathbb{R}^n$. Let $u \in \mathbb{R}^n$ be given by

$$u_i = \begin{cases} 
1 + \theta \xi, & i \in P_+ \cap I, \ x_i \geq 0 \\
1 - \xi, & i \in P_+ \cap I, \ x_i < 0 \\
(1 + \xi) \text{sign}(x_i), & i \in P_+ \cap I \\
0, & i \in P_+ \cap I, \ x_i \in \{0\} \\
\end{cases} $$

Note that $u$ has at most $s$ nonzero entries, the entries of $u$ with indices from $P_+$ belong to $[0, 1 + \theta \xi]$, and the modulae of entries in $u$ with indices from $P_-$ are $\leq 1 + \xi$, so that $u^T z \leq \Phi(z)$ for all $z$. We have

$$u^T [I - Y^T A] x = \sum_i u^T C_i[Y, A] x_i = \sum_{i : x_i \geq 0} u^T C_i[Y, A] x_i + \sum_{i : x_i < 0} u^T [-C_i[Y, A]] |x_i|$$

$\leq \sum_{i : x_i \geq 0} \Phi(C_i[Y, A]) x_i + \sum_{i : x_i < 0} \Phi(-C_i[Y, A]) |x_i| \quad [\text{since } u^T z \leq \Phi(z)]$

$\leq \sum_{i : x_i \geq 0, i \notin P_+} [\xi + (A^T v)_i] x_i + \sum_{i : x_i < 0, i \notin P_+} [\theta \xi + (A^T v)_i] x_i + \sum_{i : x_i < 0} [\xi - (A^T v)_i] x_i \quad [\text{by (19)}]$

$= \xi \left[ \sum_{i : x_i \geq 0, i \notin P_+} x_i + \theta \sum_{i : x_i \geq 0, i \in P_+} x_i + \sum_{i : x_i < 0} |x_i| \right] + x^T A^T v$

$= \xi \left[ \sum_{i \in P_+} \max[-x_i, \theta x_i] + \sum_{i \in P_-} |x_i| \right] + x^T A^T v,$

whence

$$u^T [I - Y^T A] x \leq \xi \left[ \sum_{i \in P_+} \max[-x_i, \theta x_i] + \sum_{i \in P_-} |x_i| \right] + \rho \|Ax\| \quad (21)$$

(recall that $\|\nu\|_* \leq \rho$). On the other hand, recalling the definition of $u$ and that $\|y_i\|_* \leq \sigma$, we have

$$u^T [I - Y^T A] x = u^T x - \sum_{i \in I} u_i y_i^T A x$$

$= \sum_{i \in I} \max[(1 - \xi) x_i, (1 + \theta \xi) x_i] + (1 + \xi) \sum_{i \in I \cap P_+} |x_i| - \sum_{i \in I} u_i y_i^T A x$

$\geq \sum_{i \in I \cap P_+} \max[(1 - \xi) x_i, (1 + \theta \xi) x_i] + (1 + \xi) \sum_{i \in I \cap P_+} |x_i| - \sigma \left[ \sum_{i \in I \cap P_+} (1 + \theta \xi) + \sum_{i \in I \cap P_-} (1 + \xi) \right] \|Ax\|.$

Combining the resulting inequality with (21), we get

$$\sum_{i \in I \cap P_+} [x_i + \xi \max[-x_i, \theta x_i]] + (1 + \xi) \sum_{i \in I \cap P_-} |x_i| \leq \beta \|Ax\| + \xi \left[ \sum_{i \in P_+} \max[-x_i, \theta x_i] + \sum_{i \in P_-} |x_i| \right]$$

with $\beta$ given by (20), or, equivalently,

$$\sum_{i \in I \cap P_+} x_i + \sum_{i \in I \cap P_-} |x_i| \leq \beta \|Ax\| + \xi \left[ \sum_{i \in P_+ \setminus I} \max[-x_i, \theta x_i] + \sum_{i \in P_- \setminus I} |x_i| \right].$$
The latter relation holds true for every $x \in \mathbb{R}^n$ and for every set $I \subset \{1, \ldots, n\}$ of cardinality $\leq s$, so that $A$ satisfies $SG_{k\beta}(\xi, \theta)$. □

4.1.1 Origin of the verifiable sufficient condition

The condition $\text{VSG}_s(\xi, \theta, \rho, \sigma)$ is yielded by a simple and general construction, and we believe it makes sense to present this construction in its general form. The essence of the matter is in building a verifiable sufficient condition for the validity of (8), see Proposition 2.1.iv. By positive homogeneity of degree 1 of the convex functions $\Theta, \Psi$ participating in (8), the latter relation is equivalent to

$$\text{Opt} := \max_{x} \{ \Theta(x) : Ax = 0, x \in X \} \leq \xi, \quad X = \{ x : \Psi(x) \leq 1 \}.$$  \hspace{1cm} (22)

A verifiable sufficient condition for the latter relation is essentially the same as an efficiently computable upper bound for Opt; the sufficient condition for the validity of (22) associated with such a bound merely states that the bound is $\leq \xi$. Now observe that from the origin of $\Psi$ (see (8)) it is clear that $X$ has a moderate number, $N$, of readily available extreme points $x^1, \ldots, x^N$ (in the case of (8), $N = 2n$), so that the only difficulty in computing Opt exactly comes from linear constraints $Ax = 0$. The standard way to circumvent this difficulty and to efficiently bound Opt from above is to use the Lagrange relaxation: for any $v \in \mathbb{R}^m$,

$$\text{Opt} = \max_{x \in X} \{ \Theta(x) + v^T Ax : Ax = 0, x \in X \} \leq \max_{x} \{ \Theta(x) + v^T Ax : x \in X \} = \max_{1 \leq i \leq N} [\Theta(x^i) + v^T A x^i],$$

whence the efficiently computable quantity $\inf_{v} \max_{1 \leq i \leq N} [\Theta(x^i) + v^T A x^i]$ is an upper bound on Opt. Unfortunately, in our situation the Lagrange relaxation bound can be very poor; e.g., when $X$ is symmetric with respect to the origin and $\Theta$ is even (as it happens in (8) when $P_+ = \emptyset$), it is immediately seen that the Lagrange relaxation bound becomes the trivial bound $\text{Opt} \leq \max_{x \in X} \Theta(x) = \max_i \Theta(x^i)$. In order to strengthen the relaxation, we pass to the Fenchel-type representation of $\Theta$

$$\Theta(x) = \sup_{u} [Pu + q^T x - \Theta_*(u)]$$

with a proper convex function $\Theta_*$; such a representation, even with $Pu + p \equiv u$, exists whenever $\Theta$ is a proper convex function (and can be easily found for $\Theta$ we are interested in). We now have for any $Y \in \mathbb{R}^{m \times n}, \ v \in \mathbb{R}^m$,

$$\text{Opt} = \max_{x} \{ \Theta(x) : Ax = 0, x \in X \} = \sup_{x,u} \{ [Pu + p]^T x - \Theta_*(u) : Ax = 0, x \in X \} \leq \sup_{x,u} \{ [Pu + p]^T [x - Y^T Ax] + v^T Ax - \Theta_*(u) : Ax = 0, x \in X \} \leq \max_{1 \leq i \leq N} \sup_{u} \{ [Pu + p]^T [x^i - Y^T A x^i] + v^T A x^i - \Theta_*(u) \},$$

so that the condition

$$\exists (Y \in \mathbb{R}^{m \times n}, \ v \in \mathbb{R}^m) : \Theta_i(Y, v) \leq \xi, \ 1 \leq i \leq N,$$  \hspace{1cm} (23)

is sufficient for the validity of (22). Note that the functions $\Theta_i$, by their origin, are convex, so that the condition (23) is efficiently verifiable, provided that $\Theta_i(\cdot)$ are efficiently computable.
In the case we are interested in, the extreme points of $X$ are the $2n$ vectors $-e_i, 1 \leq i \leq n, e_i, i \in P_n, $ and $\theta^{-1}e_i, i \in P_+, e_i$ being the basic orths. Implementing the outlined bounding scheme and adding additional restrictions (19.d.e) to get a control over $\beta,$ we arrive at (19). It should be stressed that the outlined scheme can be applied to bounding from above the optimal value of a whatever problem of the form (22) with a convex polytope $X$ and a proper convex objective $\Theta; all what matters is that $X$ is given as $\text{Conv}\{x^1, ..., x^N\}$ and $\Theta$ is efficiently computable. Note also that when $X$ is a polytope given by list of $M$ linear inequalities, we can efficiently represent it as the intersection of $M$-dimensional standard simplex and an affine plane, so that the outlined scheme is applicable to a whatever problem of maximizing an efficiently computable proper convex function under a (finite) system of linear inequality and equality constraints.

