

# The Mutual Information in Random Linear Estimation Beyond i.i.d. Matrices

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**Abstract**—**TO BE CONSIDERED FOR THE 2017 IEEE JACK KEIL WOLF ISIT STUDENT PAPER.** There has been definite progress recently in proving the variational single-letter formula given by the heuristic replica method for various estimation problems. In particular, the replica formula for the mutual information in the case of noisy linear estimation with random i.i.d. matrices, a problem with applications ranging from compressed sensing to statistics, has been proven rigorously. In this contribution we go beyond the restrictive i.i.d. matrix assumption and discuss the formula proposed by Takeda, Uda, Kabashima and later by Tulino, Verdu, Caire and Shamai using the replica approach for the ensemble of rotationally invariant random matrices. Using the recently introduced adaptive interpolation method and random matrix theory, we prove this formula for a relevant large sub-class of rotationally invariant matrices.

## I. INTRODUCTION

Few problems are as ubiquitous in computer science as the one of random linear estimation, that plays a fundamental role in machine learning [1], statistics [2] and communication [3]. Computing the information theoretic limitation for the estimation of a signal given the knowledge of its random linear projections has many applications, e.g., compressed sensing [2], code division multiple access (CDMA) [4], or error correcting codes [5, 6]. The problem is defined as follows: Consider a *signal* vector  $\mathbf{X} \in \mathbb{R}^n$  with i.i.d. entries distributed according to a “prior”  $P_0$  over  $\mathbb{R}$  with bounded support (an hypothesis that can be relaxed). One is given  $m$  measurements

$$Y_\mu = \sqrt{\frac{\lambda}{n}}(\Phi\mathbf{X})_\mu + Z_\mu, \quad \mu = 1, \dots, m, \quad (1)$$

in which  $\lambda > 0$  is the *signal to noise ratio* (snr),  $\mathbf{Z} = (Z_\mu)_{\mu=1}^m \stackrel{\text{i.i.d.}}{\sim} \mathcal{N}(0, 1)$  is a Gaussian noise and  $\Phi \in \mathbb{R}^{m \times n}$  is the *measurement matrix*. We will consider the “high-dimensional limit”  $m, n \rightarrow \infty$  such that  $\alpha \equiv m/n$  stays finite.

There has been a considerable amount of work on this model in the case where  $\Phi$  is a random matrix whose elements are i.i.d. standard Gaussian. In particular a pioneering work by Tanaka [4] using a statistical physics calculation and the replica method [7] proposed a single-letter formula for the normalized mutual information between the measurements and the signal  $i_n \equiv \frac{1}{n}I(\mathbf{X}; \mathbf{Y}|\Phi)$ . The so-called Tanaka formula, originally written for the CDMA problem (where each element of  $\mathbf{X}$  is taken i.i.d. from  $\pm 1$ ), has been generalized and applied to many problems (e.g. in [8, 9]). After nearly 15 years, it has been proven with different approaches [10–13], a spectacular confirmation of the replica calculation.

In this paper, we endeavour to go beyond the very restrictive simple i.i.d. measurement matrix assumption and consider instead a more complex situation where  $\Phi$  is now taken from a non-trivial, and correlated, random ensemble. This is both more relevant to practical cases, and more realistic in terms of modeling real statistical situations.

## II. RESULT AND RELATED WORKS

The random linear estimation problem with correlated, non i.i.d. matrices has been considered, again with the replica method, and a solution was proposed by Takeda, Uda and Kabashima in the case of CDMA [14] for matrices taken from a *rotationally invariant ensemble*. The replica formula was later extended by Tulino, Caire, Verdu and Shamai [9] for such similar ensembles in order to allow for more complicated priors such as Gauss-Bernoulli ones. These works point to a generic conjecture, that we now describe, giving the single-letter formula for the mutual information.

Consider a measurement matrix  $\Phi = \mathbf{O}\Sigma\mathbf{N}^\top$  where  $\mathbf{O}$  and  $\mathbf{N}$  are both orthogonal matrices and  $\Sigma$  is diagonal (possibly non-square). The matrices  $\Sigma$ ,  $\mathbf{N}$ ,  $\mathbf{O}$  are independent and  $\mathbf{N}$  is distributed uniformly, according to the *Haar measure* of its orthogonal group, in which case  $\Phi$  is said to be *right-rotationally invariant* (if  $\mathbf{O}$  is also Haar distributed the ensemble is simply called rotationally invariant). The matrix  $\mathbf{R} \equiv \frac{1}{n}\Phi^\top\Phi = \frac{1}{n}\mathbf{N}\Sigma^\top\Sigma\mathbf{N}$  plays an important role. For general rotation invariant ensembles its eigenvalues are not necessarily i.i.d. but typically are such that  $\frac{1}{n}\Sigma^\top\Sigma$  has a suitable limiting eigenvalue distribution (as in fact assumed in [14]). The limit of the normalized mutual information is conjectured to be

$$\lim_{n \rightarrow \infty} i_n = \sup_{(E,r) \in \Gamma} i_{\text{RS}}(E, r; \lambda), \quad (2)$$

where the so-called replica symmetric *potential*  $i_{\text{RS}}(E, r; \lambda) = i_{\text{RS}}$  is defined as

$$i_{\text{RS}} \equiv I(X; \sqrt{r}X + Z) + \frac{1}{2} \int_0^{E\lambda} \mathcal{R}_{\mathbf{R}}(-z) dz - \frac{rE}{2}. \quad (3)$$

Here we have used the *R-transform* of the matrix  $\mathbf{R}$  (see [3] for an introduction to such transforms).  $I(X; \sqrt{r}X + Z)$ , that we simply denote  $I(r)$  later on, is the mutual information for the scalar Gaussian channel  $Y = \sqrt{r}X + Z$ ,  $X \sim P_0$  and

$Z \sim \mathcal{N}(0, 1)$ . Moreover,  $\Gamma$  is the set of critical points of the potential, or *state evolution* fixed points ( $\rho \equiv \mathbb{E}_{P_0}[X^2]$ )

$$\Gamma \equiv \left\{ (E, r) \in [0, \rho] \times \mathbb{R}_+ \mid \begin{aligned} E &= \text{mmse}(X | \sqrt{r} X + Z), \\ r &= \lambda \mathcal{R}_{\mathbf{R}}(-E\lambda) \end{aligned} \right\}.$$

A virtue of the formula (3) is that the details of the rotation invariant matrix ensemble only enter through the R-transform.

