Sharp Support Recovery from Noisy Random Measurements by L1 minimization

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Abstract

In this paper, we investigate the theoretical guarantees of penalized ℓ_1-minimization (also called Basis Pursuit Denoising or Lasso) in terms of sparsity pattern recovery (support and sign consistency) from noisy measurements with non-necessarily random noise, when the sensing operator belongs to the Gaussian ensemble (i.e. random design matrix with i.i.d. Gaussian entries). More precisely, we derive sharp non-asymptotic bounds on the sparsity level and (minimal) signal-to-noise ratio that ensure support identification for most signals and most Gaussian sensing matrices by solving the Lasso with an appropriately chosen regularization parameter.

Our first purpose is to establish conditions allowing exact sparsity pattern recovery when the signal is strictly sparse. Then, these conditions are extended to cover the compressible or nearly sparse case. In these two results, the role of the minimal signal-to-noise ratio is crucial. Our third main result gets rid of this assumption in the strictly sparse case, but this time, the Lasso allows only partial recovery of the support. We also provide in this case a sharp ℓ_2-consistency result on the coefficient vector.

The results of the present work have several distinctive features compared to previous ones. One of them is that the leading constants involved in all the bounds are sharp and explicit. This is illustrated by some numerical experiments where it is indeed shown that the sharp sparsity level threshold identified by our theoretical results below which sparsistency of the Lasso solution is guaranteed meets the one empirically observed.

Key words: Compressed sensing, ℓ_1 minimization, sparsistency, consistency.

1. Introduction

1.1. Problem setup

The conventional wisdom in digital signal processing is the Shannon sampling theorem valid for bandlimited signals. However, such a sampling scheme excludes many signals of interest that are not necessarily bandlimited but can still be explained either exactly or accurately by a small number of degrees of freedom. Such signals are termed sparse signals.

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In fact we distinguish two types of sparsity: strict and weak sparsity (the latter is also termed compressibility). A signal x, considered as a vector in a finite dimensional subspace of $\mathbb{R}^p$, is strictly or exactly sparse if all but a few of its entries vanish; i.e., if its support $I(x) = \mathrm{supp}\,(x) = \{1 \leq i \leq p \;\; | \;\; x[i] \neq 0\}$ is of cardinality $k \ll p$. A k-sparse signal is a signal where exactly k samples have a non-zero value. Signals and images of practical interest may be *compressible* or *weakly sparse* in the sense that the sorted magnitudes $|x^{\mathrm{sorted}}[i]|$ decay quickly. Thus x can be well-approximated as k-sparse up to an error term (this property will be used when we will tackle compressible signals). If a signal is not sparse in its original domain, it may be *sparsified* in an appropriate orthobasis Φ (hence the importance of the point of view of computational harmonic analysis and approximation theory). Without loss of generality, we assume throughout that Φ is the standard basis.

The compressed sensing/sampling [1, 2, 3] asserts that sparse or compressible signals can be reconstructed with theoretical guarantees from far fewer measurements than the ambient dimension of the signal. Furthermore, the reconstruction is stable if the measurements are corrupted by an additive bounded noise. The encoding (or sampling) step is very fast since it gathers n non-adaptive linear measurements that preserve the structure of the signal x_0:

$$y = Ax_0 + w \in \mathbb{R}^n, \tag{1}$$

where $A \in \mathbb{R}^{n \times p}$ is a rectangular measurement matrix, i.e., $n < p$, and w accounts for possible noise with bounded ℓ_2 norm. In this work, we do not need w to be random and we consider that A is drawn from the Gaussian matrix ensemble[1], i.e., the entries of A are independent and identically distributed (i.i.d.) $\mathcal{N}(0, 1/n)$. The columns of A are denoted a_i, for $i = 1, \cdots, p$. In the sequel, the sub-matrix A_I is the restriction of A to the columns indexed by $I(x)$. To lighten the notation, the dependence of I on x is dropped and should be understood from the context.

The signal is reconstructed from this underdetermined system of linear equations by solving a convex program of the form:

$$x \in \underset{x \in \mathbb{R}^p}{\mathrm{argmin}} \;\; \|x\|_1 \;\text{ such that }\; Ax - y \in \mathcal{C} \;, \tag{2}$$

where $\mathcal{C}$ is an appropriate closed convex set, and $\|x\|_q := (\sum_i |x[i]|^q)^{1/q}$, $q \geq 1$ is the ℓ_q-norm of a vector with the usual adaptation for $q = \infty$: $\|x\|_\infty = \max_i |x[i]|$. We also denote $\|x\|_0$ as the ℓ_0 pseudo-norm which counts the number of non-zero entries of x. Obviously, $\|x\|_0 = |I(x)|$. For any vector x, the notation $\overline{x} \in \mathbb{R}^{|I(x)|}$ means the restriction of x to its support.

Typically, if $\mathcal{C} = \{0\}$ (no noise), we end up with the so-called Basis Pursuit [4] problem

$$\min_{x \in \mathbb{R}^p} \|x\|_1 \;\text{ such that }\; y = Ax \;. \tag{BP}$$

Taking $\mathcal{C}$ as the ℓ_2 ball of radius ϵ, we have a noise-aware variant of BP

$$\min_{x \in \mathbb{R}^p} \|x\|_1 \;\text{ such that }\; \|Ax - y\|_2 \leq \epsilon \tag{ℓ_1-constrained}$$

where the parameter $\epsilon > 0$ depends on the noise level $\|w\|_2$. This constrained form can also be shown to be equivalent to the ℓ_1-penalized optimization problem, which goes by the name of Basis Pursuit DeNoising [4] or Lasso in the statistics community after [5]:

$$\min_{x \in \mathbb{R}^p} \frac{1}{2} \|y - Ax\|_2^2 + \gamma \|x\|_1 \;, \tag{Lasso}$$

[1] In a statistical linear regression setting, we would speak of a random Gaussian design.

where γ is the regularization parameter. (ℓ_1-constrained) and (Lasso) are equivalent in the sense that there is a bijection between γ and ϵ such that both problems share the same set of solutions. However, this bijection is unknown explicitly and depends on y and A, so that in practice, one needs to use different algorithms to solve each problem, and theoretical results are stated using one formulation or the other. In this paper, we focus on the Lasso formulation. It is worth noting that the Dantzig selector [6, 7] is also a special instance of (2) when $\mathcal{C} = \{z \in \mathbb{R}^p | \left\|A^{\mathrm{T}} z\right\|_\infty \leq \gamma\}$.

The convex problems of the form (ℓ_1-constrained) and (Lasso) are computationally tractable and many algorithms have been developed to solve them, and we only mention here a few representatives. Homotopy continuation algorithms [8, 9, 10] track the whole regularization path. Many first-order algorithms originating from convex non-smooth optimization theory have been proposed to solve (Lasso). These include one-step iterative thresholding algorithms [11, 12, 13, 14], or accelerated variants [15, 16], multi-step schemes such as [17] or [18]. The Douglas-Rachford algorithm [19, 20] is a first-order scheme that can be used to solve (ℓ_1-constrained). A more comprehensive account can be found in [21, Chapter 7].

1.2. Theoretical performance measures of the Lasso

These last years, we have witnessed a flurry of research activity where efforts have been made to investigate the theoretical guarantees of ℓ_1 minimization by solving the Lasso for sparse recovery from noisy measurements in the underdetermined case $n < p$. Overall, the derived conditions hinge on strong assumptions on the structure and interaction between the variables in A as indexed by x_0. An overview of the literature pertaining to our work will be covered in Section 1.3 after notions are introduced so that the discussions are clearer.

Let x_0 be the original vector as defined in (1), $f_0 = Ax_0$ the noiseless measurements, $x(\gamma)$ a minimizer of the Lasso problem and $f(\gamma) = Ax(\gamma)$.

Consistency. ℓ_q-consistency on the signal x means that the ℓ_q-error $\|x_0 - x(\gamma)\|_q$, for typically $q = 1$, 2 or ∞, between the unknown vector x_0 and a solution $x(\gamma)$ of either (Lasso) or (ℓ_1-constrained) comes within a factor of the noise level.

Sparsistency. Sparsity pattern recovery (also dubbed sparsistency for short or variable selection in the statistical language) requires that the indices and signs of the solutions $x(\gamma)$ are equal to those of x_0 for a well chosen value of γ. Partial support recovery occurs when the recovered support is included (strictly) in that of x_0 with the correct sign pattern.

In general, it is not clear which of these performance measures is better to characterize the Lasso solution. Nevertheless, in the noisy case, consistency does not tell the whole story and there are many applications where bounds on the ℓ_q-error are insufficient to characterize the accuracy of the Lasso estimate. In this case, exact or partial recovery of the support, hence of the correct model variables, is the desirable property to have. Among other advantages, this allows for instance to circumvent the bias of the Lasso and thus enhance the estimation of x_0 and Ax_0 using a debiasing procedure: recover the support I by solving the Lasso, followed by least-squares regression on the selected variables $(a_i)_{i \in I}$; see e.g. [6, 22]. Our work falls within this scope and focuses on exact and partial support identification for both strictly sparse and compressible signals in the presence of noise on Gaussian random measurements.

1.3. Literature overview

The properties of the Lasso have been extensively studied, including consistency and distribution of its estimates. There is of course a huge literature on the subject, and covering it fairly is beyond the scope of this paper. In this section, we restrict our overview to those works pertaining to ours, i.e., sparsity pattern recovery in presence of noise.

Much recent work aims at understanding the Lasso estimates from the point of view of sparsistency. This body of work includes [22, 6, 23, 24, 25, 26, 27, 28, 29]. For the Lasso estimates to be close to the model selection estimates when the data dimensions (n, p) grow, all the aforementioned papers assumed a sparse model and used various conditions that require the irrelevant variables to be not too correlated with the relevant ones.

Mutual coherence-based conditions. Several researchers have studied independently the qualitative performance of the Lasso for either exact or partial sparsity pattern recovery of sufficiently sparse signals under a mutual coherence condition on the measurement matrix A; see for instance [23, 30, 26, 31] when A is deterministic, and [32] when A is Gaussian. However, mutual coherence is known to lead to overly pessimistic sparsity bounds.