4.1.2 Effect of increasing $\beta, \theta, \xi$

The condition $\text{SG}_{s,\beta}(\xi, \theta)$ appearing in Proposition 2.1.v clearly is “monotone” in the parameters $\beta, \theta, \xi$: whenever $A$ satisfies this condition and $\beta' \geq \beta,$ $\theta' \geq \theta$ and $\xi' \geq \xi,$ $A$ satisfies the condition $\text{SG}_{s,\beta'}(\xi', \theta')$ as well. Proposition 4.1 offers a verifiable sufficient condition for the validity of $\text{SG}_{s,\beta}(\xi, \theta),$ specifically,

$$\text{VSG}^*_s(\xi, \theta): \text{There exist } Y, v, \rho, \sigma \text{ satisfying } (19) \text{ and the relation } \rho + \sigma s(1 + \theta \xi) \leq \beta.$$  

A natural question is, whether this verifiable condition possesses the same monotonicity properties as the “target” condition $\text{SG}_{s,\beta}(\xi, \theta).$ In the case of the affirmative answer, in order to conclude that $A$ is $s$-semigood, we could check the validity of $\text{VSG}^*_s(\xi, \theta)$ for appropriately large values of $\beta, \theta$ and a close to one value of $\xi < 1;$ if the condition is satisfied, $A$ is $s$-semigood, and error bounds from Proposition 3.1 take place. Were the condition $\text{VSG}^*_s(\xi, \theta)$ “not monotone,” to justify the $s$-semigoodness of $A$ via this condition would require a problematic and time-consuming search in the space of parameters $\beta, \theta, \xi.$ Fortunately, the condition $\text{VSG}^*_s(\xi, \theta)$ indeed is monotone:

**Proposition 4.2** Let $A$ satisfy $\text{VSG}^*_s(\xi, \theta),$ and let $Y, v, \sigma, \rho$ be the corresponding certificate, that is, $\rho + \sigma s(1 + \theta \xi) \leq \beta$ and $Y, v, \sigma, \rho$ satisfy (19). Then $A$ satisfies $\text{VSG}^*_s(\xi', \theta')$ whenever $\beta' \geq \beta,$ $\theta' \geq \theta$ and $\xi' \in (\xi, 1),$ the certificate being $(Y', v, \sigma, \rho),$ where the columns $Y'_i$ of $Y'$ are multiplies of the columns $Y_i$ of $Y,$ namely,

$$Y'_i = a_i Y_i; \quad [0, 1] \ni a_i = \begin{cases} (1 + \xi \theta)/(1 + \xi' \theta'), & i \in P_+ \\ (1 + \xi)/(1 + \xi'), & i \in P_n \end{cases}$$

For the proof, see Appendix B.

4.1.3 Relation to the sufficient condition for $s$-goodness from [10] and the Restricted Isometry Property

The verifiable sufficient condition for $s$-goodness from [10] requires from an $m \times n$ matrix $A$ the existence of $\gamma < 1/2$ and $Y = [y_1, ..., y_n] \in \mathbb{R}^{m \times n}$ such that

$$\|C_i[Y, A]\|_{s,1} \leq \gamma, \quad \text{for all } 1 \leq i \leq n,$$

Setting $\theta = 1$ and $\xi = \frac{\gamma}{1 - \gamma}$ (so that $\xi < 1$ and $\gamma = \frac{\xi}{1 + \xi}$) and taking into account that in the case of $\theta = 1$ we have $\Phi(z) \leq (1 + \xi)\|z\|_{s,1},$ the latter condition implies that

$$\Phi(\pm C_i[Y, A]) \leq (1 + \xi)\gamma = \xi, \quad \forall i,$$

that is, it implies the validity of $\text{VSG}_s(\xi, 1, 0, \sigma),$ provided that $\sigma$ is large enough, specifically, $\sigma \geq \|y_i\|_s$ for all $i.$
As it was shown in the companion paper \[10\], when \(A\) satisfies the Restricted Isometry Property \(\text{RIP}(\delta, k)\) with parameters \(\delta \in (0, 1), k > 1\), the above sufficient condition for \(s\)-goodness is satisfied with \(\gamma = 1/3\) for \(s\) as large as \(O(1)(1 - \delta)\sqrt{k}\); as a result, a \(\text{RIP}(\delta, k)\)-matrix satisfies \(\text{VSG}_s(\frac{1}{2}, 1, 0, \sigma)\) provided that \(\sigma\) is large enough and \(s \leq O(1)(1 - \delta)\sqrt{k}\). Since for large \(m, n, m < n\), typical random matrices possess, with overwhelming probability, property \(\text{RIP}(\frac{1}{2}, k)\) with \(k\) as large as \(O(1)m/\ln(n/m)\), we see that our verifiable sufficient condition for \(s\)-semigoodness can certify the latter property for \(s\) as large as \(O(1)\sqrt{m/\ln(n/m)}\), provided that the matrix in question is “good enough”.

### 4.2 Upper bounding the level of \(s\)-semigoodness

Here we address the issue of bounding from above the maximal \(s = s_*(A)\) for which \(A\) is \(s\)-semigood. The construction to follow is motivated by item (iv) of Proposition 2.1. A necessary and sufficient condition for the \(s\)-semigoodness of \(A\) is the existence of \(\xi < 1\) and \(\theta \geq 1\) such that for all \(x \in \ker A\) and any set \(I\) of indices with \(\operatorname{Card}(I) \leq s\)

\[
\sum_{i \in I \cap P_+} \max[(1 - \xi)x_i, (1 + \theta \xi)x_i] + \sum_{i \in I \cap P_n} (1 + \xi)|x_i| \leq \xi \Psi(x)
\]

where

\[
\Psi(x) = \sum_{i \in P_+} \max[-x_i, \theta x_i] + \sum_{i \in P_n} |x_i|,
\]

or, equivalently,

(\!) for every \(x \in \ker A\) and every vector \(v\) with at most \(s\) nonzero entries and nonzero entries \(v_i\) belonging to \([1 - \xi, 1 + \xi \theta]\) if \(i \in P_+\) and belonging to \([-1 - \xi, 1 + \xi]\) if \(i \in P_n\), one has

\[
v^T x \leq \xi \Psi(x).
\]

Observe that the convex hull of the vectors \(v\) in question is exactly the set

\[
U^{\xi, \theta} = \left\{ v \in \mathbb{R}^n : 0 \leq v_i \leq 1 + \theta \xi, i \in P_+, |v_i| \leq 1 + \xi, i \in P_n, \sum_{i \in P_+} \frac{v_i}{1 + \theta \xi} + \sum_{i \in P_n} |v_i| \leq s \right\}.
\]

Recalling that \(P_+ = \{1, \ldots, p\}\), setting \(q = n - p = \operatorname{Card}(P_n)\) and

\[
U = \{ u \in \mathbb{R}^n : \|u\|_1 \leq s, \|u\|_\infty \leq 1, u_i \geq 0 \text{ for } i \in P_+ \}\]

we see that

\[U^{\xi, \theta} = V^{\xi, \theta} U, \quad \text{where} \quad V^{\xi, \theta} = \begin{bmatrix} (1 + \xi \theta)I_p & 0 \\ 0 & (1 + \xi)I_q \end{bmatrix}.\]

The condition (\!) now reads

\[
\max_{v \in U^{\xi, \theta}} v^T x \leq \xi \Psi(x) \quad \text{for all } x \in \ker A.
\]

Setting \(X = \{ x \in \ker A : \Psi(x) \leq 1 \}\) the latter condition, by homogeneity reason, is the same as

\[
\text{Opt} = \text{Opt}(\xi, \theta) := \max_{v, x} \left\{ v^T x : v \in U^{\xi, \theta}, x \in X \right\} \leq \xi;
\]

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recall that \( A \) is \( s \)-semigood if and only if there exist \( \theta \geq 1 \) and \( \xi < 1 \) such that (27) takes place.

We can use (27) in order to bound \( s_*(A) \) from above, as follows. In order to certify that \( s_*(A) < s \) for a given \( s \) \((s\) is the input to our algorithm\), we fix a large \( \theta \) and a close to one \( \xi < 1 \) (these are the parameters of the algorithm) and run the iterations

\[
u_0 \in \mathcal{U}^{s, \theta} \mapsto x_1 \in \text{Argmax}_{x \in X} u_0^T x \mapsto u_1 \in \text{Argmax}_{u \in \mathcal{U}^s} u^T x_1 \mapsto x_2 \in \text{Argmax}_{x \in X} u_1^T x \mapsto \ldots
\]

initiating them by a picked at random vertex \( u_0 \) of \( \mathcal{U}^{s, \theta} \). Note that the quantities \( u_i^T x_i \), \( i = 1, 2, \ldots \) clearly form a nondecreasing sequence of lower bounds on \( \text{Opt} \). We terminate the outlined iterations when the progress in the bounds – the difference \( u_i^T x_i - u_{i-1}^T x_{i-1} \) – falls below a given small threshold, and we run this process a predetermined number of times from different randomly chosen starting points. As a result, we get a bunch of lower bounds on \( \text{Opt} \) of the form \( u^T x \), where \( u \) is a vertex of \( \mathcal{U}^{s, \theta} \) and \( x \in X \). If our goal were merely to certify that \( s > s_*(A) \), then \( (28) \) is not valid for given \( s, \theta, \xi \), we could terminate this process at the first step, if any, when the current lower bound \( u^T x \) becomes \( > \xi \) (cf. \cite[Section 4.1]{10}). We, however, want to certify that \( s > s_*(A) \), or, which is the same by Proposition 2.1.i.v, that \( (33) \) fails to be true for all \( \theta \) and all \( \xi < 1 \), and not only for those \( \theta, \xi \) we have selected for our test. To overcome this difficulty, we accompany every step \( u \mapsto x \in \text{Argmax}_{x \in X} u^T x \) by an additional computation as follows. In our process, \( u \) is an extreme point of \( \mathcal{U}^{s, \theta} \), that is, a point with \( s_u \leq s \) nonzero entries, let the set of indices of these entries be \( I \). Setting \( \epsilon_i = \text{sign}(u_i) \), we solve the following LP problem

\[
\max_x \left\{ \sum_{i \in I \cap P_+} x_i + \sum_{i \in I \cap P_-} \epsilon_i x_i : \begin{cases} x_i \leq 0, \; i \in P_+ \setminus I \\ Ax = 0 \\ \sum_{i \notin I} |x_i| \leq 1 \end{cases} \right\}.
\]

If the optimal value in this problem is \( \geq 1 \), we terminate our test and claim that \( A \) is not \( s \)-good; by Proposition 2.1.ii, this indeed is the case.

As applied to a given input \( s \), the outlined test either terminates with a valid claim \( "s > s_*(A)" \), or terminates with no conclusion at all, in which case we could pass to testing a larger value of \( s \).