Note the slight difference with the potential written in [9]: In the potential (3) a factor 1/2, not present in [9], multiplies both the integrated R-transform and  $-RE$ . This is because they consider the complex  $\Phi$  case while we consider the real case (nevertheless, we believe that our proof techniques could easily be generalized to include the complex case).

Interestingly, Manoel *et al* [15] and Reeves [16] were able to formally re-derive equivalent results independently for a sub-class of rotation invariant matrices by considering multi-layered estimation problems. This line of work combined with our present rigorous work is giving a lot of credibility to the replica conjecture for the general rotation invariant ensemble.

#### A. Main result

Our main result is a proof of the replica conjecture (2) for a specific, but large, set of correlated matrices. We hope it paves the way towards a completely general proof, as the non-rigorous replica calculation only assumes right-rotational invariance of  $\Phi$ . We assume that the  $m \times n$  matrix  $\Phi$  can be decomposed as follows:

$$\Phi = \Phi' \mathbf{W}, \quad (4)$$

in which all elements of the  $m \times n$  matrix  $\mathbf{W}$  are i.i.d. Gaussians  $\mathcal{N}(0, 1/n)$  with mean zero and variance  $1/n$ ,  $\Phi'$  is a  $m \times m$  random matrix, and  $\mathbf{W}$ ,  $\Phi'$  are independent. For the matrix  $\Phi'$  our analysis is currently complete under the assumption that it is a product of a finite number of independent matrices each with i.i.d. matrix-elements that are bounded or standard Gaussians. The case of a product of i.i.d. standard Gaussian matrices constitutes an interesting example that has been considered in [15].

Our goal here is to give a rigorous proof of (2) in the setting of matrices (4) with the independence assumptions for  $\Phi'$ . Some of our technical calculations are based on previous related works, and all of them will be discussed in a complete manner in a longer contribution.

**Theorem 2.1 (Replica formula):** Assume that the prior  $P_0$  has compact support or, in other words, the signal is bounded. Then with  $n, m, \Phi, \mathbf{R}, i_{\text{RS}}$  defined as before (in particular  $\Phi$  satisfies (4) and the subsequent hypothesis) one has

$$\lim_{n \rightarrow \infty} i_n = \inf_{r \geq 0} \sup_{E \in [0, \rho]} i_{\text{RS}}(E, r; \lambda).$$

**Remark 2.1 (Equivalent expressions of the replica formula):** The right hand side in the theorem above can also be written as  $\sup_{(E, r) \in \Gamma} i_{\text{RS}}(E, r; \lambda)$  (if the extremizers are not attained at the boundaries which is the case when noise is present) or as  $\inf_{E \in [0, \rho]} \sup_{r \geq 0} i_{\text{RS}}(E, r; \lambda)$ . A proof of such equivalences, in the case of generalized estimation, is found in [13].

**Remark 2.2 (Right-rotation invariance of the ensemble):** Note that (4) implies the right-rotation invariance of  $\Phi$  because of the rotation invariance of  $\mathbf{W}$ . Our result thus covers a sub-class of right-rotation invariant matrices.

**Remark 2.3 (Relaxing the assumptions on  $\Phi'$ ):** The assumptions on  $\Phi'$  come from the fact that a complete rigorous analysis requires proving the concentration of the “free energy” of an *interpolating* model (see below; the free energy is equal to the mutual information up to a trivial additive constant). This involves the use of tools such as the McDiarmid bounded difference inequality and/or the Gaussian Poincaré inequality, which require some independence between degrees of freedom. If one *assumes* concentration of the free energy of the interpolating model then one can relax these assumptions to the following more general ones. It then suffices to assume that  $\frac{1}{n} \Phi'^T \Phi'$  has a well-defined, positively and compactly supported, asymptotic eigenvalue distribution in the limit  $n \rightarrow \infty$ . We also remark that concentration proofs of the free energy of the original and interpolated models are technically similar, however we have not established a purely logical implication between the two. If such an implication holds one could also replace the independence assumption on  $\Phi'$  by an assumption of concentration of the free energy.

**Remark 2.4 (Relaxing the assumption on  $P_0$ ):** Boundedness of the signal is again used to obtain concentration results for the free energy but it can presumably be removed using a limiting argument as in [17].

#### B. Related works

There has been a lot of effort recently [10–13] to prove the Tanaka formula for random i.i.d. matrices. Our strategy in the present paper is to follow the *adaptive interpolation method* introduced in [18, 19]. This method, in particular, has been used by the authors of [13] to reach a rigorous demonstration of the replica formula for the mutual information for the case of i.i.d. measurement matrix  $\Phi$ , in the more general situation of “generalized linear estimation” i.e., with an *arbitrary* measurement channel (instead of just a random additive noise as in (1)). Some steps of our current approach consequently follow similar ones in [13] (but with key differences) and we will refer to this work when necessary. We believe, in fact, that the approach presented in the present paper could further be generalized as well to generalized linear estimation with rotationally invariant matrices to reach the formula conjectured by Kabashima in [20]. This is left for future work.

Perhaps the most important consequence of the replica formula is that it predicts the value of the minimum mean-square error (MMSE) in the reconstruction of the signal  $\mathbf{X}$ . In fact, it is conjectured (and proved for Gaussian matrices [11, 12]) to be given by the value  $E$  that extremizes (3). While we consider here mainly the information theoretic result, a large body of work has focused on algorithmic approaches to random linear estimation, and investigated whether the MMSE is efficiently (say, in polynomial time) achievable.

