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# The Two Stage $l_1$ Approach to the Compressed Sensing Problem

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**Résumé**—This paper gives new results on the recovery of sparse signals using  $l_1$ -norm minimization. We introduce a two-stage  $l_1$  algorithm equivalent to the first two iterations of the alternating  $l_1$  relaxation introduced in [1].

## I. INTRODUCTION

The Compressed sensing problem is currently the focus of an extensive research activity and can be stated as follows : Given a sparse vector  $x^* \in \mathbb{R}^n$  and an observation matrix  $A \in \mathbb{R}^{m \times n}$  with  $m \ll n$ , try to recover the vector  $x$  from the small measurement vector  $y = Ax^*$ . Although the problem consists of solving an overdetermined system of linear equations, enough sparsity will allow to succeed as shown by the following lemma (where  $\Sigma_s$  will denote the set of all  $s$ -sparse vectors, i.e. vectors whose components are all zero except for at most  $s$  of them),

**Lemma I.1** [2] *If  $A$  is any  $m \times n$  matrix and  $2s \leq m$ , then the following properties are equivalent :*

*i. The decoder  $\Delta_0(y)$  given by*

$$\Delta_0(y) = \operatorname{argmin}_{x \in \mathbb{R}^n} \|x\|_0 \quad \text{s.t.} \quad Ax = y. \quad (1)$$

*$k$  satisfies  $\Delta_0(Ax) = x$ , for all  $x \in \Sigma_s$ ,*

*ii. For any set of indices  $T$  with  $\#T = 2k$ , the matrix  $A_T$  has rank  $2s$  where  $A_T$  stands for the submatrix of  $A$  composed of the columns indexed by  $T$  only.*

### A. The $l_1$ and the Reweighted $l_1$ relaxations

The main problem with decoder  $\Delta_0$  is that the optimization problem (1) is in general NP-hard. For this reason, the now standard  $l_1$  relaxation strategy is adopted, i.e. the decoder  $\Delta_1(y)$  is obtained as

$$\Delta_1(y) = \operatorname{argmin}_{x \in \mathbb{R}^n} \|x\|_1 \quad \text{s.t.} \quad Ax = y. \quad (2)$$

Now, solving (2) can be done in polynomial time and thus  $\Delta_1(y)$  can be efficiently computed. The second problem is to give robust conditions under which exact recovery holds. One such condition was given by Candes Romberg and Tao [3] and is now known as the Uniform Uncertainty Principle (UUP) or as the Restricted Isometry Property (RIP).

One of the main remaining challenges is to reduce the number of observations  $m$  needed to recover a given sparse

signal  $x$ . One idea is the use of  $l_p$ ,  $p < 0 < 1$  decoders  $\Delta_p(y)$ . The main draw back of the approach using  $l_p$ ,  $p < 0 < 1$  norm minimization is that the resulting decoding scheme is again NP-Hard. Another idea is to use a reweighted  $l_1$  approach as proposed in [4].

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### Algorithm 1 Reweighted $l_1$ algorithm (Rew- $l_1$ )

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**Input**  $u > 0$  and  $L \in \mathbb{N}_*$   
 $z_u^{(0)} = e$   
 $x_u^{(0)} \in \min_{x \in \mathbb{R}^n, Ax=y} \|x\|_1$   
 $l = 1$   
**while**  $l \leq N$  **do**  
 $z_u^{(l)} = \frac{1}{|x^{(l)}|+u}$  componentwise  
 $x_u^{(l)} \in \operatorname{argmax}_{x \in \mathbb{R}^n, Ax=y} \sum_{i=1}^n w_i^{(l-1)} |x_i|$   
 $l \leftarrow l + 1$   
**end while**  
**Output**  $z_u^{(L)}$  and  $x_u^{(L)}$ .

---

The main intuition behind this reweighted  $l_1$  relaxation is the following. The greater the component  $x_i$  becomes, the smaller weight it should receive since it can be considered that this component should not be set to zero.