5 Limits of performance of LP-based sufficient conditions for \( s \)-semigoodness

Unfortunately, the condition in question, same as its predecessor from \cite{10}, cannot certify \( s \)-semigoodness of an \( m \times n \) matrix in the case of \( s > O(1)\sqrt{m} \), unless the matrix is “nearly square”. The precise statement is as follows (cf. \cite[Proposition 4.2]{10}):

**Proposition 5.1** Let

\[
n > 2(2\sqrt{2m} + 1)^2
\]

and let \( \xi < 1, \theta \geq 1, \sigma \geq 0, \rho \geq 0 \), an integer \( s \) and an \( m \times n \) matrix \( A \) be such that \( A \) satisfies \( \text{VSG}_s(\xi, \theta, \rho, \sigma) \). Then

\[
s \leq 2\sqrt{2m} + 1.
\]

**Proof** is based on the following

**Lemma 5.1** Let \( Z \) be a \( \nu \times \nu \) matrix of rank \( m \), \( s > 1 \) be a positive integer, and \( \delta_i \in [0, 1], 1 \leq i \leq \nu \), be such that for the columns \( C_i \) of the matrix \( I_{\nu} - Z \) it holds \( \|C_i\|_{s, 1} \leq 1 - \delta_i \). Assume that

\[
\nu > (2\sqrt{2m} + 1)^2.
\]

Then

\[
s \leq 2\sqrt{2m} + 1.
\]
Proof of the lemma. Let $\sigma_i = Z_{ii}$, and let $\gamma_i$ be the sum of $s - 1$ largest magnitudes of the entries in $C_i$ with indices different from $i$. We have

$$1 - \sigma_i + \gamma_i \leq \|C_i\|_{s,1} \leq 1 - \delta_i,$$

whence $\sigma_i \geq \delta_i + \gamma_i > 0$. Let us set $\lambda_i = \frac{1}{\sigma_i}$, and let $\bar{Z}$ be the matrix with the columns $\bar{Z}_i = \lambda_i Z_i$, where $Z_i$ is the $i$-th column in $Z$. Note that $\bar{Z}$ is of the same rank $m$ as $Z$, and that $\bar{Z}_{ii} = 1$ for all $i$. Recalling that $\gamma_i < \sigma_i$, we have also

$$\|\bar{Z}_i\|_{s-1,1} = \lambda_i \|Z_i\|_{s-1,1} \leq \lambda_i [\gamma_i + \sigma_i] \leq 2\lambda_i \sigma_i = 2.$$

Now let $\bar{s} = \min[s - 1, \lfloor \nu^{1/2} \rfloor]$, so that $\bar{s} \geq 1$ due to $s > 1$. We have $\|\bar{Z}_i\|_{s,1} \leq \|\bar{Z}_i\|_{s-1,1} \leq 2$ and $\bar{s}^2 \leq \nu$. From the latter inequality and due to $\|\bar{Z}_i\|_{s,1} \leq \max\{1, \nu \bar{s}^{-2}\} \|\bar{Z}_i\|_{s-1,1}^2$ (cf. the proof of [10, Proposition 4.2]), it follows that $\|\bar{Z}_i\|_{2}^2 \leq 4\nu \bar{s}^{-2}$. We conclude that $\|\bar{Z}\|_{2}^2 \leq 4\nu \bar{s}^{-2}$, where for a matrix $B$, $\|B\|_2$ is the Frobenius norm of $B$. Setting $H = \frac{1}{\bar{s}}[\bar{Z} + \bar{Z}^T]$, we have therefore $\|H\|_{2}^2 \leq 4\nu \bar{s}^{-2}$. On the other hand, $\text{Tr}(H) = \sum_{i=1}^{\nu} \bar{Z}_{ii} = \nu$, while $\text{rank}(H) \leq 2m$, whence, denoting by $\mu_i$, $1 \leq i \leq 2m$, the nonzero eigenvalues of $H$, we have

$$\|H\|_{2}^2 = \sum_{i=1}^{2m} \mu_i^2 \geq \left( \sum_{i=1}^{\nu} \mu_i \right)^2 / \nu = (\text{Tr}(H))^2 / \nu \geq \nu^2 / (2m).$$

We arrive at the inequality

$$4\nu \bar{s}^{-2} \geq \|H\|_{2}^2 \geq \nu^2 / (2m),$$

whence

$$\bar{s}^2 \leq 8\nu. \quad (32)$$

Assuming that $\bar{s} = \lfloor \nu^{1/2} \rfloor$, (32) says that $\nu \leq (2\sqrt{2m} + 1)^2$, which is impossible. The only other option is that $\bar{s} = s - 1$, and we arrive at (31). $\Box$

Lemma 5.1 $\Rightarrow$ Proposition 5.1: Let $Y, v$ satisfy (19). Consider first the case when $\nu := \text{Card}(P_n) \geq n/2$. Denoting by $\hat{C}_i$ the $\nu$-dimensional vector comprised of the last $\nu$ entries in $C_i = C_i[Y, A]$ (i.e., entries with indices from $P_n$). By (19), for every $i \in P_n$ and for every set $I \subset P_n$ with $\text{Card}(I) \leq s$ we have

$$\sum_{j \in I} (1 + \xi)|[C_i]_{j}| \leq \Phi(-C_i) \leq \xi - (A^T v)_i, \quad \sum_{j \in I} (1 + \xi)|[C_i]_{j}| \leq \Phi(C_i) \leq \xi + (A^T v)_i,$$

whence for any $i \in P_n$,

$$2(1 + \xi)|\hat{C}_i|_{s,1} \leq \Phi(-C_i) + \Phi(C_i) \leq 2\xi,$$

so that $\|\hat{C}_i\|_{s,1} < 1/2$. We see that the South-Eastern $\nu \times \nu$ submatrix $Z$ of $Y^TA$ satisfies the premise of Lemma 5.1, while the size $\nu$ of $Z$ satisfies (30) due to (28) and $\nu \geq n/2$. Applying the lemma, we arrive at (29).

Now consider the case when $\text{Card}(P_n) < n/2$, that is, $\nu := \text{Card}(P_n) \geq n/2$. By (19), setting $C_i = C_i[Y, A]$, for every set $I \subset P_n$ with $\text{Card}(I) \leq s$ and every $i \in P_n$ we have

$$\sum_{j \in I} (1 + \theta \xi) \max([-|C_i|_{j}, 0]) \leq \Phi(-C_i) \leq \xi - (A^T v)_i, \quad \sum_{j \in I} (1 + \theta \xi) \max([|C_i|_{j}, 0]) \leq \Phi(C_i) \leq \theta \xi + (A^T v)_i,$$

whence

$$\sum_{j \in I} |[C_i]_{j}| \leq \frac{\xi (1 + \theta)}{1 + \theta \xi} < 1.$$
Since the latter inequality holds true for every subset $I$ of $P_+$ with $\text{Card}(I) \leq s$, when denoting by $\tilde{C}_i$ the part of $C_i$ comprised of the first $\nu$ entries (those with indexes from $P_+$), we have for all $i \in P_+$:

$$\| \tilde{C}_i \|_{s,1} < 1.$$  

Now the proof can be completed exactly as in the previous case, with the North-Western $\nu \times \nu$ submatrix of $Y^T A$ in the role of $Z$. □

Proposition 5.1 brings a not so good news about our sufficient conditions for $s$-semigoodness. Another bad news is that while our condition in “good” cases, e.g., those of RIP-matrices, allows to certify $s$-semigoodness for “large” values of $s$, it can give a very poor impression on what is the largest $s = s(A)$ for which $A$ is $s$-semigood. An instructive example in this direction is as follows. Consider the case of $P_+ = \{1, \ldots, n\}$, let $m = 2d + 1$ be odd, and let the rows of $A$ be comprised of the values of basic trigonometric polynomials

$$p_0(\phi) \equiv 1, \quad p_{2i-1}(\phi) = \cos(i\phi), \quad p_{2i}(\phi) = \sin(i\phi), \quad 1 \leq i \leq d,$$

taken along the regular grid $\phi_j = 2\pi j/n, 0 \leq j \leq n$, so that $A_{ij} = p_i(\phi_j), 0 \leq i < m, 0 \leq j < n$ (we enumerate rows and columns starting with 0 rather than with 1). It is well known [3, 6] that in this case $A$ is $s$-semigood for $s = d$. In contrast to this, when $A$ is not “nearly square”, specifically, when $n \geq 4\pi d$, whatever large be $\theta, \sigma, \rho$ and whatever close to 1 be $\xi < 1$, $A$ can satisfy the condition $\text{VSG}_s(\xi, \theta, \rho, \sigma)$ only for $s \leq 2$.