For Gaussian matrices, the most successful approach, so far, again originated in statistical physics [21, 22] and is called

approximate message-passing (AMP) [23]. AMP is Bayes-optimal and efficiently achieves the MMSE for a large set of parameters, as proven in [11]. There, however, might exist a region called “hard” where this is not the case, and polynomial algorithms improving on AMP are not known. Whether there exists an efficient algorithm that is able to beat AMP in the hard region is widely considered to be a notoriously difficult problem (see e.g. [24] and reference therein).

For rotationally invariant matrices, different but related approaches were proposed [14, 25]. In particular, the general expectation-propagation (EP) [26] leads to a powerful scheme in this context [27]. Recently, Rangan, Schniter and Fletcher proposed a variation of EP called VAMP [28] and showed that it follows the fixed point equation (called state evolution) of the potential (3). Interestingly, the multi-layer AMP algorithm of Manoel *et al.* [15] also has the same fixed point. Our result thus supports that VAMP (and multi-layer AMP) are Bayes-optimal and efficiently reach the MMSE in the “easy” region of random linear estimation with these correlated matrices, just as AMP in the case of i.i.d. Gaussian matrices.

### III. PROOF BY THE ADAPTIVE INTERPOLATION METHOD

We give here the main steps of the proof of Theorem 2.1. We will use the adaptive interpolation method, introduced in [18], and then applied in [19] and [13]. It is a powerful evolution of the interpolation method developed by Guerra and Toninelli in the context of spin glasses [29]. Many steps of the proof follow the ones of [13], and we will refer to them when necessary.

#### A. Interpolating estimation problem

Let  $E : [0, 1] \rightarrow \mathbb{R}_+$  be a continuous “interpolation function”,  $r \geq 0$  and  $t \in [0, 1]$ . Define  $\tilde{E}(t) \equiv \int_0^t E(s) ds$  (and thus  $\tilde{E}'(t) = E(t)$ ), that plays the role of a signal-to-noise ratio. Assume one has access to the following two  $t$ -dependent observation channels for  $i = 1, \dots, n$  and  $\mu = 1, \dots, m$ :

$$\begin{cases} Y_{t,\mu} &= \sqrt{\frac{\lambda(1-t)}{n}}(\Phi\mathbf{X})_\mu + \sqrt{\frac{\lambda}{n}\tilde{E}(t)}(\Phi'\mathbf{V})_\mu + Z_\mu, \\ \tilde{Y}_{t,i} &= \sqrt{rt}X_i + \tilde{Z}_i. \end{cases} \quad (5)$$

In the following we assume  $\lambda = 1$ , as it amounts to a scaling of  $\Phi$ . Here  $(\tilde{Z}_i), (Z_\mu), (V_i) \stackrel{\text{i.i.d.}}{\sim} \mathcal{N}(0, 1)$  whereas  $(X_i) \stackrel{\text{i.i.d.}}{\sim} P_0$ . The inference problem is to recover both  $\mathbf{X} = (X_i)_{i=1}^n$  and  $\mathbf{V} = (V_i)_{i=1}^m$  from the knowledge of the observations  $\mathbf{Y}_t, \tilde{\mathbf{Y}}_t$  and the matrix  $\Phi$  (and thus of  $\Phi', \mathbf{W}$  too as the decomposition (4) is assumed to be known).

In the Bayesian setting the posterior associated with this inference problem, written in the Gibbs-Boltzmann form, is

$$dP(\mathbf{x}, \mathbf{v} | \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi) = \frac{dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\mathcal{H}(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi)}}{\int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\mathcal{H}(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi)}}, \quad (6)$$

where  $\mathcal{D}\mathbf{v} \equiv \prod_{\mu=1}^m dv_\mu (2\pi)^{-1/2} e^{-v_\mu^2/2}$  is the standard Gaussian measure, and we have defined the interpolating *Hamiltonian*  $\mathcal{H} = \mathcal{H}(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi)$  as

$$\mathcal{H} \equiv \frac{1}{2} \|\mathbf{Y}_t - \sqrt{\frac{1-t}{n}} \Phi \mathbf{x} - \sqrt{\frac{\tilde{E}(t)}{n}} \Phi' \mathbf{v}\|_2^2 + \frac{1}{2} \|\tilde{\mathbf{Y}}_t - \sqrt{rt} \mathbf{x}\|_2^2.$$

It is a simple exercise (see e.g. [11]) to show that the normalized mutual information  $i_n(t) \equiv \frac{1}{n} I(\mathbf{X}, \mathbf{V}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t | \Phi)$  for the interpolation estimation problem is related to the posterior normalization (or partition function) through

$$i_n(t) = -\frac{1}{n} \mathbb{E} \ln \int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\mathcal{H}(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi)} - \frac{\alpha+1}{2}. \quad (7)$$

This *interpolating mutual information* verifies

$$\begin{cases} i_n(0) = i_n, \\ i_n(1) = I(r) + \frac{\alpha}{2} \mathbb{E}_{X'} \ln(1 + \tilde{E}(1)X'), \end{cases} \quad (8)$$

where  $X' \sim p'_n$ , with  $p'_n$  the empirical spectral distribution of the  $m \times m$  matrix  $\frac{1}{n} \Phi'^T \Phi'$ . The second term in the expression of  $i_n(1)$  (referred to as a Shannon transform in [3]) is obtained using the celebrated “log-det formula” for the mutual information  $\frac{1}{n} I(\mathbf{Y}_1; \mathbf{V} | \Phi')$  of an i.i.d. Gaussian input multiplied by the matrix  $\Phi'$  and under additive Gaussian noise, see e.g. [3].

Now a crucial step in our proof, that is a consequence of the particular form of the measurement matrix (4), is that as  $n$  grows this second term in  $i_n(1)$  can be replaced by an integrated R-transform:

$$i_n(1) = I(r) + \frac{1}{2} \int_0^{\tilde{E}(1)} \mathcal{R}_{\mathbf{R}}(-u) du + o_n(1), \quad (9)$$

where  $\mathcal{R}_{\mathbf{R}}(z)$  is the R-transform associated with the spectrum of  $\mathbf{R} = \frac{1}{n} \Phi'^T \Phi'$ . We give the definition of this transform as well as the proof of (9) in the next section.