Support structure-based conditions. These sufficient recovery conditions were refined by considering not only the cardinality of the support but also its structure, including the signs of the non-zero elements of x_0. Such criteria use the interactions between the relevant columns of $A_I = (a_i)_{i\in I}$ and the irrelevant ones $(a_i)_{i\notin I}$. More precisely, we define the following condition developed in [33] to analyze the properties of the Lasso. This condition goes by the name of irrepresentable condition in the statistical literature; see e.g. [28, 22, 27, 34] and [35] for a detailed review.

Definition 1. *Let I be the support of x_0 and I^c its complement in $\{1, \cdots, p\}$. The irrepresentable (or Fuchs) condition is fulfilled if*

$$F(x_0) := \left\| A_{I^c}^{\mathrm{T}} A_I (A_I^{\mathrm{T}} A_I)^{-1} \mathrm{sign}\,(\overline{x_0}) \right\|_\infty = \max_{i\in I^c} |\langle a_i, d(x_0)\rangle| < 1, \tag{3}$$

$$\textit{where} \quad d(x_0) := A_I (A_I^{\mathrm{T}} A_I)^{-1} \mathrm{sign}\,(\overline{x_0}) \ . \tag{4}$$

Condition (3) will also be the soul of our analysis in this paper.

The criterion (3) is closely related to the exact recovery coefficient (ERC) of Tropp [26]:

$$\mathrm{ERC}(x_0) := 1 - \max_{i\in I^c} \left\| (A_I^{\mathrm{T}} A_I)^{-1} A_I^{\mathrm{T}} a_i \right\|_1 \ . \tag{5}$$

In [26, Corollary 13], it is established that if $\mathrm{ERC}(x_0) > 0$, then the support of the Lasso solution with a large enough parameter γ is included in the one of the subset selection (i.e., ℓ_0-minimization) optimal solution.

In [28], an asymptotic result is reported showing that (3)[2] is sufficient for the Lasso to guarantee exact support recovery and sign consistency. It is also shown that (3) is essentially necessary for variable selection. [24] develop very similar results and use similar requirements. [36] and [37] derive asymptotic conditions for sparsistency of the block Lasso [38] by extending (3) and (5) to the group setting.

Reference [22] proposes a non-asymptotic analysis with a sufficient condition ensuring exact support and sign pattern recovery of most sufficiently sparse vectors for matrices

[2] In fact, a slightly stronger assumption requiring that all elements in (3) are uniformly bounded away from 1.

satisfying a weak coherence condition (of the order $(\log p)^{-1}$). Their proof relies upon (3) and a bound on norms of random sub-matrices developed in [39]. The work in [27] considers a condition of the form (3) to ensure sparsity pattern recovery. The analysis in that paper was conducted for both deterministic and standard Gaussian A in a high-dimensional setting where p and the sparsity level grow with the number of measurements n. That author also established that violation of (3) is sufficient for failure of the Lasso in recovering the support set. In [40], the sufficient bound on the number of measurements established in [27] for the standard Gaussian dense ensemble was shown to hold for sparse measurement ensembles. The works of [22] and [27] are certainly the most closely related to ours. We will elaborate more on these connections by highlighting the similarities and differences in Section 2.4.

Variations on the Lasso. Other variations of the Lasso, such as the adaptive Lasso[3] [29, 42] or multi-stage variable selection methods [43, 44, 45, 46, 34]. For an overview of other penalized methods that have been proposed for the purpose of variable selection, see [43].

Information-theoretic bounds. A recent line of research has developed information-theoretic sufficient and necessary bounds to characterize fundamental limits on *minimal* signal-to-noise ratio (SNR), the number of measurements n, and tolerable sparsity level k required for exact or partial support pattern recovery of exactly sparse signals by any algorithm including the optimal exhaustive ℓ_0 decoder [47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57]. In most of these works, the bounds are asymptotic, i.e., they provide asymptotic scaling and typically require that the sparsity level k varies at some rate (linearly or sub-linearly) with the signal dimension p when n grows to infinity. It is worth mentioning that a careful normalization is needed, for instance of the sampling matrix and noise, when comparing these results in the literature.

The paper [47] was the first to consider the information-theoretic limits of exact sparsity recovery from the Gaussian measurement ensemble, explicitly identifying the minimal SNR (or equivalently $T = \min_{i \in I(x_0)} |x_0[i]|$) as a key parameter. This analysis yielded necessary and sufficient conditions on the tuples (n, p, k, T) for asymptotically reliable sparsity recovery. This complements the analysis of [27] by showing that in the sub-linear sparsity regime, i.e. $k = o(p)$, the number of measurements required by the Lasso[4] $n \gtrsim k \log(p-k)$ achieves the information-theoretic necessary bound.

Subsequent work of [48, 49, 50, 51, 52, 53, 54, 55, 56, 57] has extended or strengthened this type of analysis to other settings (e.g. partial support recovery, other matrix ensembles, other scaling regimes, compressible case).

1.4. Contributions

Most of the results developed in the literature on sparsistency of the Lasso estimate exhibit asymptotic scaling results in terms of the triple (n, p, k), but this does not tell the whole story. One often needs to know explicitly the exact numerical constants involved in the bounds, not only their dependence on key quantities such as the SNR and/or other parameters of the signal x_0. As a consequence, the majority of sufficient conditions are more conservative than those suggested by empirical evidence.

[3] The adaptive Lasso as seen in the statistical literature turns out to be a two-step procedure, where the second step is to solve a reweighted ℓ_1 norm problem, with weights given by the Lasso estimate in the first step. In fact, this is a special case of the iteratively reweighted ℓ_1-minimization [41].

[4] The shorthand notation $f \gtrsim g$ means that $g = O(f)$.

In this paper, we investigate the theoretical properties of the Lasso estimate in terms of sparsity pattern recovery (support and sign consistency) from noisy measurements –the noise being not necessarily random– when the measurement matrix belongs to the Gaussian ensemble. We provide precise *non-asymptotic* bounds, including explicit sharp leading numerical constants, on the key quantities that come into play (sparsity level for a given measurement budget, minimal SNR, regularization parameter) to ensure exact or partial sparsity pattern recovery for both strictly sparse and compressible signals. Our results have several distinctive features compared to previous closely-connected works. This will be discussed in further details in Section 2.4. Numerical evidence are reported in Section 6 to confirm the theoretical findings.

1.5. Organization of the paper

The rest of the paper is organized as follows. We first state our main results and discuss the connections and novelties with respect to existing work. In Section 3 and 4, we detail the proofs for exact recovery with strictly sparse and compressible signals, before proving the partial support recovery result in Section 5. Numerical experiments are carried out in Section 6. Section 6 includes a final discussion and some concluding remarks.

2. Main results

Our first result Theorem 1 establishes conditions allowing exact sparsity pattern recovery when the signal is strictly sparse. Then, these conditions are extended to cover the compressible case in Theorem 2. In these two results, the role of the minimal SNR is crucial. Our third main result in Theorem 3 gets rid of this assumption in the strictly sparse case, but this time, the Lasso allows only partial recovery of the support. We also provide in this case a sharp ℓ_2-consistency result on the Lasso estimate.

The three theorems are stated following the same structure: suppose that (x_0, w) fulfill some requirements formalized by a set $\mathcal{Y}$, then with overwhelming probability (w.o.p. for short) on the choice of A, the Lasso estimate obeys some property $\mathcal{P}$. It should be noted that these theorems imply in particular that w.o.p. on the choice of A, for *most* vectors $(x_0, w) \in \mathcal{Y}$, the Lasso estimate satisfies property $\mathcal{P}$, whatever the probability measure used on the set $\mathcal{Y}$.

The proof of Theorem 1 is given in Section 3. We prove its extension to compressible signals as stated in Theorem 2 in Section 4. Both proofs capitalize on an implicit formula of the Lasso solution. The proof of Theorem 3 given in Section 5 is quite different, since no such implicit formula is used directly.

2.1. Exact Support Recovery with Strictly Sparse Signals

Theorem 1. *Let $A \in \mathbb{R}^{n\times p}$ be a Gaussian matrix, i.e. its entries are i.i.d. $\mathcal{N}(0, 1/n)$, $w \in \mathbb{R}^n$ is such that $\|w\|_2 \leq \varepsilon$, $0 \leq \alpha, \beta < 1$ and $p > e^{\frac{1}{2(1-\sqrt{\beta})}}$. Suppose that $x_0 \in \mathbb{R}^p$ obeys*

$$\|x_0\|_0 = k \leq \frac{\alpha\beta n}{2\log p} \tag{6}$$

and

$$\min_{i\in I} |x_0[i]| = T \geq \frac{5.5\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}}\ . \tag{7}$$

Solve the Lasso problem from the measurements $y = Ax_0 + w$. Then with probability $P(n, p, \alpha, \beta)$ converging to 1 as n goes to infinity, the Lasso solution $x(\gamma)$ with

$$\gamma = \frac{\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}} \tag{8}$$

is unique and satisfies

$$\operatorname{supp}(x(\gamma)) = \operatorname{supp}(x_0) \quad \textit{and} \quad \operatorname{sign}\left(\overline{x(\gamma)}\right) = \operatorname{sign}(\overline{x_0}) \ .$$

The proof (see Section 3) provides an explicit bound for $P(n, p, \alpha, \beta)$, showing in particular that $P(n, p, \alpha, \beta)$ is larger than

$$1 - \frac{1}{2}e^{-0.7\sqrt{\log n}} - \frac{1}{2\sqrt{\pi \log p}} - o\left(\frac{1}{\log p}\right) - o(e^{-0.7\sqrt{\log n}}) \ ,$$

although this bound on the probability is far from optimal.

In plain words, Theorem 1 asserts that for $(\alpha, \beta) \in [0, 1)$ the support and the sign of most vectors obeying (6) can be recovered using the Lasso if the non-zero coefficients of x_0 are large enough compared to noise. This bound on the sparsity of x_0 turns out to be optimal, since for any $c > 1$, for most vectors x_0 such that $\|x_0\|_0 \geq \frac{cn}{2\log p}$, the support cannot be recovered using the Lasso even with no noise. Indeed, [33] and [58] proved that the Lasso solution for any γ shares the same sign and the same support as x_0 when $y = Ax_0$ if and only if

$$\max_{j \notin I} |\langle a_j, A_I(A_I^{\mathrm{T}} A_I)^{-1} \operatorname{sign}(\overline{x_0})\rangle| \leq 1 \ .$$

Note in passing the difference with the strict inequality in (3). On the other hand, if $\|x_0\|_0 \geq \frac{cn}{2\log p}$ with $c > 1$, then w.o.p. $\left\|A_I(A_I^{\mathrm{T}} A_I)^{-1}\operatorname{sign}(\overline{x_0})\right\|_2^2 \geq \frac{Cn}{2\log p}$ for some $C > 1$ and sufficiently large p. As a result, $\max_{j\notin I} |\langle a_j, A_I(A_I^{\mathrm{T}} A_I)^{-1}\operatorname{sign}(\overline{x_0})\rangle| \geq \sqrt{C} > 1$. This informal optimality discussion is consistent with the information-theoretic bounds of [47], where it was proved that the number of measurements required by the Lasso achieves the (asymptotic) information-theoretic necessary bound that has the scaling (6) when the sparsity regime is sub-linear and $T^2 \sim 1/\|x_0\|_0$.