To justify our claim, let $L$ be the $n \times n$ permutation matrix corresponding to the cyclic shift $e_{\bar{j}} \mapsto e_{\bar{j}+1}, \bar{j} = (\bar{j}+1) \mod n$, of the standard basic orths $e_0, \ldots, e_{n-1}$ in $\mathbb{R}^n$, and $R$ be the $m \times n$ orthogonal block-diagonal matrix with the North-Western block $1$ and $d$ additional $2 \times 2$ diagonal blocks $\begin{pmatrix} \cos(2\pi i/n) & -\sin(2\pi i/n) \\ \sin(2\pi i/n) & \cos(2\pi i/n) \end{pmatrix}, 1 \leq i \leq d$. Denoting by $A_j$ the $j$-th column of $A$, $0 \leq j \leq n - 1$, we clearly have $RA_0 = A_{\bar{j}1},$ whence $A = RAL^{-1}$ and therefore also $A = R_j^T AL^{-i}$ for $1 \leq i \leq n$. Now assume that $Y, v$ satisfy (19) for certain $\xi < 1, \theta \geq 1, \rho, \sigma$. Then

$$\max_i [\Phi(-C_i[Y, A]) + \Phi(C_i[Y, A])] \leq \xi(1 + \theta),$$

whence, as it is immediately seen, $\max_i \| C_i[Y, A] \|_{s,1} \leq \kappa := \frac{\xi(1 + \theta)}{1 + \theta} < 1$, or, which is the same,

$$\Gamma(I - Y^T A) \leq \kappa < 1,$$

where $\Gamma(Z)$ is the maximum of the $\| \cdot \|_{s,1}$-norms of columns of $Z \in \mathbb{R}^{n \times n}$. Observe that $\Gamma$ is a convex function which is symmetric in the sense that $\Gamma(PZP^T) = \Gamma(Z)$ whenever $P$ is a permutation matrix. Now let $\bar{Y} = \frac{1}{n} \sum_{i=1}^n R^{-1} Y L^i$. Since $L^n = I_n, R^{-n} = I_m$, we have $R^{-1} \bar{Y} L = \bar{Y}$. We claim that

$$\Gamma(I - \bar{Y}^T A) \leq \kappa.$$

Indeed, we have

$$\Gamma(I - \bar{Y}^T A) = \Gamma\left( \frac{1}{n} \sum_{i=1}^n [I - L^{-i} Y^T R_i^T A] \right) \leq \frac{1}{n} \sum_{i=1}^n \Gamma(I - L^{-i} Y^T R_i^T A) \quad \text{[since $\Gamma$ is convex]} = \frac{1}{n} \sum_{i=1}^n \Gamma\left( L^{-i} \left[ I - Y^T [R_i^T A L^{-i}] \right] L^i \right) = \frac{1}{n} \sum_{i=1}^n \Gamma(I - Y^T A) \quad \text{[since $\Gamma$ is symmetric and $R_i^T A L^{-i} = A$]} = \Gamma(I - Y^T A).$$
Now let
\[ y_j(\phi) = \tilde{Y}_{0j} + \sum_{i=1}^{d} [\tilde{Y}_{2i-1,j} \cos(i\phi) + \tilde{Y}_{2i,j} \sin(i\phi)]. \]
We have \( R^{-1} \tilde{Y} L = \tilde{Y} \), that is, \( R^{-1} \tilde{Y} = \tilde{Y} L^{-1} \). In other words, the columns \( \tilde{Y}_j \) of \( \tilde{Y} \) satisfy the relation \( \tilde{Y}_j = R \tilde{Y}_j \), where \( j = (j - 1) \mod n \). This is nothing but \( y_j(\phi) \equiv y_{j-}(\phi - \delta), \delta = 2\pi/n, \) whence \( y_j(\phi) = y_0(\phi - j\delta) \). Observe that the \( j \)-th column in \( Y^T A \) has the entries
\[ \tilde{Y}_i^T A_j = y_i(j\delta) = y_0((j - i)\delta), \quad 0 \leq i \leq n - 1, \]
meaning that the columns in the matrix \( I - \tilde{Y}^T A \) are cyclic shifts of each other (so that the \( \| \cdot \|_{s,1} \)-norms of all columns are the same), and the zero column is comprised of the values of the trigonometric polynomial \( 1 - y_0(\phi) \) on the grid \( G = \{ \phi_j = \frac{2\pi j}{n} : 0 \leq j < n \} \). Assuming \( s > 1 \), when denoting by \( \gamma \) the sum of \( s - 1 \) largest magnitudes of entries in the \((n-1)\)-dimensional vector \( \{y_0(\phi_i)\}_{i=1}^{n-1} \), we have
\[ 1 - y_0(0) + \gamma \leq \|C_0[\tilde{Y}, A]\|_{s,1} \leq \kappa < 1, \]
whence \( \mu := y_0(0) > \gamma \). Now let \( M = \max_{0 \leq \phi \leq 2\pi} |y_0(\phi)| \), and let \( \tilde{\phi} \in \text{Argmax}_\phi |y_0(\phi)| \), so that \( y_0'(\tilde{\phi}) = 0 \). By Bernstein theorem, we have \( |y_0''(\phi)| \leq d^2 M \) for all \( \phi \), whence \( |y_0(\phi)| \geq M/2 \) when \( |\phi - \tilde{\phi}| \leq 1/d \), so that
\[ \text{Card}\{j : |y_0(\phi_j)| \geq M/2 \} > \frac{n}{\pi d} - 1. \]

It follows that \( \gamma \geq \min[s - 1, \frac{n}{\pi d} - 2] M/2 \), while \( \mu = y_0(0) \leq M \). Thus, the relation \( \mu > \gamma \) implies that
\[ \min[s - 1, \frac{n}{\pi d} - 2] < 2, \]
that is, \( s \leq 2 \) provided that \( n \geq 4\pi d \).

### 6 Verifiable sufficient conditions for \( s \)-semigoodness by Semidefinite relaxation

Following d’Aspremont and El Ghaoui [4], we are about to derive another verifiable sufficient condition for \( s \)-semigoodness, now - via semidefinite relaxation. The construction to follow is motivated by the development in the beginning of Section 4.2, according to which \( s \)-semigoodness of \( A \) is implied by the validity of (27) for \( \theta > 1 \) and \( \xi < 1 \).

Let, as before,
\[ \mathcal{X} = \{x \in \text{Ker} A : \Psi(x) \leq 1\} \quad \text{and} \quad \mathcal{U}^{\xi, \theta} = \{V^{\xi, \theta} u : u \in \mathcal{U}\}, \]
where \( \Psi, \mathcal{U} \) and \( V^{\xi, \theta} \) are defined in, respectively, (24), (25) and (26). The condition (27) is equivalent to
\[ \max_{u,x} \left\{ (V^{\xi, \theta} u)^T x : u \in \mathcal{U}, \ x \in \mathcal{X} \right\} \leq \xi. \quad (33) \]
Observe that for \( u \in \mathcal{U}, \ x \in \mathcal{X} \) the matrices \( U = uu^T, \ P = ux^T \) and \( X = xx^T \) satisfy the relations

\[ \exists t \in \mathbb{R}^n, V \in \mathbb{S}^{2n}, \Lambda \in \mathbb{S}^{2n} : \]

\[ \begin{bmatrix} U & P \\ P^T & X \end{bmatrix} \succeq 0; \]

\[ \begin{cases} U = \begin{bmatrix} I_n & -I_n \\ -I_n & V_{11} \end{bmatrix} \begin{bmatrix} V_{12} \\ V_{11} \end{bmatrix} L^T, \\ 0 \leq V_{ij} \leq \frac{1}{t_i}, \ V \succeq 0, \quad V_{12} = [V_{12}]^T, \quad \text{Tr}(V) \leq s, \\ \sum_{i,j} V_{ij} \leq s^2, \quad V_{ij} \geq 0 \quad \forall i,j \in \mathcal{P}_+; \end{cases} \]

\[ X = \begin{bmatrix} -I_p & 0 \\ 0 & -I_q \end{bmatrix} \begin{bmatrix} \frac{1}{p} I_p & 0 \\ 0 & \frac{1}{q} I_q \end{bmatrix} \Lambda F^T, \quad 0 \leq \Lambda_{ij}, \quad \Lambda \succeq 0, \quad \sum_{i,j} \Lambda_{ij} \leq 1; \]

\[ \begin{aligned} & (d_1) \quad \sum_{j \in \mathcal{P}_+} \max[-P_{ij}, \theta P_{ij}] + \sum_{j \in \mathcal{P}_n} |P_{ij}| \leq t_i, \quad \forall i \in \mathcal{P}_+, \\ & (d_2) \quad \sum_j |P_{ij}| \leq t_i, \quad \forall i \in \mathcal{P}_n, \\ & (d_3) \quad t_i \leq 1 \quad \forall i, \quad \sum_i t_i \leq s; \\ & (e) \quad AXA^T = 0. \end{aligned} \]

Besides this,

\[ u^T(V_{\xi, \theta}^T)x = \text{Tr}(V_{\xi, \theta} P^T). \]

The latter relation is evident. Let us verify (34). (34.a) is evident. To verify (34.b), let \( u_+ = \max[u, 0], \ u_- = \max[-u, 0] \), where max is acting coordinate-wise. Then

\[ \begin{aligned} U &= L \begin{bmatrix} u_+ u_T & u_- u_T \\ u_- u_T & u_+ u_T \end{bmatrix} L^T = L \begin{bmatrix} u_+ u_T & u_- u_T \\ u_- u_T & u_+ u_T \end{bmatrix} L^T, \\ &= L \begin{bmatrix} \frac{1}{2} [u_+ u_T + u_- u_T] & \frac{1}{2} [u_+ u_T + u_- u_T] \\ \frac{1}{2} [u_- u_T + u_+ u_T] & \frac{1}{2} [u_- u_T + u_+ u_T] \end{bmatrix} L^T, \end{aligned} \]

\[ V \]

and the matrix \( V \) we have just defined clearly satisfies all requirements from (34.b). To verify (34.c), observe that the extreme points of the set \( \mathcal{X}^+ = \{ x : \Psi(x) \leq 1 \} \supset \mathcal{X} \) are the vectors \( \pm e_i, \ i > p, \) and \( -e_i, \theta^{-1} e_i, \ i \leq p, \) so that \( x = F \lambda \) with \( \lambda \in \mathbb{R}^p_+, \sum_{i} \lambda_i \leq 1; \) setting \( \Lambda = \lambda \Lambda^T, \) we satisfy (34.c). To satisfy (34.d), it suffices to set \( t_i = |u_i| \) for all \( i \) and to take into account that \( \max[-P_{ij}, \theta P_{ij}] \geq |P_{ij}| \) for all \( i, j \) due to \( \theta \geq 1, \) and that \( u_i \geq 0 \) for \( i \in \mathcal{P}_+. \) (34.e) is evident. It follows that a sufficient condition for (33) is

\[ \text{Opt} := \max_{U,P,V,\Lambda,X,t} \left\{ \text{Tr}(V_{\xi, \theta} P^T) : X, U \in \mathbb{S}^n, \ V, \Lambda \in \mathbb{S}^{2n}, \ P \in \mathbb{R}^{n \times n}, t \in \mathbb{R}^n \text{ satisfy (34)} \right\} \leq \xi. \] (35)

The optimization problem in (35) clearly reduces to a semidefinite maximization program \( \mathcal{S}; \) by weak duality, the optimal value in the semidefinite dual \( \mathcal{D} \) to \( \mathcal{S} \) is \( \geq \text{Opt}. \) It follows that the efficiently verifiable condition

\[ \text{Opt}(\mathcal{D}) \leq \xi \]

is a sufficient condition for \( s \)-semigoodness of \( A. \) Note that the above construction depends on \( \theta \geq 1 \) and \( \xi < 1 \) as parameters.