A word about notations. We define the Gibbs Bracket  $\langle - \rangle_t$  as the expectation w.r.t. the posterior (6). In constrast we denote by  $\mathbb{E}$  the joint expectation w.r.t. all *quenched* variables (i.e. fixed by the realization of the problem), namely  $\mathbf{Y}_t$  and  $\tilde{\mathbf{Y}}_t$ , or equivalently w.r.t.  $\Phi', \mathbf{W}, \mathbf{X}, \mathbf{V}, \mathbf{Z}$  and  $\tilde{\mathbf{Z}}$ .

#### B. Useful tools from random matrix theory

In this paragraph we show how to deduce (9) from (8). Note

$$\mathbb{E}_{X'} \ln(1 + \tilde{E}(1)X') = \mathbb{E}_{X'} \int_0^{\tilde{E}(1)} du \frac{X'}{1+uX'}.$$

The result thus follows if the following relation is true

$$\mathcal{R}_{\mathbf{R}}(-u) = \alpha \mathbb{E}_{X'} \left[ \frac{X'}{1+uX'} \right] + o_n(1). \quad (10)$$

This is a well known relation in random matrix theory. For matrices of the form  $\mathbf{R} = \mathbf{W}^T \mathbf{T} \mathbf{W}$ , where  $\mathbf{W}$  is the Gaussian  $m \times n$  matrix with i.i.d.  $\mathcal{N}(0, 1/n)$  elements, and  $\mathbf{T} = \frac{1}{n} \Phi'^T \Phi'$  a non negative  $m \times m$  matrix with a limiting spectral distribution, this was already shown by Marcenko and Pastur in 1967 [30] in the language of the Stieltjes transform. See also [31] for generalizations. Denoting by  $g_{\mathbf{R}}(z)$  and  $g_{\mathbf{T}}(z)$  ( $z$  a complex number outside the spectrum of the matrices) the limiting Stieltjes transforms of the matrices  $\mathbf{R}$  and  $\mathbf{T}$ , we have [30, 31] that the Marcenko-Pastur formula takes the form

$$z(g_{\mathbf{R}}(z))^2 + \alpha g_{\mathbf{T}}(-1/g_{\mathbf{R}}(z)) + (1 - \alpha)g_{\mathbf{R}}(z) = 0.$$

Simple algebra then implies ( $g_{\mathbf{R}}^{-1}$  is the inverse function)

$$g_{\mathbf{R}}^{-1}(z) + z^{-1} = -\alpha z^{-2} (g_{\mathbf{T}}(-z^{-1}) - z).$$

Since by definition  $\mathcal{R}_{\mathbf{R}}(z) \equiv g_{\mathbf{R}}^{-1}(-z) - z^{-1}$  and  $g_{\mathbf{T}}(z) \equiv \int \frac{d\tau(x)}{x-z}$ ,  $d\tau(x)$  the limiting eigenvalue distribution of  $\mathbf{T}$ , this relation is nothing else than  $\mathcal{R}_{\mathbf{R}}(-z) = \alpha \int d\tau(x) \frac{x}{1+zx}$  which is equivalent to (10) when  $n \rightarrow \infty$ . We refer to the review [32] for a more modern discussion using free probability concepts.

### C. Mutual information variation

In order to “compare” the potential (3) with the mutual information, we use the trivial identity  $i_n = i_n(0) = i_n(1) - \int_0^1 i'_n(t) dt$  which becomes, using (9),

$$i_n = I(r) + \frac{1}{2} \int_0^{\tilde{E}(1)} \mathcal{R}_{\mathbf{R}}(-u) du - \int_0^1 i'_n(t) dt + \mathcal{O}_n(1). \quad (11)$$

We now evaluate  $i'_n(t)$ . Define the *overlap*  $Q \equiv \frac{1}{n} \sum_{i=1}^n X_i x_i$  and the vector  $\mathbf{u}_t = (u_{t,\mu})_{\mu=1}^m$  with

$$u_{t,\mu} \equiv \sqrt{\frac{1-t}{n}} (\Phi(\mathbf{X} - \mathbf{x}))_{\mu} + \sqrt{\frac{\tilde{E}(t)}{n}} (\Phi'(\mathbf{V} - \mathbf{v}))_{\mu} + Z_{\mu}.$$

**Lemma 3.1 (Mutual information variation):** For  $t \in (0, 1)$

$$i'_n(t) = \frac{r}{2} (\rho - \mathbb{E}\langle Q \rangle_t) + \mathcal{O}_n(1) + \frac{1}{2n^2} \mathbb{E}\langle \mathbf{Z}^{\top} (\Phi' \Phi'^{\top}) \mathbf{u}_t [E(t) - (\rho - Q)] \rangle_t \quad (12)$$

in which  $\lim_{n \rightarrow \infty} \mathcal{O}_n(1) = 0$  uniformly in  $t \in (0, 1)$ .

The proof of this lemma is very similar to the one of Proposition 4 of [13]. The idea is to write explicitly the derivative  $i'_n(t)$  and then to integrate by parts the quenched Gaussian variables  $\mathbf{V}$  and  $\mathbf{W}$ , before using the *Nishimori identity*. This identity is a consequence of Bayes rule and the fact that we consider the *optimal Bayesian setting*, namely that all hyperparameters in the problem such as the snr and  $P_0$  are known and used when defining the posterior, see [13, 18, 24].

### D. Overlap concentration

The next lemma essentially states that the overlap concentrates around its mean, and plays a key role in our proof. The proof technique for Bayesian inference has been developed in [11, 33–35] and is akin to the analysis reviewed for example in [36]. The point however here is that in Bayesian inference overlap concentration can be proved in the whole phase diagram. We will refer to [13, 18] where the analysis has been made quite generic.