An important feature of Theorem 1 is that all the constants are made explicit and are governed by the two numerical constants α and β. The role of α is very instructive since when lowering γ by decreasing α, the threshold on the minimal SNR is decreased to allow smaller coefficients to be recovered, but simultaneously the probability of success gets lower and the number of measurements required to recover the k-sparse signal increases. The converse applies when α is increased. On the other hand, increasing β (in an appropriate range; see Section 3.3 for details) allows a higher threshold on the sparsity level, but again at the price of a smaller probability of success.

2.2. Support Recovery with Compressible Signals

Theorem 1 can be easily extended to weakly sparse or compressible signals. We consider the best k-term approximation x^k of x_0 obtained by keeping only the k largest entries from x_0 and setting the others to zero. Obviously, $k = |I(x^k)|$. This is equivalently defined using a thresholding

$$x^k[i] = \begin{cases} x_0[i] & \text{if} \quad |x_0[i]| \geq T, \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

A signal is generally considered as compressible if the residual $x^k - x_0$ is small. For sparsistency to make sense in this compressible case, additional assumptions are required, namely that the largest components x^k of the signal are significantly larger than the residual $x^k - x_0$. This is made formal in the following theorem.

Theorem 2. *Let A, α, β and p as in Theorem 1. We measure $y = Ax_0 + w$, and let x^k be the best k-term approximation of x_0 where k satisfies* (6)*. We denote*

$$\Delta = \frac{2}{\sqrt{1 + 2\sqrt{\alpha} - 3\alpha}} \sqrt{\frac{2 \log p}{n}}.$$

Suppose that

$$\|w\|_2 + 4 \left\| x_0 - x^k \right\|_2 \leq \varepsilon, \tag{10}$$

T as defined in (9) *is such that*

$$T \geq 5.5 \Delta \varepsilon \tag{11}$$

and

$$\left\| x_0 - x^k \right\|_\infty \leq \frac{4}{5}(1 - \sqrt{\alpha}) \Delta \varepsilon. \tag{12}$$

Then, with probability $P_2(n, p, \alpha, \beta)$ converging to 1 as n goes to infinity, the solution $x(\gamma)$ of the Lasso from measurements y with

$$\gamma = \Delta \varepsilon \tag{13}$$

is unique and satisfies

$$\operatorname{supp}\left(x(\gamma)\right) = \operatorname{supp}\left(x^k\right) \quad \textit{and} \quad \operatorname{sign}\left(\overline{x(\gamma)}\right) = \operatorname{sign}\left(\overline{x^k}\right) \ .$$

Again, all the leading constants are explicit. Conditions (11) and (12) impose compressibility constraints on the signal, namely that the magnitude of the k largest components of x_0 are well above the average magnitude $\varepsilon/\sqrt{n}$ of the residual, and that the latter is "flat", since the ratio of its ℓ_∞ and ℓ_2 norms should be small.

The proof (see Section 4) provides an explicit bound for $P_2(n, p, \alpha, \beta)$, showing that $P_2(n, p, \alpha, \beta)$ is greater than

$$1 - \frac{1}{2} e^{-0.7\sqrt{\log n}} - \frac{1}{2\sqrt{\pi \log p}} - o\left(\frac{1}{\log p}\right) - o(e^{-0.7\sqrt{\log n}}) \ ,$$

although once again this bound on the probability is far from optimal.

Theorem 2 encompasses the strictly sparse case, Theorem 1, which is easily recovered by letting $x_0 = x^k$. The parameter α plays a similar role in both theorems. Furthermore, in Theorem 2, the Lasso solution becomes more tolerant to compressibility errors $x_0 - x^k$ as α decreases. This however comes at the price of a lower probability of success as indicated in our proof.

2.3. Partial Support Recovery with Strictly Sparse Signals

In both previous theorems, the assumption on T plays a pivotal role: if T is too small, there is no way to distinguish the small components of x_0 from the noise; see also the discussion and literature review in Section 1.3. Nevertheless, if no assumptions are made on T, one can nevertheless expect to partly recover the support of x_0. This is formalized in the following result.

Theorem 3. *Let A, α and β as in Theorem 1. We measure $y = Ax_0 + w$, where x_0 fulfills (6). Then with probability $P_3(n, p, \alpha, \beta)$ converging to 1 as n goes to infinity, the solution $x(\gamma)$ of the Lasso form measurements y with*

$$\gamma = \frac{\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}}$$

is unique and satisfies

$$\operatorname{supp}(x(\gamma)) \subset \operatorname{supp}(x_0)\,.$$

Moreover, the Lasso solution is ℓ_2-consistent:

$$\|x_0 - x(\gamma)\|_2 \leq \left(2 + \sqrt{\frac{\alpha}{1-\alpha}}\right)\,\varepsilon\,. \tag{14}$$

The proof in Section 5 provides an explicit lower bound for $P_3(n, p, \alpha, \beta)$, and shows that $P_3(n, p, \alpha, \beta)$ is larger than

$$1 - e^{-\frac{n\left(1-\sqrt{\beta}-\sqrt{\frac{k}{n}}\right)^2}{2}} - \frac{1}{2\sqrt{\pi\log p}}\,.$$

As before, this bound on the probability is not optimal.

If γ is large enough it is clear that $\operatorname{supp}(x(\gamma)) \subset \operatorname{supp}(x_0)$ since for $\gamma \geq \left\|A^{\mathrm{T}}y\right\|_\infty$, $x(\gamma) = 0$. Theorem 3 provides a parameter γ proportional to ε that ensures a partial support recovery without any assumption on T. It also gives a sharp upper bound on ℓ_2-error of the Lasso solution. This result remains valid under the additional hypotheses of Theorem 1 or 2 allowing exact recovery of the support.

2.4. Connections to related works

Sparsistency. As we mentioned in Section 1.3, our work is closely related to [22, 27], but is different in many important ways that we summarize as follows.

- Deterministic vs random measurement matrices: the work of [22] considers deterministic matrices satisfying a weak incoherence condition. Our work focuses on the classical Gaussian ensemble.
- Asymptotic vs non-asymptotic analysis: the analysis in [27] applies to high-dimensional setting where even the sparsity level k grows with the number of measurements n. As a result, k appears in the statements of the probabilities, which thus requires that $k \to +\infty$. This is very different from our setting as well as that of [22] where the probabilities depend solely on the dimensions of A. We believe that this is more natural in many applications.

- Random vs deterministic noise: in both previous works, the noise is stochastic (Gaussian in [22] and sub-Gaussian in [27]). In our work, we handle any noise with a finite ℓ_2-norm.
- Leading numerical constants: these are not always explicit and sharp in those works. The constant involved in the sparsity level upper-bound in [22, Theorem 1.3] is not given, whereas (6) gives an explicit and sharp bound. The bounds (7) and (8) on T and γ are similar to those given in [22, Theorem 1.3] once specialized for $\alpha = 3/4$. In [27, Theorem 2], the constant appearing in the lower-bound on T is not given, whereas (7) provides an explicit expression that is shown to be reasonably good in Section 6.
- Compressible signals: to the best of our knowledge, the compressible case has not been covered in the literature, and Theorem 2 appears then as a distinctively novel result of this paper.
- ℓ_2-consistency: such a result is not given in those references. A bound on the ℓ_2-prediction error on $Ax_0 - Ax(\gamma)$ is proved in [22]. An ℓ_∞-consistency is established in [27], which is an immediate consequence of sparsistency. Our method of proof differs significantly from the one used in [27], and in particular it naturally leads to the ℓ_2-consistency result.
- Exact and partial support recovery: in [22] the partial recovery case was not considered. In [27], exact and partial recovery are somewhat handled simultaneously, while we give two distinct results for each case.

ℓ_2-consistency. This property of the Lasso estimate has been widely studied by many authors under various sufficient conditions. Theorem 3 may then be compared to this literature, and we here focus on results based on the restricted isometry property (RIP) [59] and more or less similar variants in the literature; see the discussion in [34] and the review in [35].

The RIP results are uniform and ensure ℓ_2-stability of the Lasso estimate for *all* sufficiently sparse vectors from noisy measurements, whereas Theorem 3 guarantees that the Lasso estimate is ℓ_2-consistent for *most* sparse vectors and a given matrix. When A is Gaussian, the scaling of the sparsity bound is $O(n/\log(p/n))$ for RIP-based results which is better than $O(n/\log p)$ in Theorem 3. Note that the scaling $O(n)$ was derived in [60] when A belongs to the uniform spherical ensemble to ensure ℓ_2-stability of the Lasso estimate for most matrices A, although the leading constants are not given explicitly. However, the RIP is a worst-case analysis, and the price is that the leading constants in the sufficient sparsity bounds are overly small. In contrast, the leading numerical constants in our sparsity and ℓ_2-consistency upper-bounds are explicit and solely controlled by $(\alpha, \beta) \in [0, 1)^2$. For instance, it can be verified from our proof that the value of the sparsity upper-bound we provide is actually larger than the bounds obtained from the RIP for p up to e^{100}. Finally, the RIP is a deterministic property that turns out to be satisfied by many ensembles of random matrices other than the Gaussian. Our Theorem 3 could presumably be extended to sub-Gaussian matrices (e.g. using [61, Corollary V.2.1]), but this needs further investigation that we leave for a future work.

3. Proof of Support Identification of Exactly Sparse Signals

This section gives the proof of Theorem 1. Recall that $\bar{x}$ is the restriction of x to its support $I(x)$, and A_I the corresponding sub-matrix. We also denote the Moore-Penrose

pseudo-inverse of A_I as

$$A_I^+ = (A_I^{\mathrm{T}} A_I)^{-1} A_I^{\mathrm{T}}.$$

3.1. Optimality Conditions for Penalized Minimization

From classical convex analysis, the first order optimality conditions show that a vector $x^\star$ is a solution of the Lasso if and only if

$$\begin{cases} A_I^{\mathrm{T}}(y - Ax^\star) = \gamma \mathrm{sign}\left(\overline{x^\star}\right) \\ \forall j \notin I, \quad |\langle a_j,\, y - Ax^\star\rangle| \leq \gamma, \end{cases} \tag{15}$$

where $I = I(x^\star)$.