Consider the case of \( \mathcal{P}_+ = \emptyset, \) where \( \mathcal{X} = \{ x \in \mathbb{R}^n : \|x\|_1 \leq 1, Ax = 0 \} \supset \mathcal{Z} = \{ x \in \mathbb{R}^n : \|x\|_1 \leq 1 \}. \) In this case, the standard semidefinite relaxation of the set \( \mathcal{C}_* = \text{Conv}\{xx^T : x \in \mathcal{Z} \} \) is

\[ \mathcal{C} = \left\{ X : X \succeq 0, \sum_{i,j} |X_{ij}| \leq 1 \right\} \]
Given Set 1

Algorithm 7.1

A, b

The Matching Pursuit algorithm for signal recovery has been first introduced in [11] and is motivated by the desire to provide a reduced complexity alternative to the $\ell_1$-recovery problem. Several implementations of Matching Pursuit have been proposed in the Compressive Sensing literature (see, e.g., the review [1]). All of them are based on successive Euclidean projections of the signal and the corresponding performance results rely upon the bounds on mutual incoherence $\mu(A)$ of the sensing matrix. We are about to show that the verifiable sufficient conditions from the previous section can be used to construct a specific version of the Matching Pursuit algorithm which we refer to Non-Euclidean Matching Pursuit (NEMP) algorithm.

Suppose that we have in our disposal $\tau, \tau_\pm \geq 0$ and a matrix $Y = [y_1, ..., y_n]$, such that

\[
\begin{align*}
(a) & \quad -\tau_- \leq [I - Y^T A]_{ij} \leq \tau_+, \quad \forall i \in P_+, \forall j, \\
(b) & \quad -\tau \leq [I - Y^T A]_{ij} \leq \tau, \quad \forall i \in P_n, \forall j, \\
(c) & \quad \|y_j\|_1 \leq \sigma, \quad \forall j.
\end{align*}
\]

Consider a signal $w \in P_n$ such that $\|w - w^s\|_1 \leq \mu$, where $w^s$ is the vector obtained from $w$ by replacing all but $s$ largest magnitudes of entries in $w$ with zeros, and let $y$ and $\delta$ be such that $\|Ay - y\| \leq \delta$.

Suppose that

$$\rho = s \max\{\tau_+, \tau_-, \tau\} < 1.$$

To simplify notation, we denote $\max[a, b]$ by $a \lor b$. Consider the following iterative procedure:

**Algorithm 7.1**

1. **Initialization**: Set $v^{(0)} = 0$,

\[
\alpha_0 = \frac{\|Y^T y\|_{s,1} + s\sigma\delta + \mu}{1 - \rho}.
\]

2. **Step $k$, $k = 1, 2, \ldots$**: Given $v^{(k-1)} \in \mathbb{R}^n$ and $\alpha_{k-1} \geq 0$, compute
(a) $u = Y^T(y - Av^{(k-1)})$ and $n$ segments

$$S_i = \begin{cases} [u_i - \tau\alpha_{k-1} - \sigma\delta, u_i + \tau\alpha_{k-1} + \sigma\delta], & i \in P_+, \\ [u_i - \sigma\alpha_{k-1} - \sigma\delta, u_i + \tau\alpha_{k-1} + \sigma\delta], & i \in P_n. \end{cases}$$

Define $\Delta \in \mathbb{R}^n$ by setting

$$\Delta_i = \begin{cases} [u_i - \tau\alpha_{k-1} - \sigma\delta], & i \in P_+, \\ [u_i - \sigma\alpha_{k-1} - \sigma\delta], & i \in P_n, \quad u_i \geq 0, \\ -[|u_i| - \sigma\alpha_{k-1} - \sigma\delta], & i \in P_n, \quad u_i < 0 \end{cases}$$

(here $[a]_+ = \max[0,a]$).

(b) Set $v^{(k)} = v^{(k-1)} + \Delta$ and

$$\alpha_k = s[2\tau + (\tau_+ + \tau_-)]\alpha_{k-1} + 2s\sigma\delta + \mu.$$  \hspace{1cm} (38)

and loop to step $k + 1$.

3. The approximate solution found after $k$ iterations is $v^{(k)}$.

**Proposition 7.1** Assume that $w_i \geq 0$ for $i \in P_+$, (37) takes place, and that $\|w - w^*\|_1 \leq \mu$ with a known in advance value of $\mu$. Then the approximate solution $v^{(k)}$ and the value $\alpha_k$ after the $k$-th step of Algorithm 7.1 satisfy

(a) $v_i^{(k)} \in \text{Conv}\{0; w_i\}$

(b) $\|w - v^{(k)}\|_1 \leq \alpha_k$.

**Proof.** Let us proceed by induction. First, let us show that $(a_{k-1}, b_{k-1})$ implies $(a_k, b_k)$. Thus, assume that $(a_{k-1}, b_{k-1})$ holds true. Let $z^{(k-1)} = w - v^{(k-1)}$. By $(a_{k-1})$, $z^{(k-1)}$ is supported on the support of $w$ and is such that $z_i^{(k-1)} \geq 0$ for $i \in P_+$. Note that

$$z^{(k-1)} - u = w - v^{(k-1)} - Y^T(y - Av^{(k-1)}) = (I - Y^T A)(w - v^{(k-1)}) - Y^T e$$

$$= (I - Y^T A)z^{(k-1)} - Y^T e,$$

where $e = y - Aw$ with $\|Y^T e\|_\infty \leq \sigma\delta$ due to (36.c). Then by (36.a,b) for any $i \in P_+$,

$$-\tau_+ \left[ \sum_{j \in P_+} z_j^{(k-1)} + \sum_{j \in P_n} |z_j^{(k-1)}| \right] - \sigma\delta \leq z_i^{(k-1)} - u_i \leq \tau_+ \left[ \sum_{j \in P_+} z_j^{(k-1)} + \sum_{j \in P_n} |z_j^{(k-1)}| \right] + \sigma\delta,$$

whence

$$-\gamma_- := -\tau_+ \alpha_{k-1} - \sigma\delta \leq z_i^{(k-1)} - u_i \leq \gamma_+ := \tau_+ \alpha_{k-1} + \sigma\delta.$$  \hspace{1cm} (39)

We conclude that for any $i \in P_+$ the interval $S_i = [u_i - \gamma_-, u_i + \gamma_+]$ of the width

$$\ell_+ = [\tau_+ + \tau_-] \alpha_{k-1} + 2\sigma\delta,$$

covers $z_i^{(k-1)}$. In the same way for any $i \in P_n$

$$-\gamma := -\tau \alpha_{k-1} - \sigma\delta \leq z_i^{(k-1)} - u_i \leq \tau \alpha_{k-1} + \sigma\delta = \gamma,$$
so that the interval $S_i = [u_i - \gamma, u_i + \gamma]$ of the width 
\[
\ell = 2\tau \alpha_{k-1} + 2\sigma \delta,
\]
covers $z_i^{(k-1)}$ when $i \in P_h$. 

Recalling that $z_i^{(k-1)} \geq 0$ for $i \in P_+$, the closest to 0 point of $S_i$ is 
\[
\widetilde{\Delta}_i = [u_i - \gamma]_+ \quad \text{for } i \in P_+,
\]
\[
\Delta_i = [u_i - \gamma]_+ \quad \text{for } i \in P_h, \ u_i \geq 0,
\]
\[
\Delta_i = -[|u_i| - \gamma]_+ \quad \text{for } i \in P_n, \ u_i < 0,
\]
that is, $\widetilde{\Delta}_i = \Delta_i$ for all $i$. Since the segment $S_i$ covers $z_i^{(k-1)}$ and $\Delta_i$ is the closest to 0 point in $S_i$, while the width of $S_i$ is at most $\ell \vee \ell_+$, we clearly have 
\[
(a) \quad \Delta_i \in \text{Conv} \left\{ 0, z_i^{(k-1)} \right\},
\]
\[
(b) \quad |z_i^{(k-1)} - \Delta_i| \leq \ell \vee \ell_+.
\]

Since $(a_{k-1})$ is valid, $(40.a)$ implies that 
\[
v_i^{(k)} = v_i^{(k-1)} + \Delta_i \in \left[ v_i^{(k-1)} + \text{Conv} \left\{ 0, w - v_i^{(k-1)} \right\} \right] \subseteq \text{Conv} \{0, w_i\},
\]
and $(a_k)$ holds. Further, let $I$ be the support of $w^\ast$. Relation $(a_k)$ clearly implies that $|z_i^{(k)}| \leq |w_i|$, and we can write due to $(40.b)$: 
\[
||w - v^{(k)}||_1 = \sum_{i \in I} |w - [v_i^{(k-1)} + \Delta_i]| + \sum_{i \not\in I} |z_i^{(k)}| \leq \sum_{i \in I} |z_i^{(k-1)} - \Delta_i| + \sum_{i \not\in I} |w_i| \leq s(\ell \vee \ell_+) + \mu = \alpha_k,
\]
which is $(b_k)$. The induction step is justified.