We introduce a “small” perturbation of the interpolating estimation problem by *adding* to the interpolating Hamiltonian  $\mathcal{H}$  the term  $\sum_{i=1}^n (\epsilon x_i^2 / 2 - \epsilon x_i X_i - \sqrt{\epsilon} x_i \hat{Z}_i)$  where  $(\hat{Z}_i)_{i=1}^n \stackrel{\text{i.i.d.}}{\sim} \mathcal{N}(0, 1)$ . This term can be interpreted as coming from a set of extra observations from a Gaussian side-channel  $\hat{Y}_i = \sqrt{\epsilon} X_i + \hat{Z}_i$  for  $i = 1, \dots, n$ . Importantly this term preserves the Nishimori identity. The new Hamiltonian defines a new Gibbs bracket  $\langle - \rangle_{t,\epsilon}$  and interpolating mutual information  $i_{n,\epsilon}(t)$ . All the calculations of the previous section trivially extend. This perturbation induces only a small change in the mutual information, namely of the order of  $\epsilon$ :

**Lemma 3.2 (Small mutual info. variation under perturbation):** Let  $P_0$  with bounded support. For all  $\epsilon > 0$  and all  $t \in [0, 1]$ ,  $|i_{n,\epsilon}(t) - i_n(t)| = \mathcal{O}(\epsilon)$  where  $\mathcal{O}(\epsilon)$  depends only on the size of the support of  $P_0$  and  $\alpha$ .

*Proof:* A computation using Gaussian integration by parts and the Nishimori identity gives  $|\frac{\partial f_{n,\epsilon}(t)}{\partial \epsilon}| = \frac{1}{2} |\mathbb{E}\langle Q \rangle_{t,\epsilon}|$ . ■

This small perturbation forces the overlap to concentrate:

**Lemma 3.3 (Overlap concentration):** For any  $0 < a < b < 1$ ,  $\lim_{n \rightarrow \infty} \int_a^b d\epsilon \int_0^1 dt \mathbb{E}\langle (Q - \mathbb{E}\langle Q \rangle_{t,\epsilon})^2 \rangle_{t,\epsilon} = 0$ .

We refer to [13, 18] for a detailed proof. As long as the concentration of the free energy of the interpolating model holds and that the unperturbed Hamiltonian satisfies the Nishimori identity (i.e., comes from a Bayesian inference problem) the analysis in [13, 18] applies verbatim. In other words the details of the unperturbed Hamiltonian do not matter. We stress that this lemma is the only place where the concentration of the free energy of the interpolating model is needed. For the present model under the assumptions on  $\Phi'$  this follows from Gaussian Poincaré and McDiarmid inequalities much as in [13].

Note that the existence of the limit of the integrand in Lemma 3.3 as  $n \rightarrow \infty$  is not known (and seems difficult to prove). Hence one cannot use Lebesgue’s dominated convergence theorem to exchange the limit and the  $\epsilon$ -integral. However, an elementary analysis argument based on the mean value theorem shows the existence of a sequence  $(\epsilon_n)_{n \geq 1}$  that converges to 0 such that

$$\lim_{n \rightarrow \infty} \int_0^1 dt \mathbb{E}\langle (Q - \mathbb{E}\langle Q \rangle_{t,\epsilon_n})^2 \rangle_{t,\epsilon_n} = 0. \quad (13)$$

Note that Lemma 3.2 gives that  $i_{n,\epsilon_n}(t)$  and  $i_n(t)$  have same limit provided it exists. In the next sections, in order to alleviate the notations in this short manuscript, we abusively remove the perturbation subscript  $\epsilon_n$  since it makes no essential difference for the subsequent proofs but it is understood that all quantities are computed for the  $\epsilon_n$ -perturbed model.

### E. Upper and lower bounds

This part is similar to parts 5.3 and 5.4 of [13], or to what is done in [19]. As suggested by (12), in order to recover the potential on the r.h.s. of (11), we want to choose for the interpolating function

$$E(t) = \tilde{E}'(t) = \rho - \mathbb{E}\langle Q \rangle_t. \quad (14)$$

Note that (14) is actually a first-order differential equation in  $\tilde{E}(t)$  ( $\mathbb{E}\langle Q \rangle_t$  is a function of  $\tilde{E}(t)$ ). Because  $\mathbb{E}\langle Q \rangle_t$  is a bounded  $\mathcal{C}^1$  function of  $(\tilde{E}(t), r)$ , the parametric Cauchy-Lipschitz theorem gives the following existence lemma.

**Lemma 3.4 (Optimal interpolation function):** Let  $n \in \mathbb{N}^*$ . For all  $r \geq 0$ , the differential equation (14) admits a unique solution  $E_n^{(r)}(t) \in [0, \rho]$ . Moreover the mapping  $r \in \mathbb{R}_+ \mapsto \int_0^1 E_n^{(r)}(s) ds \in [0, \rho]$  is continuous.

We choose this optimal solution  $E_n^{(r)}(t)$ . We then apply the concentration (13) for replacing the overlap by its mean  $\mathbb{E}\langle Q \rangle_t$  in (12) under the integral in (11). We use the Cauchy-Schwartz inequality to show that this is possible up to an  $\mathcal{O}_n(1)$  correction. This leads to  $\int_0^1 i'_n(t) dt = (r/2) \int_0^1 E_n^{(r)}(t) dt + \mathcal{O}_n(1)$ . Therefore (11) and (12) allow to deduce the following.