Hence if the goal pursued is to ensure that $I(x^\star) = I(x_0) = I$ and $\mathrm{sign}\,(x^\star) = \mathrm{sign}\,(x_0)$, the only candidate solution of the Lasso is

$$\overline{x^\star} = \overline{x_0} - \gamma (A_I^{\mathrm{T}} A_I)^{-1} \mathrm{sign}\,(\overline{x_0}) + A_I^+ w. \tag{16}$$

Consequently, a vector $x^\star$ is a solution of the Lasso if and only the two following conditions are met :

$$\mathrm{sign}\,(x_0) = \mathrm{sign}\,(x^\star) \tag{C_1}$$

$$\forall j \notin I(x_0), \quad |\langle a_j, \gamma d(x_0) + P_{V_I{}^\perp}(w)\rangle| \leq \gamma \tag{C_2}$$

where $V_I = \mathrm{Span}(A_I)$, $P_{V_I{}^\perp}$ is the orthogonal projection on the subspace orthogonal to V_I, and $d(x_0)$ is defined in (4).

Sections 3.2 and 3.3 show that under the hypotheses of Theorem 1, conditions (C_1) and (C_2) are in force with probability converging to 1 as n goes to infinity. This will thus conclude the proof of Theorem 1.

3.2. Condition (C_1)

To ensure that $\mathrm{sign}\,(x_0) = \mathrm{sign}\,(x^\star)$, it is sufficient that

$$\left\|\gamma (A_I^{\mathrm{T}} A_I)^{-1} \mathrm{sign}\,(\overline{x_0}) + A_I^+ w\right\|_\infty \leq T\ . \tag{17}$$

We prove that this is indeed the case w.o.p. .

Lemma 4, whose proof is given in Appendix A.3, shows that $\gamma = \frac{\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}} \leq \frac{T}{5.5}$ implies

$$\gamma \left\|(A_I^{\mathrm{T}} A_I)^{-1} \mathrm{sign}\,(\overline{x_0})\right\|_\infty \leq \frac{T(1+4\sqrt{\alpha})}{5.5}$$

with probability greater than $1 - kp^{-1.28} - 2e^{-\frac{n\alpha(0.75\sqrt{2}-1)^2}{4\log p}}$.

To prove (17), we will now bound $\left\|A_I^+ w\right\|_\infty$. To this end, we split it as follows

$$\left\|A_I^+ w\right\|_\infty = D_1 \times D_2 \times D_3 \times \|w\|_2\,,$$

where

$$D_1 = \frac{\left\|A_I^+ w\right\|_\infty}{\left\|A_I^+ w\right\|_2}, \quad D_2 = \frac{\left\|A_I^+ w\right\|_2}{\left\|A_I^{\mathrm{T}} w\right\|_2}, \quad D_3 = \frac{\left\|A_I^{\mathrm{T}} w\right\|_2}{\|w\|_2}.$$

Bounding D_1. As A and w are independent, Lemma 5, proved in Appendix A.4, shows that the distribution of $A_I^+ w$ is invariant under orthogonal transforms on $\mathbb{R}^k$. Therefore the random variable

$$\frac{A_I^+ w}{\left\|A_I^+ w\right\|_2}$$

is uniformly distributed on the unit ℓ_2 sphere of $\mathbb{R}^k$.

Using the concentration Lemma 7, detailed in Appendix B, with $\epsilon = \left(\frac{8 \log n \log k}{k^2}\right)^{\frac{1}{4}}$, it follows that

$$\begin{aligned} P\left(D_1 \leq \sqrt{\frac{2}{k}}(2 \log n \log k)^{\frac{1}{4}}\right) &\geq 1 - 4ke^{-\sqrt{2 \log n \log k}} \\ &\geq 1 - \max\left(4n^{-\frac{1}{3}}, 8e^{-\sqrt{2\log(2n)}}\right). \end{aligned} \tag{18}$$

One can notice that $D_1 \leq 1$ actually gives a better bound if k is small compared to n. Moreover the bound on the probability is $1 - 4n^{-\frac{1}{3}}$ for k big.

Bounding D_2. D_2 is bounded by the maximum of the eigenvalue of $(A_I^{\mathrm{T}} A_I)^{-1}$. Indeed, owing to Lemma 3 with $t = 1 - \sqrt{\frac{k}{n}} - 2^{-\frac{1}{8}}$, we arrive at

$$P\left(D_2 \leq 2^{\frac{1}{4}}\right) \geq 1 - e^{-\frac{n}{2}\left(1 - 2^{-\frac{1}{8}} - \frac{1}{\sqrt{2 \log p}}\right)^2}. \tag{19}$$

Bounding D_3. Let's write

$$D_3^2 = \frac{1}{\|w\|_2^2} \sum_{i \in I} |\langle a_i,\, w \rangle|^2.$$

Since each $\langle a_i, w \rangle$ is a zero-mean Gaussian variable with variance $\frac{\|w\|_2^2}{n}$, the variable

$$\frac{n \left\|A_I^{\mathrm{T}} w\right\|_2^2}{\|w\|_2^2},$$

follows a χ^2 distribution with k degrees of freedom. Therefore, in virtue of the concentration Lemma 8, stated in Appendix B, applied with

$$1 + \delta = 2\sqrt{\frac{\log n}{\log k}}$$

we obtain

$$P\left(D_3^2 \leq \frac{2k\sqrt{\log n}}{n\sqrt{\log k}}\right) \geq 1 - \frac{1}{\sqrt{2\pi k}} e^{-k\left(\sqrt{\frac{\log n}{\log k}} - \frac{1}{2} - \frac{\log 2}{2} - \frac{1}{4}\log\left(\frac{\log n}{\log k}\right)\right)} \geq 1 - \frac{1}{2} e^{-0.7\sqrt{\log n}}$$

This last bound may be pessimistic; when k is large this probability is actually much bigger. This shows that w.o.p. ,

$$D_3 \leq \sqrt{\frac{2k}{n}} \left(\frac{\log n}{\log k}\right)^{\frac{1}{4}}. \tag{20}$$

Putting (18), (19) and (20), we conclude that

$$\left\|A_I^+ w\right\|_\infty \leq 2\varepsilon \sqrt{\frac{2 \log n}{n}}, \tag{21}$$

with probability greater than

$$1-\frac{1}{2}e^{-0.7\sqrt{\log n}}-e^{-\frac{n}{2}\left(1-2^{-\frac{1}{8}}-\frac{1}{\sqrt{2\log p}}\right)^2}-\max\left(4n^{-\frac{1}{3}},8e^{-\sqrt{2\log(2n)}}\right)-kp^{-1.28}-2e^{-\frac{n\alpha(0.75\sqrt{2}-1)^2}{4\log p}}$$

which converges to 1 as $n \to +\infty$.

In turn, the bound (21) becomes, under assumption (7) on T,

$$\left\|A_I^+ w\right\|_\infty \leq \frac{2T\sqrt{1-\alpha}}{5.5}.$$

This shows that condition (C_1) is in force with probability converging to 1 as $n \to +\infty$.

3.3. Condition (C_2)

Let's introduce the following vector

$$u = \gamma d(x_0) + P_{V_I{}^\perp}(w), \tag{22}$$

which depends on both x_0 and w.

Clearly, to comply with (C_2), we need to bound $(\langle a_j, u\rangle)_{j\notin I}$ w.o.p. . We will start by bounding $\|u\|_2$.

Bounding $\|u\|_2$. As $d(x_0) \in V_I$, the Pythagorean theorem yields

$$\|u\|_2^2 = \gamma^2 \|d(x_0)\|_2^2 + \left\|P_{V_I{}^\perp}(w)\right\|_2^2. \tag{23}$$

Let $S = \operatorname{sign}(\overline{x_0})$. Then

$$\frac{nk}{\|d(x_0)\|_2^2} = \frac{n\|S\|_2^2}{S^{\mathrm{T}}(A_I^{\mathrm{T}}A_I)^{-1}S}.$$

Since x_0 and A are independent, Lemma 6, stated in Appendix B, shows that $\frac{nk}{\|d(x_0)\|_2^2}$ is χ^2-distributed with $n-k+1$ degrees of freedom. Thanks to Lemma 9, see Appendix B, it follows that for all $\delta > 0$,

$$P\left(\frac{nk}{n-k+1} < (1-\delta)\|d(x_0)\|_2^2\right) \leq e^{\frac{(n-k+1)\log(1-\delta)}{2}} .$$

Since $\frac{k}{n} \leq \frac{1}{2\log p}$, we obtain for $p \geq e^{\frac{1}{2\delta}}$,

$$P\left(k < \|d(x_0)\|_2^2 (1-\delta)^2\right) \leq e^{\frac{n\log(1-\delta)(4-\delta)}{8}}.$$

Choosing δ such that $(1-\delta) > \sqrt{\beta}$, we have

$$P\left(\|d(x_0)\|_2^2 \leq \frac{k}{\beta}\right) \geq 1 - e^{\frac{n(3-\sqrt{\beta})\log\beta}{16}} .$$

This shows that

$$\|d(x_0)\|_2^2 \leq \frac{k}{\beta}$$

with probability converging to 1 as $n \to +\infty$.

It is worthy to mention that the condition $p > e^{\frac{1}{2(1-\sqrt{\beta})}}$ actually guarantees the existence of a suitable δ.

As $P_{V_I{}^\perp}$ is an orthogonal projector, we have $\left\|P_{V_I{}^\perp}(w)\right\|_2 \leq \|w\|_2 \leq \varepsilon$. Together with (23), this shows that

$$P\left(\|u\|_2^2 \leq \gamma^2\frac{k}{\beta} + \varepsilon^2\right) \geq 1 - e^{\frac{n(3-\sqrt{\beta})\log\beta}{16}} . \tag{24}$$

Bounding $\max_{j\notin I} |\langle u,\, a_j\rangle|$. For a fixed u, the random variables $(\langle a_j, u\rangle)_{j\notin I}$ are zero-mean Gaussian variables with variance $\frac{\|u\|_2^2}{n}$.