The main drawback of the reweighted  $l_1$  approach is that an unknown parameter is to be tuned whose order of magnitude is hard to know ahead of time.

### B. The Alternating $l_1$ algorithm

Another approach was proposed in [1] and uses Lagrange duality. Let us write down problem (1), to which  $\Delta_0$  is the solution map, as the following equivalent problem

$$\max_{z \in \{0,1\}^n, x \in \mathbb{R}^n} e^t z \quad \text{s.t.} \quad z_i x_i = 0, \quad i = 1, \dots, n, \quad Ax = y$$

where  $e$  denotes the vector of all ones. Here since the sum of the  $z_i$ 's is maximized, the variable  $z$  plays the role of an indicator function for the event that  $x_i = 0$ . This problem is clearly nonconvex due to the quadratic equality constraints  $z_i x_i = 0$ ,  $i = 1, \dots, n$ . However, these constraints can be merged into the unique constraint  $\|D(z)x\|_1 = 0$ , leading to the following equivalent problem

$$\max_{z \in \{0,1\}^n, x \in \mathbb{R}^n} e^t z \quad \text{s.t.} \quad \|D(z)x\|_1 = 0, \quad Ax = y. \quad (3)$$

The Alternating  $l_1$  algorithm consists of a suboptimal alternating minimization procedure to approximate the dual function at  $u$ . The algorithm is as follows.

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**Algorithm 2** Alternating  $l_1$  algorithm (Alt- $l_1$ )

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**Input**  $u > 0$  and  $L \in \mathbb{N}_*$   
 $z_u^{(0)} = e$   
 $x_u^{(0)} \in \max_{x \in \mathbb{R}^n, Ax=y} \mathcal{L}(x, z^{(0)}, u)$   
 $l = 1$   
**while**  $l \leq N$  **do**  
 $z_u^{(l)} \in \operatorname{argmax}_{z \in \{0,1\}^n} \mathcal{L}(x_u^{(l)}, z, u)$   
 $x_u^{(l)} \in \operatorname{argmax}_{x \in \mathbb{R}^n, Ax=y} \mathcal{L}(x, z_u^{(l)}, u)$   
 $l \leftarrow l + 1$   
**end while**  
**Output**  $z_u^{(L)}$  and  $x_u^{(L)}$ .

---

Notice that, similarly to the reweighted  $l_1$  algorithm, the Alternating  $l_1$  method also requires the tuning of an unknown parameter  $u$ . However, the main motivation for this proposal is that this parameter  $u$  has a clear meaning : it is a dual variable which, in the case where the dual function  $\theta(u)$  is well approximated by the sequence  $\mathcal{L}(x^{(l)}, z^{(l)}, u)$ , can be efficiently optimized without additional prior information, due to the convexity of the dual function.

## II. THE TWO STAGE $l_1$ METHOD

The main remark about the alternating  $l_1$  method is the following (see [1]) : for a given dual variable  $u$ , the alternating  $l_1$  algorithm can be seen a sequence  $(x_u^{(l)})_{l \in \mathbb{N}}$  of truncated  $l_1$ -norm minimizers of the type

$$x_u^l = \operatorname{argmin}_{x \in \mathbb{R}^n} \|x_{T_u^l}\|_1 \quad \text{s.t.} \quad Ax = y. \quad (4)$$

where  $T_u^l$  is the set of indices for which  $|x_i^{l-1}| < \frac{1}{u}$ . Therefore, the Alternating  $l_1$  algorithm can be seen as an iterative thresholding scheme with threshold value equal to  $\frac{1}{u}$ . Now assume for instance that a fraction  $\rho m$  of the non zero components is well identified by the plain  $l_1$  step with solution  $x^{(l)}$ . Then, the practitioner might ask if the appropriate value for  $u$  is the one which imposes an  $l_1$  penalty on the index set corresponding to the  $n - \rho m$  smallest components of  $x^{(l)}$ . Moreover, the large scale simulation experiments which have been performed on the plain  $l_1$  relaxation seemed to agree on the fact that the breakdown point occurs near  $\frac{m}{4}$ . Thus, a practitioner could be tempted to wonder whether  $\rho = \frac{1}{4}$  is a sensible value. Motivated by the previous practical considerations, the two stage  $l_1$  algorithm is defined as follows (the parameter  $u$  is now replaced by the parameter  $\rho = \frac{1}{u}$ ).