**Lemma 3.5 (Fundamental identity):** Let  $(r_n)_{n \in \mathbb{N}} \in \mathbb{R}_+^{\mathbb{N}}$  be a bounded sequence. Then

$$i_n = i_{\text{RS}}(\int_0^1 E_n^{(r_n)}(s) ds, r_n) + \mathcal{O}_n(1). \quad (15)$$

It immediately implies an upper bound:

**Proposition 3.1 (Upper bound):** The mutual info. verifies

$$\limsup_{n \rightarrow \infty} i_n \leq \inf_{r \geq 0} \sup_{E \in [0, \rho]} i_{\text{RS}}(E, r). \quad (16)$$

*Proof:* Choose a constant sequence  $r_n = r$ . Lemma 3.5 then implies  $\limsup_{n \rightarrow \infty} i_n \leq \sup_{E \in [0, \rho]} i_{\text{RS}}(E, r)$ . This is true for any  $r \geq 0$ , therefore the result. ■

The lower bound is a bit more involved. Details of similar computations can be found in [13, 19]

**Proposition 3.2 (Lower bound):** The mutual info. verifies

$$\liminf_{n \rightarrow \infty} i_n \geq \inf_{r \geq 0} \sup_{E \in [0, \rho]} i_{\text{RS}}(E, r). \quad (17)$$

*Proof:* Note that due to our hypothesis and its consequence (10), the function  $h : z \mapsto \mathcal{R}_{\mathbf{R}}(-z)$  is a  $\mathcal{C}^1$  function defined for all  $z \geq 0$ , and verifies *i*)  $h(0) = \mathcal{R}_{\mathbf{R}}(0)$  is finite; *ii*)  $h'(z) < 0$  for all  $z > 0$ ; and *iii*)  $h(z) > 0$  for all  $z > 0$ .

Define  $K \equiv \max(\rho, h(0))$ . Then the mapping  $r \in [0, K] \mapsto h(\int_0^1 E_n^{(r)}(t) dt) \in [0, K]$  is continuous by composition. It must thus admit a fixed point  $r_n^*$ . It thus only remains to show

$$i_{\text{RS}}(\int_0^1 E_n^{(r_n^*)}(t) dt, r_n^*) = \sup_{E \in [0, \rho]} i_{\text{RS}}(E, r_n^*). \quad (18)$$

This is true because at fixed  $r$ , the function  $g_r(E) \equiv i_{\text{RS}}(E, r)$  is strictly concave since  $g_r''(E) = h'(E)/2 < 0$ . The conclusion follows from the fact that the derivative can only vanish at the (achieved) maximum, and that  $g_{r_n^*}'(\int_0^1 E_n^{(r_n^*)}(t) dt) = 0$ ; indeed this is the fixed point equation  $r_n^* = h(\int_0^1 E_n^{(r_n^*)}(t) dt)$ .

Finally (15) yields  $i_n = \sup_{E \in [0, \rho]} i_{\text{RS}}(E, r_n^*) + \mathcal{o}_n(1) \geq \inf_{r \geq 0} \sup_{E \in [0, \rho]} i_{\text{RS}}(E, r) + \mathcal{o}_n(1)$ , and thus the result. ■

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## A. Nishimori identity

**Lemma A.1:** Let  $(X, Y)$  be a couple of random variables on a polish space  $E$ . For a given  $k \in \mathbb{N}^*$ , let  $(X^{(i)})_{i=1}^k$  be i.i.d random variables from the distribution (conditional over  $Y$ )  $P(X = \cdot | Y)$ . Denote  $\langle - \rangle$  the expectation with respect to this probability distribution, and  $\mathbb{E}$  the expectation with respect to the probability measure of  $(X, Y)$ . Then, for all  $f : E^{k+1} \rightarrow \mathbb{R}$  continuous and bounded

$$\mathbb{E}\langle f(Y, X^{(1)}, \dots, X^{(k)}) \rangle = \mathbb{E}\langle f(Y, X^{(1)}, \dots, X^{(k-1)}, X) \rangle.$$

*Proof:* This is a trivial consequence of Bayes formula:

$$\begin{aligned} \mathbb{E}_{X, Y}\langle f(Y, X^{(1)}, \dots, X^{(k-1)}, X) \rangle &= \mathbb{E}_Y \mathbb{E}_{X|Y}\langle f(Y, X^{(1)}, \dots, X^{(k-1)}, X) \rangle \\ &= \mathbb{E}\langle f(Y, X^{(1)}, \dots, X^{(k)}) \rangle. \end{aligned}$$

■

## B. Proof of Lemma 3.1

The proof is done in two steps. First, we show the following formula:

$$i'_n(t) = \frac{r}{2}(\rho - \mathbb{E}\langle Q \rangle_t) + \frac{1}{2n^2} \sum_{\mu=1}^m \sum_{\nu=1}^m \mathbb{E}\left\langle Z_\mu \langle \Phi' \Phi'^\top \rangle_{\mu\nu} u_{t,\nu} \left[ E(t) - \left( \frac{1}{n} \sum_{i=1}^n X_i^2 - Q \right) \right] \right\rangle_t. \quad (19)$$

We will then conclude using the concentration of  $\frac{1}{n} \sum_{i=1}^n X_i^2$  on  $\rho$  by the central limit theorem as  $n \rightarrow \infty$ .

Recall that we defined the Gibbs bracket

$$\langle A(\mathbf{x}, \mathbf{v}) \rangle_t = \frac{\int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\mathcal{H}(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi)} A(\mathbf{x}, \mathbf{v})}{\int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\mathcal{H}(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi)}}. \quad (20)$$

From this and the definition of  $i_n(t)$  (7), one gets

$$i'_n(t) = \frac{1}{n} \mathbb{E}[\mathcal{H}'(t, \mathbf{X}, \mathbf{V}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi) \ln \mathcal{Z}] + \frac{1}{n} \mathbb{E}\langle \mathcal{H}'(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi) \rangle_t, \quad (21)$$

where the partition function  $\mathcal{Z}$  and Hamiltonian derivatives read

$$\mathcal{H}'(t, \mathbf{X}, \mathbf{V}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi) = \frac{1}{2} \sum_{\mu=1}^m Z_\mu \left( \sqrt{\frac{1}{n(1-t)}} (\Phi \mathbf{X})_\mu - \frac{E(t)}{\sqrt{n\tilde{E}(t)}} (\Phi' \mathbf{V})_\mu \right) - \frac{1}{2} \sum_{i=1}^n \tilde{Z}_i \sqrt{\frac{r}{t}} X_i, \quad (22)$$

$$\mathcal{Z} = \mathcal{Z}(t, \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi) \equiv \int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\mathcal{H}(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi)}. \quad (23)$$

The Nishimori identity Lemma A.1 directly implies

$$\mathbb{E}\langle \mathcal{H}'(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi) \rangle_t = \mathbb{E}\mathcal{H}'(t, \mathbf{X}, \mathbf{V}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi) = 0. \quad (24)$$