Using the bound (24), traditional arguments from the concentration of the maximum of Gaussian variables tell us that

$$\max_{j\notin I} |\langle a_j, u\rangle| \leq \sqrt{\frac{2\log p}{n}\left(\gamma^2\frac{k}{\beta}+\varepsilon^2\right)} \tag{25}$$

with a probability larger than

$$1 - e^{\frac{n(3-\sqrt{\beta})\log\beta}{16}} - \frac{1}{2\sqrt{\pi\log p}}.$$

In turn, this implies that condition (C_2) is in force w.o.p. if

$$\sqrt{\frac{2\log p}{n}\left(\gamma^2\frac{k}{\beta}+\varepsilon^2\right)} \leq \gamma.$$

This holds if

$$\frac{\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}} \leq \gamma.$$

This concludes the proof of Theorem 1, and shows that overall

$$\begin{aligned} P(n,p,\alpha,\beta) \geq 1 - \frac{1}{2}e^{-0.7\sqrt{\log n}} - e^{-\frac{n}{2}\left(1-2^{-\frac{1}{8}}-\frac{1}{\sqrt{2\log p}}\right)^2} - \max\left(4n^{-\frac{1}{3}}, 8e^{-\sqrt{2\log(2n)}}\right) \\ - kp^{-1.28} - 2e^{-\frac{n\alpha(0.75\sqrt{2}-1)^2}{4\log p}} - e^{\frac{n(3-\sqrt{\beta})\log\beta}{16}} - \frac{1}{2\sqrt{\pi\log p}}. \end{aligned}$$

4. Proof of Support Identification of Compressible Signals

To prove this theorem, we capitalize on the results of Section 3.1 by noting that $y = Ax^k + A(x_0 - x^k) + w := Ax^k + Ah + w$, and replacing x_0 by x^k and w by $w_2 = Ah + w$. With these change of variables, it is then sufficient to check conditions (C_1) and (C_2) with the notable difference that the noise w_2 is not independent of A anymore. More precisely, w_2 is independent of $(a_i)_{i\in I}$ but not of $(a_j)_{j\notin I}$.

Condition (C_1). Since this condition only depends on A_I, it is verified with probability converging to 1 as $n \to +\infty$, as in the proof of Theorem 1, provided that $T \geq 5.5\gamma$ and $\|w_2\|_2 \leq \frac{T}{5.5}\sqrt{\frac{(1-\alpha)n}{2\log p}}$. The first condition is a direct consequence of assumptions (11) and (13). Moreover, $\|w_2\|_2 \leq \|w\|_2 + \|Ah\|_2$, where Ah is a zero-mean Gaussian vector, whose entries are independent with variance $\frac{\|h\|_2^2}{n}$. Therefore $\frac{n\|Ah\|_2^2}{\|h\|_2^2}$ has a χ^2 distribution with n degrees of freedom. We then derive from the concentration Lemma 8 that

$$P\left(\|Ah\|_2 \leq 2\|h\|_2\right) \geq 1 - \frac{1}{3\sqrt{2\pi n}}e^{-0.8n}\ .$$

Under assumptions (10)-(11), the last inequality implies that

$$\|w_2\|_2 \leq \|w\|_2 + 2\|h\|_2 \leq \varepsilon \leq \frac{T}{5.5\Delta} \leq \frac{T}{5.5}\sqrt{\frac{(1-\alpha)n}{2\log p}}$$

with probability that tends to 1 as $n \to +\infty$. Condition (C_1) is thus satisfied with a probability larger than

$$1 - \frac{1}{2}e^{-0.7\sqrt{\log n}} - e^{-\frac{n}{2}\left(1-2^{-\frac{1}{8}}-\frac{1}{\sqrt{2\log p}}\right)^2} - \max\left(4n^{-\frac{1}{3}}, 8e^{-\sqrt{2\log(2n)}}\right) - kp^{-1.28}$$
$$- 2e^{-\frac{n\alpha(0.75\sqrt{2}-1)^2}{4\log p}} - \frac{1}{3\sqrt{2\pi n}}e^{-0.8n}.$$

Condition (C_2). For any $j \notin I$, define the vector $v_j = w_2 - h[j]a_j$. In particular, v_j is independent of a_j. Condition (C_2) now reads:

$$\forall j \notin I, |\langle a_j, \gamma d(x^k) + P_{V_I{}^\perp}(v_j) + h[j]P_{V_I{}^\perp}(a_j)\rangle| \leq \gamma \ ,$$

where the vector $d(x^k)$ is defined replacing x_0 by x^k in (4).

Similarly to (24), it can be shown that w.o.p.

$$\left\|\gamma d(x^k) + P_{V_I{}^\perp}(v_j)\right\|_2^2 \leq \gamma^2\frac{k}{\beta} + \|v_j\|_2^2 \ .$$

On the other hand, $\|v_j\|_2 \leq \|w_2\|_2 + \|h\|_\infty \|a_j\|_2$, and $n\|a_j\|_2^2$ is χ^2-distributed with n degrees of freedom. Applying Lemma 8 to bound $\|a_j\|_2$ by 2 for all j and using similar arguments to those leading to (25), we get

$$\max_{j\notin I} |\langle a_j, \gamma d(x^k) + P_{V_I{}^\perp}(v_j)\rangle| \leq \sqrt{\frac{2\log p}{n}\left(\gamma^2\frac{k}{\beta} + (\|w\|_2 + 4\|h\|_2)^2\right)}$$

with probability larger than $1 - \frac{p+1}{3\sqrt{2\pi n}}e^{-0.8n} - \frac{1}{2\sqrt{\pi\log p}}$, converging to 1 as $n \to +\infty$. It then follows from assumptions (10) and (13) that w.o.p.

$$\max_{j\notin I} |\langle a_j, \gamma d(x^k) + P_{V_I{}^\perp}(v_j)\rangle| \leq \frac{\gamma}{2}(1+\sqrt{\alpha}) \ . \tag{26}$$

As an orthogonal projector is a self-adjoint idempotent operator, we have for all $j \leq p$,

$$|h[j]\langle a_j, P_{V_I{}^\perp}(a_j)\rangle| \leq \|h\|_\infty \left\|P_{V_I{}^\perp}(a_j)\right\|_2^2,$$

where $\left\|P_{V_I{}^\perp}(a_j)\right\|_2^2$ is the squared ℓ_2-norm of the projection of a Gaussian vector on the subspace $V_I{}^\perp$ whose dimension is $n-k$. As $V_I{}^\perp$ is independent of a_j, for $j \notin I$, $n\left\|P_{V_I{}^\perp}(a_j)\right\|_2^2$ follows a χ^2 distribution with $n-k$ degrees of freedom. Using Lemma 8 together with assumptions (12)-(13), the following bound holds w.o.p.

$$\max_{j\notin j} |h[j]\langle a_j, P_{V_I{}^\perp}(a_j)\rangle| \leq 2.5\|h\|_\infty \leq \frac{\gamma}{2}(1-\sqrt{\alpha}) \tag{27}$$

In summary, (26) and (27) show that (C_2) is fulfilled with probability larger than $1 - \frac{1}{3\sqrt{2\pi n}}e^{-0.8n} - \frac{1}{3\sqrt{2\pi n}}e^{-0.3n} - \frac{1}{\sqrt{2\pi(n-k)}}e^{-0.009n}$.

5. Proof of Partial Support Recovery

To prove the first part of Theorem 3, we need to show that with w.o.p. , the extension $x_1(\gamma)$ on $\mathbb{R}^p$ of the solution of

$$\min_{x\in\mathbb{R}^{|I|}} \frac{1}{2}\left\|y_1 - A_I x\right\|_2^2 + \gamma\left\|x\right\|_1 \tag{28}$$

with $y_1 = P_{A_I}(y)$, is the solution of the Lasso. By definition, the support J of this extension is included in I.

Proving this assertion amounts to showing that $x_1(\gamma)$ fulfills the necessary and sufficient optimality conditions

$$\begin{cases} A_J^{\mathrm{T}}(y - Ax_1(\gamma)) = \gamma \mathrm{sign}\left(\overline{x_1(\gamma)}\right), \\ \forall l \notin J, \quad |\langle a_l,\, y - Ax_1(\gamma)\rangle| \leq \gamma. \end{cases} \tag{29}$$

Since $y_1 = P_{A_I}(y)$ and $J \subset I$, $A_J^{\mathrm{T}}(y - Ax_1(\gamma)) = A_J^{\mathrm{T}}(y_1 - Ax_1(\gamma))$. In addition, as $x_1(\gamma)$ is the extension of the solution of (28), the optimality conditions associated to (28) yield

$$\begin{cases} A_J^{\mathrm{T}}(y - Ax_1(\gamma)) = \gamma \mathrm{sign}\left(\overline{x_1(\gamma)}\right), \\ \forall l \in (I \cap J^c), \quad |\langle a_l,\, y - Ax_1(\gamma)\rangle| \leq \gamma. \end{cases}$$

To complete the proof, it remains now to show that w.o.p.

$$\forall l \notin I, \quad |\langle a_l,\, y - Ax_1(\gamma)\rangle| \leq \gamma. \tag{30}$$

As in the proofs of Theorems 1 and 2, to bound these scalar products, the key argument is the independence between the vectors $(a_l)_{l\notin I}$ and the residual vector $y - Ax_1(\gamma)$.

We first need the following intermediate lemma.

Lemma 1. *Let $A \in \mathbb{R}^{n\times k}$ such that $(A^{\mathrm{T}}A)$ is invertible. Take $x(\gamma)$ as a solution of the Lasso from observations $y \in \mathbb{R}^n$. The mapping $f : \mathbb{R}^{+*} \to \mathbb{R}^+$, $\gamma \mapsto f(\gamma) = \frac{\|y - Ax(\gamma)\|_2}{\gamma}$ is well-defined and non-increasing.*

Proof: The authors in [8] and [58] independently proved that under the assumptions of the lemma:

- the solution $x(\gamma)$ of the Lasso is unique;
- there is a finite increasing sequence $(\gamma_t)_{t\leq K}$ with $\gamma_0 = 0$ and $\gamma_K = \left\|A^{\mathrm{T}}y\right\|_\infty$ such that for all $t < K$, the sign and the support of $x(\gamma)$ are constant on each interval (γ_t, γ_{t+1}).
- $x(\gamma)$ is a continuous function of γ.