Notice that we restrict  $\rho$  to lie in  $(0, \frac{1}{2})$ . The reason should be obvious since, due to Lemma I.1, even decoder  $\Delta_0(y)$  is unable to identify more than  $\frac{m}{2}$ -sparse vectors. Another remark is that the procedure could be continued for more than 2 steps but simulation experiments of the Alternating  $l_1$  method seem to confirm that in most cases two steps suffice to converge.

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**Algorithm 3** Two stage  $l_1$  algorithm (2Stage- $l_1$ )

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**Input**  $\rho \in (0, \frac{1}{2})$   
**Step 0** :  $x^{(0)} \in \operatorname{argmax}_{x \in \mathbb{R}^n, Ax=y} \|x\|_1$  and  $T = \text{index set of the } \rho m \text{ largest components of } x^{(0)}$   
**Step 1** :  $x^{(1)} \in \operatorname{argmax}_{x \in \mathbb{R}^n, Ax=y} \|x_{T^c}\|_1$   
**Output**  $x_\rho^{(1)}$ .

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## III. MAIN RESULTS

At Step 1 of the method, a subset  $T$  is selected with cardinal  $\rho m$  and optimization is then performed with objective function  $\|x_{T^c}\|_1$ . In this section, we will adopt the following notations :  $S$  will denote the support of  $x^*$ ,  $T$  will denote the index set of the  $\rho m$  largest components of  $x^{(0)}$  as defined in the two-stage  $l_1$  algorithm.  $T_g^c$  will be an abbreviation of  $(T^c)_g$ , the "good" subset of  $T^c$  or, in mathematical terms, the subset of indices of  $S$  which also belong to  $T^c$ . On the other hand,  $T_b^c$  will denote the complement of  $T_g^c$  in  $T^c$ .

**Lemma III.1** *Assume the cardinal of  $T_g^c$  is less than  $\gamma/2$  and that  $A$  satisfies  $RIP(\delta, \gamma s)$ . Let  $h^{(1)} = x^{(1)} - x^*$ . Then, there exists a positive number  $C^*$  depending on  $x^*$  such that  $\|h_T^{(1)}\|_1 \leq C^* \|x_{T_b^c}^*\|_1$ . Moreover, if  $\|h_T^{(1)}\|_1 = 0$ , then  $\|x_{T_b^c}^*\|_1 = 0$ .*

**Proof.** Let  $N(h_T)$  denote the optimal value of the problem

$$\min_{h_{T_b^c} \in \mathbb{R}^{n-s}} \|x_{T_b^c}^* + h_{T_b^c}\|_1 \quad (5)$$

subject to

$$A_{T_b^c}(x_{T_b^c}^* + h_{T_b^c}) + A_{T_g^c}x_g^{(1)} = y - A_T(x_T^* + h_T).$$

Assume that  $x_{T_b^c}^* = 0$ . Then,  $N(h_T)$  plays the role of a norm for  $h_T$  although it does not satisfy the triangle inequality. In particular,  $N(h_T)$  is nonnegative, convex and  $N(h_T) = 0$  implies that  $h_T = 0$ .