We now compute  $\mathbb{E}[\tilde{Z}_i X_i \ln \mathcal{Z}]$ . Using a Gaussian integration by parts, which reads for any real function  $f$  with continuous derivative  $\mathbb{E}[\tilde{Z}_i f(\tilde{Z}_i)] = \mathbb{E}[f'(\tilde{Z}_i)]$  for  $\tilde{Z}_i \sim \mathcal{N}(0, 1)$ , we obtain the first term of (21) as

$$\begin{aligned} & - \frac{1}{2n} \sqrt{\frac{r}{t}} \sum_{i=1}^n \mathbb{E}\left[ X_i \tilde{Z}_i \ln \int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\mathcal{H}(t, \mathbf{x}, \mathbf{v}; \mathbf{Y}_t, \tilde{\mathbf{Y}}_t, \Phi)} \right] \\ &= - \frac{1}{2n} \sqrt{\frac{r}{t}} \sum_{i=1}^n \mathbb{E}\left[ X_i \tilde{Z}_i \ln \int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{\text{term}_1(\mathbf{v}, \mathbf{x}) - \frac{1}{2} \sum_i (\sqrt{tr}(X_i - x_i) + \tilde{Z}_i)^2} \right] \\ &= \frac{1}{2n} \sqrt{\frac{r}{t}} \sum_{i=1}^n \mathbb{E}\left[ X_i \langle \sqrt{tr}(X_i - x_i) + \tilde{Z}_i \rangle_t \right] \\ &= \frac{r\rho}{2} - \frac{r}{2} \mathbb{E}\left\langle \frac{1}{n} \sum_{i=1}^n X_i x_i \right\rangle_t \\ &= \frac{r}{2}(\rho - \mathbb{E}\langle Q \rangle_t). \end{aligned} \quad (25)$$

In the same way, an integration by parts with respect to  $V_i \sim \mathcal{N}(0, 1)$  yields

$$\begin{aligned}
& -\frac{1}{2n} \frac{E(t)}{\sqrt{n\tilde{E}(t)}} \sum_{\mu=1}^m \mathbb{E} \left[ Z_\mu (\Phi' \mathbf{V})_\mu \ln \mathcal{Z} \right] \\
&= -\frac{1}{2n} \frac{E(t)}{\sqrt{n\tilde{E}(t)}} \sum_{\mu=1}^m \sum_{i=1}^n \mathbb{E} \left[ Z_\mu \Phi'_{\mu i} V_i \ln \int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\frac{1}{2} \sum_\nu \left( \sqrt{\frac{1-t}{n}} (\Phi'(\mathbf{X}-\mathbf{x}))_\nu + \sqrt{\frac{\tilde{E}(t)}{n}} (\Phi'(\mathbf{V}-\mathbf{v}))_\nu + Z_\nu \right)^2 + \text{term}_2(\mathbf{x})} \right] \\
&= \frac{1}{2n^2} E(t) \sum_{\mu=1}^m \sum_{\nu=1}^m \sum_{i=1}^n \mathbb{E} \left[ Z_\mu \Phi'_{\mu i} \Phi'_{\nu i} \left\langle \sqrt{\frac{1-t}{n}} (\Phi'(\mathbf{X}-\mathbf{x}))_\nu + \sqrt{\frac{\tilde{E}(t)}{n}} (\Phi'(\mathbf{V}-\mathbf{v}))_\nu + Z_\nu \right\rangle_t \right] \\
&= \frac{1}{2n^2} E(t) \sum_{\mu=1}^m \sum_{\nu=1}^m \mathbb{E} \left[ Z_\mu (\Phi' \Phi'^\top)_{\mu\nu} \langle u_{t,\nu} \rangle_t \right]. \tag{26}
\end{aligned}$$

Let us now look at the final term we need to compute. By our hypothesis (4), this term reads, using again a Gaussian integration by part but this time with respect to  $W_{ji} \sim \mathcal{N}(0, 1/n)$ ,

$$\begin{aligned}
& \frac{1}{2n} \sqrt{\frac{1}{n(1-t)}} \sum_{\mu=1}^m \mathbb{E} \left[ Z_\mu (\Phi' \mathbf{W} \mathbf{X})_\mu \ln \mathcal{Z} \right] \\
&= \frac{1}{2n} \sqrt{\frac{1}{n(1-t)}} \sum_{\mu=1}^m \sum_{i,j=1}^n \mathbb{E} \left[ Z_\mu \Phi'_{\mu j} W_{ji} X_i \ln \int dP_0(\mathbf{x}) \mathcal{D}\mathbf{v} e^{-\frac{1}{2} \sum_\nu \left( \sqrt{\frac{1-t}{n}} (\Phi' \mathbf{W}(\mathbf{X}-\mathbf{x}))_\nu + \sqrt{\frac{\tilde{E}(t)}{n}} (\Phi'(\mathbf{V}-\mathbf{v}))_\nu + Z_\nu \right)^2 + \text{term}_2(\mathbf{x})} \right] \\
&= -\frac{1}{2n^3} \sum_{\mu,\nu=1}^m \sum_{i,j=1}^n \mathbb{E} \left[ Z_\mu \Phi'_{\mu j} \Phi'_{\nu j} X_i \left\langle (X_i - x_i) \left( \sqrt{\frac{1-t}{n}} (\Phi'(\mathbf{X}-\mathbf{x}))_\nu + \sqrt{\frac{\tilde{E}(t)}{n}} (\Phi'(\mathbf{V}-\mathbf{v}))_\nu + Z_\nu \right) \right\rangle_t \right] \\
&= -\frac{1}{2n^2} \sum_{\mu,\nu=1}^m \mathbb{E} \left[ Z_\mu (\Phi' \Phi'^\top)_{\mu\nu} \left\langle u_{t,\nu} \left( \frac{1}{n} \sum_{i=1}^n X_i^2 - \frac{1}{n} \sum_{i=1}^n X_i x_i \right) \right\rangle_t \right].
\end{aligned}$$

Combining all three terms leads to (19).