It remains to show that $(a_0, b_0)$ holds true. Since $(a_0)$ is evident, all we need is to justify $(b_0)$. Let 
\[
\alpha_\ast = ||w||_1,
\]
and let $u = Y^T y$. Same as above (cf. (39)), we have for all $i$: 
\[
|w_i - u_i| \leq \max \{ \tau_-, \tau_+, \tau \} \alpha_\ast + \sigma \delta = \frac{\rho}{s} \alpha_\ast + \sigma \delta.
\]
Then 
\[
\alpha_\ast = \sum_{i \in I} |w_i| + \sum_{i \not\in I} |w_i| \leq \sum_{i \in I} [|u_i| + \frac{\rho}{s} \alpha_\ast + \sigma \delta] + \mu \leq ||u||_{s,1} + \rho \alpha_\ast + s \sigma \delta + \mu.
\]
Hence 
\[
\alpha_\ast \leq \alpha_0 = \frac{||u||_{s,1} + s \sigma \delta + \mu}{1 - \rho},
\]
which implies $(b_0)$. □

Let 
\[
\lambda = s[2\tau \vee (\tau_- + \tau_+)];
\]
if $\lambda < 1$, then also $\rho < 1$, so that Proposition 7.1 holds true. Furthermore, by (38) the sequence $\alpha_k$ converges exponentially fast to the limit $\alpha_\infty := \frac{2s \sigma \delta + \mu}{1 - \lambda}$: 
\[
\alpha_k = \lambda^k[\alpha_0 - \alpha_\infty] + \alpha_\infty.
\]

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Note that when $P_+ = \emptyset$, we can set $\tau_- = \tau_+ = 0$ to obtain $\lambda = 2s\tau$; in the case of $P_n = \emptyset$, by setting $\tau = 0$, we have $\lambda = s(\tau_- + \tau_+)$. The bottom line is: if the optimal value in the convex program

$$\text{Opt} = \min_{\tau, \tau, s, Y} \left\{ s \left[ 2\tau \vee (\tau_- + \tau_+) \right] : \begin{array}{l}
-\tau_- \leq [I - Y^T A]_{ij} \leq \tau_+, \quad \forall i \in P_+, \forall j \\
-\tau \leq [I - Y^T A]_{ij} \leq \tau, \quad \forall i \in P_n, \forall j \\
\tau, \tau \geq 0
\end{array} \right\}$$

is $< 1$, the above procedure, as yielded by an optimal solution to the latter problem, possesses the following properties:

1. All approximations $v^{(k)}$, $k = 0, 1, \ldots$ of $w$ are supported on the support of $w$;
2. For $i \in P_+$, $v_i^{(k)} \geq 0$ are nondecreasing in $k$ and are $\leq w_i$ for all $k$;
3. For $i \in P_n$,
   - if $w_i > 0$, then $0 \leq v_i^{(k)} \leq w_i$ and $v_i^{(k)}$ are nondecreasing in $k$;
   - if $w_i < 0$, then $w_i \leq v_i^{(k)} \leq 0$ and $v_i^{(k)}$ are nonincreasing in $k$;
4. As $k$ grows, the upper bound $\alpha_k$ on the $\ell_1$-error of approximating $w$ by $v^{(k)}$ goes exponentially fast to

$$\alpha_\infty = \frac{2s\sigma + \mu}{1 - \text{Opt}}.$$

Let now $\xi \in (0, 1)$, $\sigma \geq 0$ and $\theta \geq 1$ and suppose that an $m \times n$ matrix $A$ verifies the following condition:

$\overline{\text{VSG}}_s(\xi, \sigma, \theta)$: There exists $m \times n$ matrix $Y = [y_1, \ldots, y_n]$ such that $\|y_i\|_s \leq \sigma$ for all $i$ and

$$\begin{align}
-\frac{\xi s}{(1 + \xi \theta)s} &\leq [I - Y^T A]_{ij} \leq \frac{\xi s}{(1 + \xi \theta)s}, \quad \forall i \not\in P_+, \forall j, \\
-\frac{\xi s}{(1 + \xi \theta)s} &\leq [I - Y^T A]_{ij} \leq \frac{\xi s}{(1 + \xi \theta)s}, \quad \forall i \in P_+, \forall j \not\in P_+, \\
-\frac{\xi s}{(1 + \xi \theta)s} &\leq [I - Y^T A]_{ij} \leq \frac{\xi s}{(1 + \xi \theta)s}, \quad \forall i \in P_+, \forall j \in P_+.
\end{align} \quad (41)$$

Observe that (41) is a system of convex inequalities in $Y$. Further, $\overline{\text{VSG}}_s(\xi, \sigma, \theta)$ certainly implies $\text{VSG}_s(\xi, \sigma, \theta)$, and is therefore sufficient condition of the $s$-semigoodness of the matrix $A$.

When $\overline{\text{VSG}}_s(\xi, \sigma, \theta)$ is satisfied with $\xi \in (0, 1)$ and $\theta > 1$, by taking

$$\tau_- = \frac{\xi}{1 + \xi \theta}s, \quad \tau_+ = \frac{\xi \theta}{1 + \xi \theta}s$$

and

$$\tau = \frac{\xi}{1 + \xi s},$$

we obtain

$$\lambda = \max \left( \frac{\xi + \xi \theta}{1 + \xi s}, \frac{2\xi}{1 + \xi} \right) < 1. \quad (42)$$

Combining this condition with Proposition 7.1 gives:

**Corollary 7.1** Suppose that $A$ satisfies the condition $\overline{\text{VSG}}_s(\xi, \sigma, \theta)$ with certain $\xi \in (0, 1)$, $\sigma \geq 0$ and $\theta \geq 1$. Let $w \in P_n$ be a vector with $\|w - w^*\|_s \leq \mu$ where $w^*$ is the vector obtained from $w$ by replacing all but $s$ largest in magnitude entries in $w$ with zeros, and let $y$ be such that $\|Ay - w\| \leq \delta$. Then the approximate solution $v^{(t)}$ found by Algorithm 7.1 after $t$ iterations satisfies $v_i^{(t)} \geq 0$ for all $i \in P_+$ and

$$\|w - v^{(t)}\|_1 \leq \frac{2s\sigma \delta + \mu}{1 - \lambda} + \lambda t \left[ \frac{\|Y^T y\|_{s,1} + s\sigma \delta + \mu}{1 - \rho} - \frac{2s\sigma \delta + \mu}{1 - \lambda} \right],$$

where $\lambda$ is given by (42) and $\rho = \frac{\xi \theta}{1 + \xi \theta}$.  

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It should be noted the NEMP algorithm has several drawbacks as compared with the \( \ell_1 \)-recovery. First, the pursuit algorithm requires a priori knowledge of several parameters \((\sigma, Y, \tau, \tau_-, \tau_+, \tau, s \text{ and } \mu)\). Second, the value \((1 - \lambda)^{-1}(2s\sigma\delta + \mu)\) is a conservative upper bound on the error of the \( \ell_1 \)-recovery, but the error bound in Corollary 7.1 is exact. On the other hand, the NEMP algorithm can be an interesting option if the \( \ell_1 \)-recovery is to be used repeatedly on the observations obtained with the same sensing matrix \( A \); the numerical complexity of the pursuit algorithm for a given matrix \( A \) may only be a fraction of that of the \( \ell_1 \)-recovery, especially when used on high-dimensional data.

Our concluding remark is on the condition

\[
\frac{\mu(A)}{1 + \mu(A)} < \frac{1}{2s},
\]

where \( \mu(A) \) is the mutual incoherence of \( A \) (see (6)). This condition is usually used in order to establish convergence results for the Matching Pursuit algorithms (see, e.g. [8, 9, 2]). As it is immediately seen, when \( \mu(A) \) is well defined (i.e., all columns in \( A \) are nonzero), the matrix \( Y = [y_1, ..., y_n] \) with the columns

\[
y_i = \frac{A_i}{(1 + \mu(A))A_i^T A_i}
\]

devalues for all \( i = 1, ..., m \) and \( j = 1, ..., n \) the relations

\[
|\{I - Y^T A\}_{ij}| \leq \frac{\mu(A)}{1 + \mu(A)}.
\]

In the case of (43), setting \( \theta = 1 \) and specifying \( \xi \) from the relation \( \frac{\xi}{1 + \xi} = \frac{\mu(A)}{1 + \mu(A)} \), we get \( 0 < \xi < 1 \) meet all inequalities in (41). It follows that \( Y \) certify the validity of the condition \( \mathbf{VSG}_s(\xi, \sigma, 1) \) with the outlined \( \xi \) and with all \( \sigma \geq \max_i \frac{\|A_i\|_2}{(1 + \mu(A))\|A_i\|_2} \), and thus the above \( Y \) can be readily used in Matching Pursuit. Note that in the situation in question Corollary 7.1 recovers some results from [8, 9, 2].