Nonnegativity and convexity are straightforward. Assume that  $N(h_T) = 0$ , i.e. the solution  $\tilde{h}$  of (5) is null. This implies that  $A_{T_g^c}x_{T_g^c}^{(1)} = y - A_Tx_T^* = A_{T_b^c}x_{T_b^c}^*$ , which implies that  $x_{T_g^c}^{(1)} - x_{T_b^c}^*$  is in the kernel of  $A_{T_g^c}$ . Using the fact that  $T_g^c$  has cardinal less than  $\gamma s/2$  and the  $RIP(\delta, \gamma s)$  assumption, we conclude that  $x_{T_g^c}^{(1)} = x_{T_b^c}^*$ . In order to finish the proof of the lemma, it remains to recall that  $N(h_T)$  is convex and that, by Theorem 1.1 in [5],  $\|h^{(1)}\|_1$  (and thus  $\|h_T^{(1)}\|_1$ ) is bounded from above by  $C \inf_{\#U \leq \gamma/2} \|x_{U^c}\|_1$  in order to obtain existence of a sufficiently small positive constant  $C^*$  depending on  $x^*$  such that  $N(h_T) \geq C^* \|h_T\|_1$  for all  $h_T$  in the ball  $B(0, C \|x^*\|_1)$ . The desired result then follows.

To prove that  $N(h_T) = 0$  if  $h_T = 0$  is a bit harder. Thus, assume that  $h_T = 0$ . Then, the solution  $\tilde{h}$  of (5) is just the solution of

$$\min_{h_{T_b^c} \in \mathbb{R}^{n-s}} \|h_{T_b^c}\|_1 \quad A_{T_b^c}h_{T_b^c} = y - A_T - x_T^* - A_{T_g^c}x_g^{(1)}.$$

Now since  $y = Ax^*$ , we obtain that  $y - A_T x_T^* - A_{T_g^c} x_g^{(1)} = A_{T_g^c} (x_{T_g^c}^* - x_g^{(1)})$  and thus, the right hand side term is nothing but the image of a  $\gamma s/2$ -sparse vector. Now, recalling that we assumed  $RIP(\delta, \gamma s)$ , Theorem 1.1 in [5] implies that  $\tilde{h}$  must be the sparsest solution of the system  $A_{T_g^c} h_{T_g^c} = y - A_T x_T^* - A_{T_g^c} x_g^{(1)}$  from which we deduce that  $\tilde{h}$  is  $\gamma s/2$ -sparse. Therefore the vector  $(h_{T_g^c}, x_{T_g^c}^{(1)})$  is  $\gamma s$  which solves  $A_{T_g^c} x_{T_g^c} = y - A_T x_T^*$ . On the other hand,  $x_{T_g^c}^*$  also solves  $A_{T_g^c} x_{T_g^c} = y - A_T x_T^*$  and its support is included in the support of  $(h_{T_g^c}, x_{T_g^c}^{(1)})$ . Therefore,  $(h_{T_g^c}, x_{T_g^c}^{(1)}) - x_{T_g^c}^*$  is a  $\gamma s/2$  sparse vector which lies in the kernel of  $A$ . Using again the fact that  $RIP(\delta, \gamma s)$  holds, we conclude that  $(h_{T_g^c}, x_{T_g^c}^{(1)}) - x_{T_g^c}^* = 0$ . Thus,  $h_{T_g^c} = 0$  and  $x_{T_g^c}^{(1)} = x_{T_g^c}^*$ .  $\square$

Using this lemma, we deduce the following theorem.

**Theorem III.1** Assume that  $RIP(\delta, \gamma s)$  holds and that an index set  $T_g$  of cardinal greater than or equal to  $(1 - \gamma/2)s$  has been recovered at Step 0 after thresholding, then  $x^{(1)}$  satisfies

$$\|x^{(1)} - x^*\|_1 \leq C^{**} \|x_{T_g^c}^*\|_1.$$

for some constant  $C^{**}$  depending on  $x^*$ .