We now go to the last step. By adding and subtracting a term to (19) we reach

$$\begin{aligned}
i'_n(t) &= \frac{r}{2} (\rho - \mathbb{E}\langle Q \rangle_t) + \frac{1}{2n^2} \sum_{\mu=1}^m \sum_{\nu=1}^m \mathbb{E} \langle Z_\mu (\Phi' \Phi'^\top)_{\mu\nu} u_{t,\nu} [E(t) - (\rho - Q)] \rangle_t \\
&\quad + \frac{1}{2n^2} \sum_{\mu=1}^m \sum_{\nu=1}^m \mathbb{E} \langle Z_\mu (\Phi' \Phi'^\top)_{\mu\nu} u_{t,\nu} \left( \rho - \frac{1}{n} \sum_{i=1}^n X_i^2 \right) \rangle_t. \tag{27}
\end{aligned}$$

Using the Cauchy-Schwarz inequality we obtain that the last term can be bounded as

$$\frac{1}{n^2} \left| \mathbb{E} \left\langle \mathbf{Z}^\top (\Phi' \Phi'^\top) \mathbf{u}_t \left( \rho - \frac{1}{n} \sum_{i=1}^n X_i^2 \right) \right\rangle_t \right| \leq \left\{ \frac{1}{n^4} \mathbb{E} \left\langle \left( \mathbf{Z}^\top (\Phi' \Phi'^\top) \mathbf{u}_t \right)^2 \right\rangle_t \mathbb{E} \left[ \left( \rho - \frac{1}{n} \sum_{i=1}^n X_i^2 \right)^2 \right] \right\}^{1/2}. \tag{28}$$

As the  $X_i$  are independent the central limit theorem implies that  $\mathbb{E}[(\rho - \frac{1}{n} \sum_{i=1}^n X_i^2)^2] = \mathcal{O}(1/n)$ . Thus it remains to show that the multiplicative term in front is bounded:

$$\begin{aligned}
& \frac{1}{n^4} \mathbb{E} \langle \left( \mathbf{Z}^\top (\Phi' \Phi'^\top) \mathbf{u}_t \right)^2 \rangle_t \leq \frac{1}{n^4} \mathbb{E} \langle \|\mathbf{Z}\|^2 \|\mathbf{u}_t\|^2 \|\Phi' \Phi'^\top\|_{\mathbb{F}}^2 \rangle_t \\
& \leq \frac{1}{n^4} \sqrt{\mathbb{E} \langle \|\mathbf{Z}\|^4 \|\mathbf{u}_t\|^4 \rangle_t} \mathbb{E} [\|\Phi' \Phi'^\top\|_{\mathbb{F}}^4] \leq \frac{1}{n^4} \sqrt{\mathbb{E} [\|\mathbf{Z}\|^8] \mathbb{E} \langle \|\mathbf{u}_t\|^8 \rangle_t} \mathbb{E} [\|\Phi' \Phi'^\top\|_{\mathbb{F}}^4] = \mathcal{O}(1). \tag{29}
\end{aligned}$$

The last equality follows from the following observations. By construction of  $\Phi'$ ,  $\mathbb{E}[\|\Phi' \Phi'^\top\|_{\mathbb{F}}^4]^{1/2} = \mathcal{O}(n^2)$ . Moreover, as  $\mathbf{Z}$  is a  $m$ -dimensional Gaussian vector with i.i.d. components  $\mathbb{E}[\|\mathbf{Z}\|^8]^{1/4} = \mathcal{O}(n)$ . Finally, the Nishimori identity leads to  $\mathbb{E}[\langle \|\mathbf{u}_t\|^8 \rangle_t]^{1/4} = \mathcal{O}(n)$ . This claim is proven using a consequence the triangle inequality:

$$\forall \mathbf{x}, \mathbf{y} \in \mathbb{R}^n \quad \|\mathbf{x} + \mathbf{y}\|^8 \leq 2^7 (\|\mathbf{x}\|^8 + \|\mathbf{y}\|^8),$$

which is combined with the Nishimori identity:

$$\begin{aligned}\mathbb{E}[\langle \|\mathbf{u}_t\|^8 \rangle_t] &= \mathbb{E} \left\langle \left\| \sqrt{\frac{1-t}{n}} \Phi(\mathbf{X} - \mathbf{x}) + \sqrt{\frac{\tilde{E}(t)}{n}} \Phi'(\mathbf{V} - \mathbf{v}) + \mathbf{Z} \right\|^8 \right\rangle_t \\ &\leq 2^7 \mathbb{E}[\|\mathbf{Z}\|^8] + 2^{22} (1-t)^4 \mathbb{E} \left[ \left\| \frac{1}{\sqrt{n}} \Phi \mathbf{X} \right\|^8 \right] + 2^{22} \tilde{E}(t)^4 \mathbb{E} \left[ \left\| \frac{1}{\sqrt{n}} \Phi' \mathbf{V} \right\|^8 \right].\end{aligned}\quad (30)$$

One can now use that both  $\frac{1}{n} \Phi^\top \Phi$  and  $\frac{1}{n} \Phi'^\top \Phi'$  have almost surely bounded Euclidian (or Frobenius) norm when  $n \rightarrow \infty$ . This implies that there exists  $C > 0$  such that

$$\mathbb{E} \left[ \left\| \frac{1}{\sqrt{n}} \Phi \mathbf{X} \right\|^8 \right] \leq C \mathbb{E}[\|\mathbf{X}\|^8].$$

Moreover  $\mathbb{E}[\|\mathbf{X}\|^8] = \mathcal{O}(n^4)$  because we assumed the prior distribution  $P_0$  to be compactly supported. The same argument can be conducted for bounding  $\mathbb{E} \left[ \left\| \frac{1}{\sqrt{n}} \Phi' \mathbf{V} \right\|^8 \right]$  since  $\mathbb{E}[\|\mathbf{V}\|^8] = \mathcal{O}(n^4)$  as  $\mathbf{V}$  is a standard Gaussian vector.