References


A Proof of Proposition 2.1

(i)⇒(ii): Let $A$ be $s$-semigood, and let, in contrast to what is stated by (ii), $J$ be a subset of \{1, ..., $n$\} with $\text{Card}(J) \leq s$ and $x \in \text{Ker} A \setminus \{0\}$ be such that $x_i \leq 0$ for all $i \in P_+ \setminus J$ and

$$\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_n} |x_i| \geq \sum_{i \notin J} |x_i|.$$ 

Let $I = (J \cap P_n) \cup \{i \in J \cap P_+ : x_i \geq 0\}$ so that $I \subseteq J$. From the construction of $I$, we have $x_i \leq 0$ for $i \in J \setminus I$ implying that $x_i \leq 0$ for $i \in P_+ \setminus I$. Further,

$$\sum_{i \in I \cap P_+} x_i + \sum_{i \in I \cap P_n} |x_i| = \sum_{i \in J \cap P_+} x_i - \sum_{i \in J \setminus I} x_i + \sum_{i \in J \cap P_n} |x_i|$$

$$\geq \sum_{i \notin J} |x_i| - \sum_{i \notin J \setminus I} x_i$$

$$= \sum_{i \notin J \cap P_+} x_i + \sum_{i \in J \setminus I} |x_i| = \sum_{i \notin J} |x_i|.$$ 

Hence $I$ also violates the condition in (ii). Setting $u_i = x_i$ when $i \in I$ and $u_i = 0$ otherwise and setting $v = u - x$, we have $u_i \geq 0$ for any $i \in I \cap P_+$, $u_i = 0$ for any $i \in P_+ \setminus I$, and $v_i \geq 0$ for $i \in P_+ \setminus I$, $v_i = 0$ for $i \in I \cap P_+$ and $\sum_i |u_i| \geq \sum_i |v_i|$. In addition, $Au = Av$ due to $Ax = 0$, and $u$ is $s$-sparse; finally, $u \neq v$ due to $x \neq 0$. We see that the $s$-sparse vector $u \in P_n$ is not the unique solution to

$$\min \left\{ \sum_i |z_i| : Az = Au, \quad z_i \geq 0 \; \forall i \in P_+ \right\},$$

which is a desired contradiction.
(ii)⇒(iii): Let A satisfy (ii). Let \( J \) be the family of all subsets \( J \) of \( \{1,...,n\} \) of cardinality \( \leq s \). For \( J \in J \), let
\[
X_J = \{ x \in \text{Ker} A : \|x\|_1 = 1, \ x_i \leq 0 \ \forall i \in P_+ \setminus J \}.
\]
Assuming that \( X_J \neq \emptyset \), let \( x \in X_J \). By (ii), we have
\[
\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_0} |x_i| < \sum_{i \notin J} |x_i|.
\]
We claim that \( \sum_{i \notin J} |x_i| > 0 \).

Indeed, otherwise \( x_i \neq 0 \) implies that \( i \in J \). Let \( I_+ \) and \( I_- \) be the subsets of \( J \) such that \( x_i > 0 \) for \( i \in I_+ \) and \( x_i < 0 \) for \( i \in I_- \). At least one of these sets is nonempty due to \( x \neq 0 \). W.l.o.g. we can assume that \( \sum_{i \in I_+} x_i \geq \sum_{i \in I_-} |x_i| \) (otherwise we could replace \( x \) with \(-x\) and swap \( I_+ \) and \( I_- \)). Applying (ii) to \( x \) and to \( I_+ \) in the role of \( J \), we should have
\[
\sum_{i \in I_+ \cap P_+} x_i + \sum_{i \in I_+ \cap P_0} |x_i| = \sum_{i \in I_-} |x_i| = \sum_{i \notin J} |x_i|,
\]
which is not the case. This contradiction shows that \( \sum_{i \notin J} |x_i| > 0 \) whenever \( x \in X_J \).

From our claim it follows that the function
\[
\frac{\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_0} |x_i|}{\sum_{i \notin J} |x_i|}
\]
is continuous on \( X_J \) and is \( < 1 \) at every point of this set. Since \( X_J \) is compact, we conclude that when \( J \in J \) is such that \( X_J \neq \emptyset \), there exists \( \xi_J < 1 \) such that
\[
\sum_{i \in \cap J \cap P_+} x_i + \sum_{i \in J \cap P_0} |x_i| \leq \xi_J \sum_{i \notin J} |x_i| \text{ for any } x \in X_J.
\]
Setting \( \xi = \max_{J \in J \setminus x \neq \emptyset} \xi_J \), we clearly ensure the validity of (iii). The implication (ii)⇒(iii) is proved.

(iii)⇒(i): Let (iii) take place; let us prove that \( A \) is \( s \)-semigood. Thus, let \( u \) with \( u_i \geq 0 \) for all \( i \in P_+ \) be \( s \)-sparse; we should prove that \( u \) is the unique optimal solution to the problem
\[
\min \ z \left\{ \sum_i |z_i| : Az = Au, \ z_i \geq 0 \ \forall i \in P_+ \right\}.
\]

Assume, on the contrary to what should be proved, that the latter problem has an optimal solution \( v \) different from \( u \), and let \( x = u - v \), so that \( x \in \text{Ker} A \) and \( x \neq 0 \). Setting \( I = \{ i : u_i \neq 0 \} \), we have Card(\( I \)) \( \leq s \) and \( x_i \leq 0 \) when \( i \in P_+ \setminus I \), whence by (iii)
\[
\sum_{i \in I \cap P_+} x_i + \sum_{i \in I \cap P_0} |x_i| \leq \xi \sum_{i \notin I} |x_i| = \xi \sum_{i \notin I} |v_i|,
\]
whence also
\[
\sum_{i \in I \cap P_+} u_i + \sum_{i \in I \cap P_0} |u_i| \leq \sum_{i \in I \cap P_+} v_i + \sum_{i \in I \cap P_0} |v_i| + \xi \sum_{i \notin I} |v_i|. \tag{44}
\]
Since \( \sum_i |v_i| \leq \sum_i |u_i| = \sum_{i \notin I} |u_i| \) due to the origin of \( v \), (44) implies that \( \sum_{i \notin I} |v_i| = 0 \), that is, both \( u \) and \( v \) are supported on \( I \), so that \( x \) is supported on \( I \) as well. Now let \( I_+ = \{ i \in I \cap P_+ : x_i \geq 0 \} \),
\( I_- = \{ i \in I \cap P_+ : x_i < 0 \} \) and \( I_n = I \cap P_n \). Replacing, if necessary, \( x \) with \(-x\) and swapping \( I_+ \) and \( I_- \), we can assume that \( \sum_{i \in I_+} x_i = \sum_{i \in I_-} |x_i| \geq \sum_{i \in I_-} |x_i| \). Applying (iii) to \( x \) and to \( I_+ \cup I_n \) in the role of \( J \), we get
\[
\sum_{i \in I_+} x_i + \sum_{i \in I_-} |x_i| \leq \xi \sum_{i \in I_-} |x_i|,
\]
whence \( \sum_{i \in I_+} x_i = \sum_{i \in I_-} |x_i| = \sum_{i \in I_-} |x_i| = 0 \) due to \( \sum_{i \in I_+} x_i \geq \sum_{i \in I_-} |x_i| \). Thus, \( x = 0 \), which is a desired contradiction.

We have proved that the properties (i) – (iii) of \( A \) are equivalent to each other.

(iii)\(\iff\)(iv): The implication (iv)\(\Rightarrow\)(iii) is evident. Let us prove the inverse implication. Thus, let \( A \) satisfy (iii) (and thus \( - (i) - (ii) \) as well), and let \( \xi' \in (\xi, 1) \). Let, as above, \( J \) be the family of all subsets \( J \) of \( \{1, ..., n\} \) of cardinality \( \leq s \). Let \( X = \{ x \in \text{Ker} A : ||x||_1 = 1 \} \), and let \( J \in J \). Let \( x \in X \). We claim that there exists a neighborhood \( U_x \) of \( x \) in \( X \) such that for any \( u \in U_x \) and \( \theta \geq \theta_{J,x} \) it holds
\[
\sum_{i \in J \cap P_+} u_i + \sum_{i \in J \cap P_n} |u_i| \leq \xi' \left( \sum_{i \in P_n \setminus J} |u_i| + \sum_{i \in P_+ \setminus J} \max[-u_i, \theta u_i] \right). \tag{45}
\]
The claim is clearly true when there exists \( i \in P_+ \setminus J \) such that \( x_i > 0 \). Now assume that \( x_i \leq 0 \) for \( i \in P_+ \setminus J \). Then \( \sum_{i \notin J} |x_i| > 0 \). Indeed, otherwise \( x_i = 0 \) for all \( i \notin J \), which combines with \( s \)-semigoodness of \( A \) and the relation \( Ax = 0 \) to imply that \( x = 0 \) (since assuming \( x \neq 0 \), we have \( x = u - v \) with \( s \)-sparse \( u \geq 0, v \geq 0 \) with non-overlapping supports, and \( Au = Av \) due to \( Ax = 0 \), which of course contradicts the \( s \)-semigoodness of \( A \)), while \( x \) definitely is nonzero (since \( ||x||_1 = 1 \) due to \( x \in X \)). Now, since \( x \in \text{Ker} A \) and \( x_i \leq 0 \), \( i \in P_+ \setminus J \), we have
\[
\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_n} |x_i| \leq \xi \sum_{i \notin J} |x_i| < \xi' \sum_{i \notin J} |x_i|
\]
where the first inequality is due to (iii), and the second – due to \( \sum_{i \notin J} |x_i| > 0 \). The concluding strict inequality clearly implies the validity of (45) with \( \theta = 1 \), provided that \( U_x \) is a small enough neighborhood of \( x \). Thus, our claim is true.

From the validity of our claim, extracting from the covering \( \{ U_x \}_{x \in X} \) of the compact set \( X \) a finite subcovering, we conclude that there exists \( \theta_J \in [1, \infty) \) such that
\[
\forall (x \in X, \theta \geq \theta_J) : \sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_n} |x_i| \leq \xi' \left( \sum_{i \in P_n \setminus J} |x_i| + \sum_{i \in P_+ \setminus J} \max[-x_i, \theta x_i] \right).
\]
Setting \( \theta = \max_{J \in J} \theta_J \), we see that \( A \) satisfies \( \text{SG}_s(\xi', \theta) \).