Moreover $x(\gamma)$ with support J satisfies

$$\overline{x(\gamma)} = A_J^{+}y - \gamma(A_J^{\mathrm{T}}A_J)^{-1}\mathrm{sign}\left(\overline{x(\gamma)}\right), \tag{31}$$

which implies that

$$r(\gamma) := y - Ax(\gamma) = P_{A_J^{\perp}}(y) - \gamma A_J(A_J^{\mathrm{T}}A_J)^{-1}\mathrm{sign}\left(\overline{x(\gamma)}\right) \ .$$

Therefore, on each interval (γ_t, γ_{t+1}), $r(\gamma)$ is an affine function of γ which can be written

$$r(\gamma) = z - \gamma v,$$

where $z := P_{A_J^\perp}(y)$ and $v := A_J(A_J^{\mathrm{T}}A_J)^{-1}\mathrm{sign}\left(\overline{x(\gamma)}\right)$. As $v \in V_J$ and $z \in V_J^\perp$, the Pythagorean theorem allows to write for $\gamma \in (\gamma_t, \gamma_{t+1})$ that

$$\frac{\|r(\gamma)\|_2^2}{\gamma^2} = \frac{\|z\|_2^2}{\gamma^2} + \|v\|_2^2 \ . \tag{32}$$

We then deduce that $f(\gamma) = \frac{\|r(\gamma)\|_2}{\gamma}$ is a non-increasing function of γ on each interval (γ_t, γ_{t+1}). By continuity of f, it follows that f is non-increasing on $\mathbb{R}^{+*}$.

■

Remark 1. *If $(A_I^{\mathrm{T}}A_I)$ is not invertible, the Lasso may have several solutions. Nevertheless $r(\gamma)$ is always uniquely defined and the lemma should also apply.*

From Lemma 1, we deduce that $\frac{\|y_1 - Ax_1(\gamma)\|_2}{\gamma}$ is a non-increasing function of γ. Because $y_1 \in V_I$ and A_I has full column-rank, we also have

$$\lim_{\gamma \to 0} x_1(\gamma) = x_1,$$

where on I, the entries of x_1 are those of the unique vector of $\mathbb{R}^{|I|}$ such that $A_I x = y_1$. Therefore,

$$x_1[i] = x_0[i] + (A_I^+ w)[i], \quad \text{for} \quad i \in I \ . \tag{33}$$

Since A_I is Gaussian and independent from x_0 and w, the support of x_1 is almost surely equal to I. Hence there exists $\gamma_1 > 0$ such that if $\gamma < \gamma_1$, the support and the sign of $x_1(\gamma)$ are equal to those of x_1. More precisely, if $\gamma < \gamma_1$, $x_1(\gamma)$ satisfies

$$\overline{x_1(\gamma)} = \overline{x_1} - \gamma(A_I^{\mathrm{T}}A_I)^{-1}\mathrm{sign}\left(\overline{x_1}\right) \quad \text{and} \quad r(\gamma) := y_1 - Ax_1(\gamma) = \gamma A_I(A_I^{\mathrm{T}}A_I)^{-1}\mathrm{sign}\left(\overline{x_1}\right) \ .$$

It then follows that for $\gamma \in (0, \gamma_1)$,

$$\frac{\|y_1 - Ax_1(\gamma)\|_2}{\gamma} = \left\|A_I(A_I^{\mathrm{T}}A_I)^{-1}\mathrm{sign}\left(\overline{x_1}\right)\right\|_2 .$$

Now, since

$$\left\|A_I(A_I^{\mathrm{T}}A_I)^{-1}\mathrm{sign}\left(\overline{x_1}\right)\right\|_2^2 = \left\langle (A_I^{\mathrm{T}}A_I)^{-1}\mathrm{sign}\left(\overline{x_1}\right), \mathrm{sign}\left(\overline{x_1}\right)\right\rangle,$$

we deduce that for all $\gamma > 0$,

$$\frac{\|y_1 - Ax_1(\gamma)\|_2}{\gamma} \leq \sqrt{|I|\rho((A_I^{\mathrm{T}}A_I)^{-1})},$$

where $\rho((A_I^{\mathrm{T}}A_I)^{-1})$ is the spectral radius of $(A_I^{\mathrm{T}}A_I)^{-1}$. Using Lemma 3 with $\beta < \left(1 - \sqrt{\frac{k}{n}}\right)^2$ then leads to

$$P\left(\frac{\|y_1 - Ax_1(\gamma)\|_2}{\gamma} \leq \sqrt{\frac{k}{\beta}}\right) \geq 1 - e^{-\frac{n\left(1-\sqrt{\beta}-\sqrt{\frac{k}{n}}\right)^2}{2}} \ . \tag{34}$$

By the Pythagorean theorem and the fact that $\left\|P_{V_I{}^\perp} w\right\|_2 \leq \varepsilon$, we have

$$\begin{aligned}\|y - Ax_1(\gamma)\|_2^2 &= \|y - y_1\|_2^2 + \|y_1 - Ax_1(\gamma)\|_2^2 \\ &= \left\|P_{V_I{}^\perp} w\right\|^2 + \|y_1 - Ax_1(\gamma)\|_2^2 \\ &\leq \varepsilon^2 + \|y_1 - Ax_1(\gamma)\|_2^2 \ .\end{aligned}$$

With similar arguments as those leading to (25), it can then be deduced that

$$\max_{l \notin I} |\langle a_l,\, y - Ax_1(\gamma)\rangle| \leq \sqrt{\frac{2\log p}{n}\left(\varepsilon^2 + \frac{\gamma^2 k}{\beta}\right)} \ . \tag{35}$$

with probability larger than $1 - e^{-\frac{n\left(1-\sqrt{\beta}-\sqrt{\frac{k}{n}}\right)^2}{2}} - \frac{1}{2\sqrt{\pi \log p}}$,

If $k \leq \frac{\alpha\beta n}{2\log p}$ and $\gamma \geq \frac{\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}}$, then $\sqrt{\frac{2\log p\left(\varepsilon^2 + \frac{\gamma^2 k}{\beta}\right)}{n}} \leq \gamma$, and therefore inequality (30) is satisfied w.o.p. . This ends the proof of the first part of the theorem.

Let's now turn to the proof of (14). To prove this inequality we notice that for large γ, the Lasso solution $x(\gamma)$ is also the extension of the solution of (28) w.o.p. and we use the Lipschitz property of the mapping $\gamma \mapsto x_1(\gamma)$.

Indeed, by the triangle inequality,

$$\|x_0 - x_1(\gamma)\|_2 \leq \|x_0 - x_1\|_2 + \|x_1 - x_1(\gamma)\|_2 \ . \tag{36}$$

Recalling from (33) that $\overline{x_0} - \overline{x_1} = A_I^+ w$, it follows that

$$\|x_0 - x_1\|_2 \leq \varepsilon\sqrt{\rho((A_I^{\mathrm{T}} A_I)^{-1})},$$

which, using again Lemma 3, leads to the bound

$$\|x_0 - x_1\|_2 \leq 2\varepsilon$$

with probability larger than $1 - e^{-\frac{n}{2}\left(0.5-\sqrt{\frac{k}{n}}\right)^2}$.

For all $\gamma > 0$, $x_1(\gamma)$ obeys (31), and since $\lim_{\gamma\to 0} x_1(\gamma) = x_1$, we get that

$$\|x_1 - x_1(\gamma)\|_2 \leq \gamma \max_{J\subset I, S\in\{-1,1\}^{|J|}} \left\|(A_J^{\mathrm{T}} A_J)^{-1} S\right\|_2 . \tag{37}$$

For all $J \subset I$, the inclusion principe tells us that $\rho((A_J^{\mathrm{T}} A_J)^{-1}) \leq \rho((A_I^{\mathrm{T}} A_I)^{-1})$. Furthermore, for all $S \in \{-1,1\}^{|J|}$, $\|S\|_2 \leq \sqrt{k}$. Using Lemma 3 once again implies that

$$P\left(\|x_1 - x_1(\gamma)\|_2 \leq \gamma\sqrt{\frac{k}{\beta}}\right) \geq 1 - e^{-\frac{n}{2}\left(1-\sqrt{\beta}-\sqrt{\frac{k}{n}}\right)^2}.$$

If $\gamma = \frac{\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}}$ and $k \leq \frac{\alpha\beta n}{2\log p}$, then w.o.p.

$$\|x_1 - x_1(\gamma)\|_2 \leq \varepsilon\sqrt{\frac{\alpha}{1-\alpha}} \ .$$

This concludes the proof.

6. Numerical Illustrations

This section aims at providing empirical support of the sharpness of our bounds by assessing experimentally the quality of the constants involved in Theorem 1. More specifically, we perform a probabilistic analysis of support and sign recovery, to show that the bounds (6), (8) and (7) are quite tight[5].

In all the numerical tests, we use problems of size $(n, p) = (8000, 32000)$ and $(n, p) = (3000, 36000)$, corresponding to moderate and high redundancies. These are realistic high-dimensional settings in agreement with signal and image processing applications. We perform a randomized analysis, where the probability of exact recovery of supports and signs (sparsistency) are computed by Monte-Carlo sampling with respect to a probability distribution on the measurement matrix, k-sparse signals and on the noise w. As detailed in Section 1.1, the matrix A is drawn from the Gaussian ensemble. We assume that the non-zero entries $x[i]$ for $i \in I(x)$ of a vector $x \in \mathbb{R}^p$ are independent realizations of a Bernoulli variable taking equiprobable values $\{+T, -T\}$. We also assume that the noise w is drawn from the uniform distribution on the sphere $\{w \in \mathbb{R}^n \setminus \|w\| = \varepsilon\}$. Since only the SNR matters in the bounds, we fix $\varepsilon = 1$ and only vary the value of T.