**Proof.** The vector  $x^{(1)}$  satisfies

$$\|x_{T_g^c}^{(1)}\|_1 \leq \|x_{T_g^c}^*\|_1. \quad (6)$$

Let us write  $h^{(1)} = x^{(1)} - x^*$ . Using (6), a now standard decomposition gives

$$\|x_{T_g^c}^*\|_1 - \|h_{T_g^c}\|_1 + \|h_{T_g^c}\|_1 - \|x_{T_g^c}^*\|_1 \leq \|x_{T_g^c}^*\|_1 + \|x_{T_g^c}^*\|_1.$$

We thus obtain

$$\|h_{T_g^c}\|_1 \leq \|h_{T_g^c}\|_1 + 2\|x_{T_g^c}^*\|_1. \quad (7)$$

However, since  $RIP(\delta, \gamma s)$  holds,  $NSP(C, \gamma/2s)$  holds too, with  $C < 1$ . Therefore, we obtain that

$$\|h_{T_g^c}\|_1 \leq C(\|h_{T_g^c}\|_1 + \|h_T\|_1). \quad (8)$$

Combining (7) and (8), we obtain

$$\|h_{T_g^c}\|_1 \leq \frac{C}{1-C} \|h_T\|_1 + \frac{2}{1-C} \|x_{T_g^c}^*\|_1. \quad (9)$$

As a consequence, we obtain that

$$\begin{aligned} \|h\|_1 &\leq C(2\|x_{T_g^c}^*\|_1 + C'\|h_T\|_1) + \|h_T\|_1 + 2\|x_{T_g^c}^*\|_1 \\ &\quad + C\|h_T\|_1 + \|h_T\|_1 \\ &= (1 + C + CC')\|h_T\|_1 + 2(1 + C)\|x_{T_g^c}^*\|_1. \end{aligned}$$

which, using Lemma III.1, implies

$$\|h\|_1 \leq ((1 + C + CC')C^* + 2(1 + C))\|x_{T_g^c}^*\|_1. \quad (10)$$

which is the desired bound.  $\square$

The following corollary is a straightforward consequence of the previous theorem.

**Corollary III.1** Assume that the assumptions of Theorem III.1 are satisfied. Then, exact reconstruction is obtained if  $x_{T_g^c}^* = 0$ , i.e.  $x^*$  is  $s$ -sparse.

## IV. MONTE CARLO EXPERIMENTS

The following Monte Carlo experiments show that the performance of the two-stage  $l_1$  algorithm which drops the penalty over the index set of the  $m/4$  largest components of the solution of plain  $l_1$  are almost as good as the performance of the reweighted  $l_1$  with the best parameter which is usually unknown in practice. A Python program is available at <http://stephane.g.chretien.googlepages.com/alternatingl1> and can be used to perform these experiments and other involving the Alternating  $l_1$  algorithm.

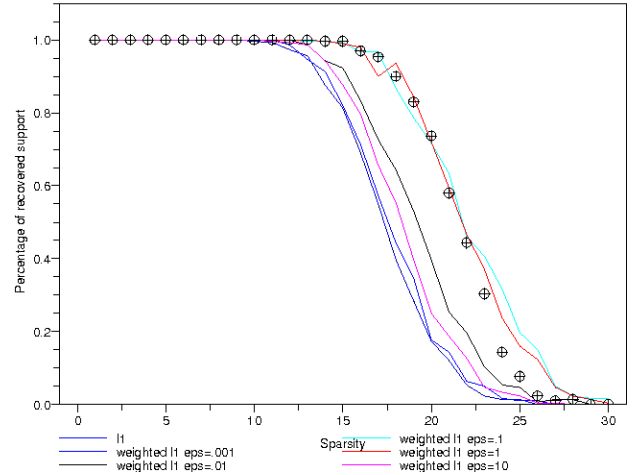


FIG. 1. Rate of success over 300 Monte Carlo experiments in recovering the support of the signal vs. signal sparsity  $k$  for  $n = 128$ ,  $m = 50$ ,  $L = 4$ ,  $u = 3$ .  $A$  and nonnull components of  $x$  were drawn from the gaussian  $\mathcal{N}(0, 1)$  distribution. The results for the two-stage  $l_1$  method are represented by the “+ in a circle” sign.

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