(iv)\(\Rightarrow\)(v): Let \( A \) satisfy \( \text{SG}_s(\xi, \theta) \) for certain \( \xi \in (0, 1), \theta \in [1, \infty) \) and let \( || \cdot || \) be a norm on \( \mathbb{R}^m \). Let, further, \( P \) be the orthogonal projector of \( \mathbb{R}^n \) on \( \text{Ker} A \). Then clearly with a properly chosen \( C \) one has
\[
||Px - x||_1 \leq C||Ax||
\]
for any $x \in \mathbb{R}^n$. Now let $J$ be a subset of $\{1, ..., n\}$ of cardinality $\leq s$, $x \in \mathbb{R}^n$ and $u = Px$. We have
\[
\sum_{i \in J \cap P_+} x_i + \sum_{i \in J \cap P_n} |x_i| \leq \sum_{i \in J \cap P_+} u_i + \sum_{i \in J \cap P_n} |u_i| + \sum_{i \in J} |u_i - x_i|
\]
so that $A$ satisfies $SG_{s,\beta}(\xi, \theta)$ with $\beta = \max(1, \theta \xi)C$. The implication (iv)$\Rightarrow$(v) is proved.

(v)$\Rightarrow$(vi)$\Rightarrow$(iii): These implications are evident. \(\square\)

## B Proof of Proposition 4.2

Let $Y = [Y_1, ..., Y_n]$, $v, \sigma, \rho$ certify the validity of $VSG^*_{s, \beta}(\xi, \theta)$, and let $\beta' \geq \beta, \theta' \geq \theta$ and $\xi' \in [\xi, 1)$. Let us set
\[
\lambda = \frac{1 + \theta \xi}{1 + \theta' \xi'}, \quad \mu = \frac{1 + \xi}{1 + \xi'},
\]
so that $\lambda, \mu \in [0, 1]$, and let $Y'$ be as in the assertion to be proved, that is, the columns of $Y'$ are multiples of those of $Y$: $Y'_i = \lambda Y_i$ when $i \in P_+$ and $Y'_i = \mu Y_i$ otherwise. All we need to prove is that $(Y', v, \sigma, \rho)$ certify the validity of $VSG^*_{s, \beta'}(\xi', \theta')$, and this immediately reduces to verification of the following fact:

**Lemma B.1** Let $i, 1 \leq i \leq n$, be fixed, and let $z \in \mathbb{R}^n$ for any $I \subset \{1, ..., n\}$ of cardinality $s$ satisfy the relations
\[
(a) \quad (1 + \theta \xi) \sum_{j \in P_+ \cap I} \max[\lambda z_j - \delta_{ij}, 0] + (1 + \xi) \sum_{j \in P_+ \cap I} |z_j - \delta_{ij}| + (Av)_i \leq \xi,
\]
\[
(b) \quad (1 + \theta \xi) \sum_{j \in P_+ \cap I} \max[\delta_{ij} - \lambda z_j, 0] + (1 + \xi) \sum_{j \in P_+ \cap I} |z_j - \delta_{ij}| - (Av)_i \leq \eta = \begin{cases} \theta \xi, & i \in P_+ \\ \xi, & i \in P_n \end{cases}
\]

where $\delta_{ij} = \begin{cases} 0, & j \neq i \\ 1, & i = j \end{cases}$. Then for every set $I \subset \{1, ..., n\}$ of cardinality $s$ we have
\[
(a) \quad (1 + \theta' \xi') \sum_{j \in P_+ \cap I} \max[\lambda z_j - \delta_{ij}, 0] + (1 + \xi') \sum_{j \in P_+ \cap I} |z_j - \delta_{ij}| + (Av)_i \leq \xi',
\]
\[
(b) \quad (1 + \theta' \xi') \sum_{j \in P_+ \cap I} \max[\delta_{ij} - \lambda z_j, 0] + (1 + \xi') \sum_{j \in P_+ \cap I} |z_j - \delta_{ij}| - (Av)_i \leq \eta = \begin{cases} \theta' \xi', & i \in P_+ \\ \xi', & i \in P_n \end{cases}
\]

**Proof.** Taking into account the definition of $\lambda, \mu$, in the case of $i \not\in I$ the relations (47) are readily given by (46), hence we can assume $i \in I$. Consider two possible cases: $i \in P_+ \cap I$ and $i \in P_n \cap I$. 25
The case of $i \in P_+ \cap I$. In this case (46) reads:

\[ (a) \quad (1 + \theta \xi) \max[z_i - 1, 0] + (1 + \theta \xi) \sum_{j \in P_+ \cap I, j \neq i} \max[z_j, 0] \\
+ (1 + \xi) \sum_{j \in P_+ \cap I} |z_j| + (Av)_i \leq \xi, \]

\[ (b) \quad (1 + \theta \xi') \max[1 - z_i, 0] + (1 + \theta \xi') \sum_{j \in P_+ \cap I, j \neq i} \max[-z_j, 0] \\
+ (1 + \xi) \sum_{j \in P_+ \cap I} |z_j| - (Av)_i \leq \theta \xi', \]

and our goal is to verify that then

\[ (a) \quad (1 + \theta' \xi') \max[\lambda z_i - 1, 0] \\
= (1 + \theta' \xi') \lambda \sum_{j \in P_+ \cap I, j \neq i} \max[z_j, 0] + (1 + \xi) \mu \sum_{j \in P_+ \cap I} |z_j| + (Av)_i \leq \xi', \]

\[ (b) \quad (1 + \theta' \xi') \max[1 - \lambda z_i, 0] \\
+ (1 + \theta \xi) \sum_{j \in P_+ \cap I} \max[-z_j, 0] + (1 + \xi) \sum_{j \in P_+ \cap I} |z_j| - (Av)_i \leq \theta' \xi'. \]

We have $\lambda z_i - 1 \leq \lambda(z_i - 1)$ due to $\lambda \leq 1$, whence

\[ \max[\lambda z_i - 1, 0] \leq \max[\lambda(z_i - 1), 0] = \lambda \max[z_i - 1, 0], \]

and therefore (49.a) follows from (48.a) due to $(1 + \theta' \xi') \lambda = 1 + \theta \xi$ and $\theta' \xi' \geq \xi$. It remains to verify (49.b). Assume, first, that $\lambda z_i \leq 1$. From (48.b) it follows that

\[ (1 + \xi)[1 - z_i] + R \leq (1 + \theta \xi) \max[1 - z_i, 0] + R \leq \theta \xi, \]

whence $z_i \geq \frac{1 + R}{1 + \theta \xi}$ and therefore

\[ 1 - \lambda z_i \leq 1 - \frac{1 + R}{1 + \theta' \xi} = \frac{\theta' \xi' - R}{1 + \theta' \xi}. \]

Since we are in the case $1 - \lambda z_i \geq 0$, we arrive at

\[ (1 + \theta' \xi') \max[1 - \lambda z_i, 0] + R = (1 + \theta' \xi')[1 - \lambda z_i] + R \leq (1 + \theta' \xi') \frac{\theta' \xi' - R}{1 + \theta' \xi} + R = \theta' \xi', \]

as required in (49.b). The case of $1 - \lambda z_i \leq 0$ is trivial, since here the left hand side in (49.b) clearly is $\leq$ the left hand side in (48.b), while $\theta' \xi' \geq \theta \xi$, so that (49.b) is readily given by (48.b). Thus, when $i \in P_+ \cap I$, (49) follows from (48).

The case of $i \in P_n \cap I$. In this case (46) means that

\[ (a) \quad (1 + \theta \xi) \sum_{j \in P_n \cap I, j \neq i} \max[z_j, 0] + (1 + \xi)|1 - z_i| + (1 + \xi) \sum_{j \in P_n \cap I, j \neq i} |z_j| + (Av)_i \leq \xi, \]

\[ (b) \quad (1 + \theta \xi) \sum_{j \in P_n \cap I} \max[-z_j, 0] + (1 + \xi)|1 - z_i| + (1 + \xi) \sum_{j \in P_n \cap I, j \neq i} |z_j| - (Av)_i \leq \xi, \]

and our goal is to verify that then

\[ (a) \quad (1 + \theta' \xi') \sum_{j \in P_n \cap I, j \neq i} \max[\lambda z_j, 0] \\
+ (1 + \xi)|1 - \mu z_i| + (1 + \xi) \mu \sum_{j \in P_n \cap I, j \neq i} |z_j| + (Av)_i \leq \xi', \]

\[ (b) \quad (1 + \theta' \xi') \sum_{j \in P_n \cap I} \max[-\lambda z_j, 0] \\
+ (1 + \xi)|1 - \mu z_i| + (1 + \xi) \sum_{j \in P_n \cap I, j \neq i} |\mu z_j| - (Av)_i \leq \xi'. \]
Comparing (50.a) with (51.a), and (50.b) with (51.b), we see that all we need in order to derive (51) from (50) is to verify the following statement: if \((1 + \xi)|1 - z| \leq \xi + a\), then \((1 + \xi')|1 - \mu z| \leq \xi' + a\). This is immediate: assuming \((1 + \xi)|1 - z| \leq \xi + a\), the premises in the following two implication chains hold true:

\[
(1 + \xi)[1 - z] \leq \xi + a \Rightarrow z \geq \frac{1 - a}{1 + \xi} \Rightarrow \mu z \geq \frac{1 - a}{1 + \xi} \Rightarrow 1 - \mu z \leq 1 - \frac{1 - a}{1 + \xi} = \frac{\xi' + a}{1 + \xi'}
\]
\[
\Rightarrow (1 + \xi')[1 - \mu z] \leq \xi' + a.
\]

\[
(1 + \xi)[z - 1] \leq \xi + a \Rightarrow z \leq 1 + \frac{\xi + a}{1 + \xi} \Rightarrow \mu z \leq \frac{1 + 2\xi + a}{1 + \xi} \Rightarrow \mu z - 1 \leq \frac{2\xi - \xi' + a}{1 + \xi'}
\]
\[
\Rightarrow (1 + \xi')[\mu z - 1] \leq 2\xi - \xi' + a \Rightarrow (1 + \xi')[\mu z - 1] \leq \xi' + a,
\]

while the resulting inequalities in these chains lead to the desired conclusion \((1 + \xi')|1 - \mu z| \leq \xi' + a\). □