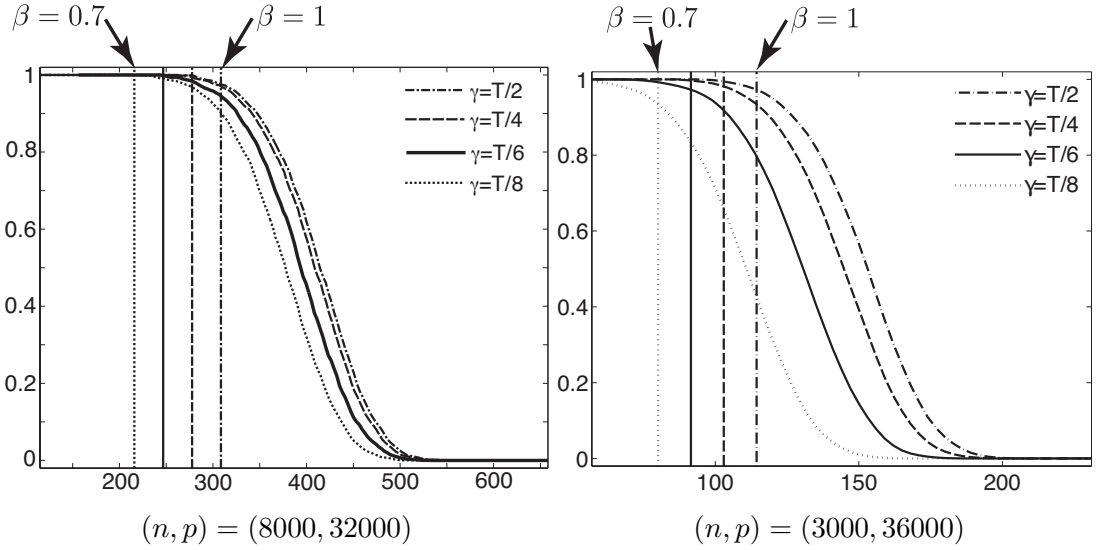

Figure 1: *Probability of sparsistency as a function of k and $\alpha = 0.8$. The vertical lines corresponds to our sparsistency bound k_β, from left to right, for $\beta = 0.7, 0.8, 0.9, 1$.*

Challenging the sparsity bound (6). We first evaluate, for $\alpha = 0.8$, and for a varying value of k, the probability of sparsistency given that

$$T = \frac{5.5\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}} \quad \text{and} \quad \gamma = \frac{T}{5.5} \tag{38}$$

which are values in accordance with the bounds (7) and (8).

In order to compute numerically this probability, for each k, we generate 1000 sparse signals x_0 with $\|x_0\|_0 = k$, and check whether conditions (C_1) and (C_2) defined in Section 3.1 are satisfied. Figure 1 shows how this probability decays when k increases. The

[5]The MATLAB code to reproduce the figures are freely available for download from `http://www.ceremade.dauphine.fr/~peyre/codes/`.

vertical lines correspond to the critical sparsity thresholds

$$k_\beta = \frac{\alpha\beta n}{2\log p} \tag{39}$$

as identified by the bound (6). The estimated probability exhibits a typical phase transition that is located precisely around the critical value k_β for β close to one. This shows that our bound is quite sharp. We also display the same probability curve for other, less conservative, values of $\gamma \in \{T/4, T/2\}$, which improves slightly the probability with respect to $\gamma = T/5.5$.

Challenging the regularization parameter value (8). We evaluate, for $(\alpha, \beta) = (0.8, 0.8)$, the probability of sparsistency using a value of γ different from

$$\gamma_0 = \frac{\varepsilon}{\sqrt{1-\alpha}}\sqrt{\frac{2\log p}{n}} \tag{40}$$

given in (8), for which Theorem 1 is valid. We use the critical sparsity level $k = k_\beta$ defined in (39). To study only the influence of γ, we use a SNR that is infinite, meaning that ε is negligible in comparison with T. This implies in particular that in this regime, only condition (C_1) has to be checked to estimate the probability of sparsistency.

Figure 2 shows the increase in this probability as the ratio γ/γ_0 increases. This makes sense because the signal is large with respect to the noise so that a large threshold should be preferred. One can see that at the critical value $\gamma = \gamma_0$ suggested by Theorem 1, this probability is close to 1. This again confirms that the value (8) of γ is quite sharp.

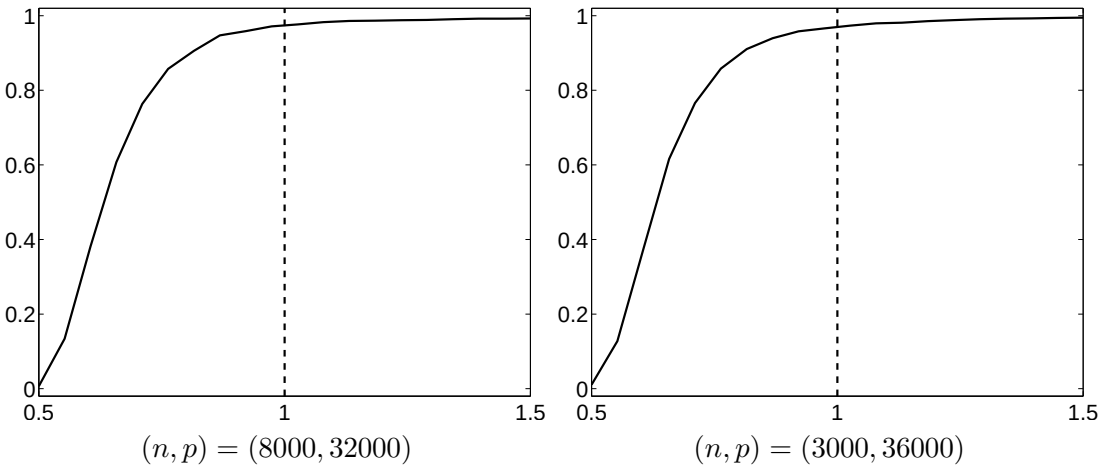

Figure 2: *Probability of support recovery for large T as a function of γ/γ_0 for $k = k_\beta$ and $(\alpha, \beta) = (0.8, 0.8)$.*

Challenging the signal-to-noise ratio (7). Lastly, we estimate, for $(\alpha, \beta) = (0.8, 0.8)$, the minimal signal level T that is required to ensure the inclusion of the support, meaning that $I(x(\gamma)) \subset I(x_0)$. We use the critical sparsity $k = k_\beta$ and $\gamma = \gamma_0$, with k_β and γ_0 as defined respetively in (39) and (40). Since we are only interested in support inclusion, it is only needed to check condition (C_2).

The bound in (7) suggests that $T \geq 5.5\gamma_0$ is enough. Figure 3 however shows that this bound is pessimistic, and that $T \geq 2\gamma_0$ appears to be enough to guarantee the support inclusion with high probability. A few reasons may explain this sub-optimality.

- There is no guarantee that the concentration lemmas we use are optimal.

- The limit ratio $\frac{T}{\varepsilon}$ relies mainly on Lemma 4 and especially on the bound $1+4\sqrt{b}$ in it. This bound can be improved by at least three ways.
  - Using the same proof, the bound can be slightly enhanced by decaying the probability of success.
  - The result in the lemma is non-asymptotic. The bound and the probability were computed to be available for all $\alpha \leq 1, \beta \leq 1$ and for all $p \geq 1212$. With the values used in the numerical experiments, and decaying a bit the probability of success, the bound can turn into $1+2.7\sqrt{b}$, yielding a better bound $T \geq 4.37\gamma_0$.
  - In the proof of Lemma 4, the inequality $\|B_i\|_2 \leq \rho(B)$, is used, where $\rho(B)$ is the spectral radius of B. This bound is available for any matrix, but one might perhaps do better by exploiting Gaussiannity of the measurement matrix.

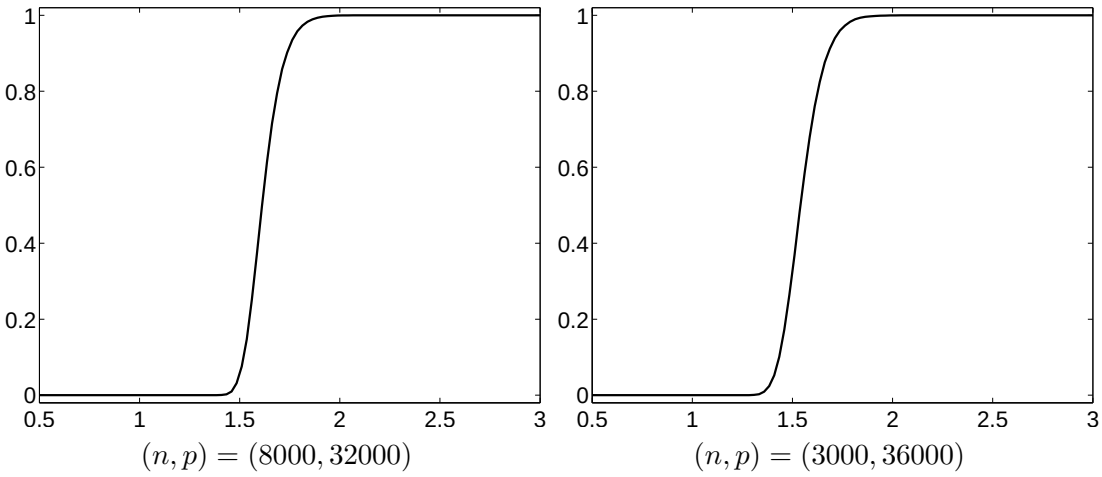

Figure 3: *Probability of support inclusion as a function of T/γ_0 for $k = k_\beta$ and $(\alpha, \beta) = (0.8, 0.8)$.*

Conclusion

This paper has presented a novel analysis of the sparsistency of the Lasso from noisy Gaussian measurements. We derived sharp bounds on the sparsity of the signal to guarantee sparsistency with high probability. This result is extended to handle compressible signals and to establish sharp ℓ_2-consistency. A distinctive feature of our analysis is that it provides explicit constants for the three key parameters of the problem: the sparsity of the signal, the minimal signal-to-noise ratio and the Lasso regularization parameter. Numerical results support the claim that these constants are either sharp or at least reasonably well behaved.

A. Properties of Wishart Matrices

A.1. Signs of non-diagonal entries of an inverse Wishart matrix

Lemma 2. *If $B \in \mathbb{R}^{k\times k}$ is the inverse of a Wishart matrix, then for all $i \leq k$, the variables $(\operatorname{sign}(B_{i,j}), j \neq i)$ form a Rademacher sequence, that is they are independent and uniformly distributed on $\{-1, 1\}$. Moreover this sequence is independent of $B_{i,i}$, and of $(|B_{i,j}|)_{j\neq i}$.*

Proof: If $B = (B_{i,j})_{i\leq k, j\leq k} \in \mathbb{R}^{k\times k}$ is the inverse of a Wishart matrix, then $B = (A^{\mathrm{T}}A)^{-1}$ where $A \in \mathcal{M}_{n,k}(\mathbb{R})$ is a Gaussian matrix. Let $E \in \mathcal{M}_{k,k}(\mathbb{R})$ be diagonal such that for all $1 \leq i \leq k, |E_{i,i}| = 1$. Then $(AE)^{\mathrm{T}}AE = EA^{\mathrm{T}}AE$, hence

$((AE)^{\mathrm{T}}(AE))^{-1} = E(A^{\mathrm{T}}A)^{-1}E$. Therefore the entries of $C = ((AE)^{\mathrm{T}}AE)^{-1}$ are $C_{i,j} = E_{i,i}E_{j,j}B_{i,j}$ for $1 \leq i, j \leq k$.
But A and AE have the same law, hence B and C also have the same law. Hence for all $(\epsilon_j)_{j\leq k, j\neq i} \in \{-1,1\}^{k-1}$, the laws of $(B_{i,1}, \ldots, B_{i,k})$ and $(\epsilon_1 B_{i,1}, \ldots, B_{i,i}, \ldots, \epsilon_k B_{i,k})$ are the same. This implies that the variables $(\mathrm{sign}\,(B_{i,j})\,, j \neq i)$ form a Rademacher sequence, and this sequence is independent of $B_{i,i}$, and of $(|B_{i,j}|)_{j\neq i}$.

A.2. Extreme eigenvalues of a Wishart matrix

The proof of the following lemma can be found in [62, page 42].

Lemma 3. *If $A \in \mathbb{R}^{n\times k}$ is a Gaussian matrix whose coefficients are centered of variance $\frac{1}{n}$, then the maximal and minimal eigenvalues of the Wishart matrix $B = A^{\mathrm{T}}A$ satisfy for all $t > 0$*

$$P\left(\lambda_{\max}(B) \geq \left(1 + \sqrt{\frac{k}{n}} + t\right)^2\right) \leq e^{-\frac{nt^2}{2}}$$

and

$$P\left(\lambda_{\min}(B) \leq \left(1 - \sqrt{\frac{k}{n}} - t\right)^2\right) \leq e^{-\frac{nt^2}{2}}$$

A.3. Sup-norm of a projected Rademacher sequence

Lemma 4. *If $C \in \mathbb{R}^{n\times k}$ is a Gaussian matrix, with $k \leq \frac{nb}{2\log p}$ with $0 < b \leq 1$ and if $S \in \{-1,1\}^k$ is drawn independently from C, then if $p \geq 1212$,*

$$P\left(\left\|(C^{\mathrm{T}}C)^{-1}S\right\|_\infty \leq 1 + 4\sqrt{b}\right) \geq 1 - kp^{-1.28} - 2e^{-\frac{nb(0.75\sqrt{2}-1)^2}{4\log p}}\,.$$

Proof: We use the following splitting

$$(C^{\mathrm{T}}C)^{-1} = I + ((C^{\mathrm{T}}C)^{-1} - I) = I + B.$$

This shows that

$$\left\|(C^{\mathrm{T}}C)^{-1}S\right\|_\infty \leq \|S\|_\infty + \|BS\|_\infty = 1 + \|BS\|_\infty\,.$$

One can then observe that $(BS)[i] = \sum_{j\leq k} |B_{i,j}|S[j]\mathrm{sign}\,(B_{i,j})$; one has $B_{i,i} > 0$, and according to Lemma 2, for given i, the variables $\mathrm{sign}\,(B_{i,j})_{j\neq i}$ form a Rademacher sequence (this means that they are independent and uniformly distributed on $\{-1,1\}$), and this sequence is independent of $B_{i,i}$ and of $(|B_{i,j}|)_{j\neq i}$. Hence one can apply Hoeffding's Lemma 10 (multiplying the line by an independent variable uniform on $\{-1,1\}$ to take care of the fact that $\mathrm{sign}\,(B_{i,i})$ is not uniformly distributed), thus getting for any $i \leq k$ and any $t > 0$,

$$P\left(\left|\sum_{j=1}^{k} B_{i,j}S[j]\right| \geq t\,\|B_i\|_2\right) \leq e^{-\frac{t^2}{2}}\,. \tag{41}$$

Now, for all $i \leq k$, $\|B_i\|_2 \leq \rho(B)$, where $\rho(B)$ is the spectral radius of B. Using Lemma 3 with $t = (0.75 - \frac{1}{\sqrt{2}})\sqrt{\frac{b}{\log p}}$ and the fact that $\frac{k}{n} \leq \frac{b}{2\log p}$, we get

$$P\left(\lambda_{\min}(C^{\mathrm{T}}C) \leq \left(1 - 0.75\sqrt{\frac{b}{\log p}}\right)^2\right) \leq e^{-\frac{nb(0.75\sqrt{2}-1)^2)}{4\log p}}\,.$$

Consequently

$$P\left(\lambda_{\max}((C^{\mathrm{T}}C)^{-1}) \geq \left(1-0.75\sqrt{\frac{b}{\log p}}\right)^{-2}\right) \leq e^{-\frac{(0.75\sqrt{2}-1)^2 bn}{4\log p}} .$$

Similarly, we have

$$P\left(\lambda_{\min}((C^{\mathrm{T}}C)^{-1}) \leq \left(1+0.75\sqrt{\frac{b}{\log p}}\right)^{-2}\right) \leq e^{-\frac{(0.75\sqrt{2}-1)^2 bn}{4\log p}} .$$

It finally follows that with probability larger than $1-2e^{-\frac{nb(0.75\sqrt{2}-1)^2)}{4\log p}}$,

$$\rho(B) \leq \max\left(\left|(1+0.75\sqrt{\frac{b}{\log p}})^{-2}-1\right|, \left|(1-0.75\sqrt{\frac{b}{\log p}})^{-2}-1\right|\right) .$$

In particular, taking $\frac{\log(p)}{b} \geq \frac{15^2}{(17-\sqrt{129})^2} \simeq 7.07$ leads to $\rho(B) \leq 2.5\sqrt{\frac{b}{\log p}}$ with probability greater than $1-2e^{-\frac{nb(0.75\sqrt{2}-1)^2}{4\log p}}$.

Using this bound in (41) with $t = 1.6\sqrt{\log(p)}$ yields

$$\begin{aligned} P\left(\|BS\|_\infty \geq 4\sqrt{b}\right) &\leq P\left(\|BS\|_\infty \geq t\,\|B_i\|_2 \text{ and } \rho(B) \leq 2.5\sqrt{\frac{b}{\log p}}\right) \\ &\quad + P\left(\rho(B) \geq 2.5\sqrt{\frac{b}{\log p}}\right) \\ &\leq kp^{-1.28} + 2e^{-\frac{nb(0.75\sqrt{2}-1)^2}{4\log p}} . \end{aligned}$$

If we set $\frac{\log(p)}{b} \geq 7.08$, the following holds,

$$P\left(\left\|(C^{\mathrm{T}}C)^{-1}S\right\|_\infty \leq 1+4\sqrt{b}\right) \geq 1-kp^{-1.28}-2e^{-\frac{nb(0.75\sqrt{2}-1)^2}{4\log p}} .$$

■

Remark 2. *It is worth noting that if* $\frac{\log p}{b} \geq 16.2$ *as in the numerical experiments* ($b = 0.64, p = 32000$)*, one can adapt this proof and, by loosing a bit on the probability (i.e. applying the concentration lemmas with smaller values of* t*), one can get* $\left\|(C^{\mathrm{T}}C)^{-1}S\right\|_\infty \leq 1+2.7\sqrt{b}$ *w.o.p.* .

A.4. Rotation invariance

Lemma 5. *If* $C \in \mathbb{R}^{n\times k}$ *is a Gaussian matrix, and* $w \in \mathbb{R}^n$ *is independent of* C*, the law of* C^+w *is invariant under orthogonal transforms on* $\mathbb{R}^k$*.*

Proof: If $C \in \mathbb{R}^{n\times k}$ is a Gaussian matrix, then for any orthogonal matrix $U \in \mathbb{R}^{k\times k}$, $D = CU$ and C have the same distribution. The law of D^+w and C^+w are thus the same. Since for all w, one has

$$D^+w = U^{-1}C^+w,$$

the law of $U^{-1}C^+w$ is the same as that of C^+w.

A.5. Distribution of a quadratic form

The following lemma is a consequence of [63, Theorem 3.2.12].

Lemma 6. *If B is a Wishart matrix as described in Lemma 3, then for all $X \in \mathbb{R}^k$ independent of B, the random variable $\frac{n\|X\|_2^2}{X^T B^{-1} X}$ follows a χ^2 distribution with $n-k+1$ degrees of freedom.*

B. Concentration inequalities

The following lemma is well known; a proof can be found in [64].

Lemma 7. *Let μ_k denote the uniform probability on the unit sphere $\mathbb{S}^{k-1}$ in $\mathbb{R}^k$, and let $A \subset \mathbb{S}^{k-1}$ such that $\mu_k(A) \geq \frac{1}{2}$. Then $\mu_k(\{x \in \mathbb{S}^{k-1}, d(x,A) \leq \epsilon\}) \geq 1 - 2e^{-\frac{k\epsilon^2}{2}}$. As a corollary, $\mu_k(x \in \mathbb{S}^{k-1}, |x_1| \leq \epsilon\} \geq 1 - 4e^{-\frac{k\epsilon^2}{2}}$.*

The following lemma is due to Cai et Silverman, see [65].

Lemma 8. *If X follows a χ^2 distribution with k degrees of freedom, then for all $\delta > 0$,*

$$P\left(X > (1+\delta)k\right) \leq \frac{1}{\sqrt{2\pi k\delta}} e^{-\frac{k}{2}(\delta - \log(1+\delta))}$$

The following lemma is due to Hoeffding, see [66].

Lemma 9. *If X follows a χ^2 distribution with k degrees of freedom, then for all $\delta > 0$,*

$$P(X < (1-\delta)k) \leq e^{\frac{k\log(1-\delta)}{2}}$$

The following lemma can be obtained by applying the Chernoff-Hoeffding inequality.

Lemma 10. *If $(\varepsilon_i)_{i \leq k}$ is a Rademacher sequence, then for all $a = (a_i)_{i \leq k} \in \mathbb{R}^k$ and for all $t > 0$,*

$$P\left(\left|\sum_{i=1}^{k} \varepsilon_i a_i\right| \geq t\,\|a\|_2\right) \leq e^{-\frac{t^2}{2}}\ .$$

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