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Abstract

In this paper we study the uniform tail-probability estimates of a regularized least-squares estimator for the linear regression model, by making use of the polynomial type large deviation inequality for the associated statistical random fields, which may not be locally asymptotically quadratic. Our results provide a measure of rate of consistency in variable selection in sparse estimation, which in particular enable us to verify various arguments requiring convergence of moments of estimator-dependent statistics, such as the expected maximum-likelihood for AIC-type and many other moment based model assessment procedure including the C_p-type.

Keywords Moment convergence · Regularized least-squares estimation · Large deviation inequality · Sparse estimation

1 Introduction

Assume that we have a sample $\{(X_i, Y_i)\}_{i=1}^n$, where $Y_i \in \mathbb{R}$ and $X_i = (X_{i,1}, \dots, X_{i,p}) \in \mathbb{R}^p$, obeying the linear regression model:

$$Y_i = \theta_0^\top X_i + \epsilon_i, \quad i = 1, \dots, n, \tag{1.1}$$

where θ_0 is a p-dimensional true value of parameter contained in the interior of a compact parameter space $\Theta \subset \mathbb{R}^p$ and $\epsilon_1, \epsilon_2, \dots$ represent noises. Through this paper, the number of variables p is fixed. Though not essential, we suppose that the covariate X is non-random; usually $X_1, \cdots, X_n$ are standardized from the beginning, but for brevity we omit the dependence of X_i and Y_i on n from the notation. In this paper we deal with the situation

$$\theta_0 = (z_0, \rho_0) = (z_{0,1}, \dots, z_{0,p_0}, \rho_{0,1}, \dots, \rho_{0,p_1}),$$

where $z_{0,k} = 0$ and $\rho_{0,l} \neq 0$ for any $k \in \{1, \dots, p_0\}$ and $l \in \{1, \dots, p_1\}$; divide the compact parameter space $\Theta = \Theta_0 \times \Theta_1 \subset \mathbb{R}^{p_0} \times \mathbb{R}^{p_1}$ such that $z_0 = 0 \in \Theta_0$ and $\rho_0 \in \Theta_1$. We can rewrite the linear regression model (1.1) to

$$Y_i = z_0^\top X_i^{(z)} + \rho_0^\top X_i^{(\rho)} + \epsilon_i, \quad i = 1, \dots, n, \tag{1.2}$$

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where $X_i^{(z)} := (X_{i,1}, \dots, X_{i,p_0})$ and $X_i^{(\rho)} := (X_{i,p_0+1}, \dots, X_{i,p_0+p_1})$, representing irrelevant and relevant covariate vectors, respectively. Then we define the regularized least-squares estimator (regularized-LSE) $\hat{\theta}_n = (\hat{z}_n, \hat{\rho}_n)$ as the minimizer of the contrast function

$$Z_n(\theta) = Z_n(z, \rho) := \sum_{i=1}^{n} (Y_i - z^\top X_i^{(z)} - \rho^\top X_i^{(\rho)})^2 + \sum_{j=1}^{p} \mathfrak{p}_n(\theta_j) \tag{1.3}$$

over Θ, where $\mathfrak{p}_n(\cdot)$ is a non-random non-negative function such that $\mathfrak{p}_n(0) = 0$. There is a huge literature on the sparse linear regression via regularization, where the estimator $\hat{z}_n$ of $z_0 = 0$ satisfies the *sparse consistency* $P(\hat{z}_n = 0) \to 1$ as $n \to \infty$, which implies that $R_n \hat{z}_n = o_p(1)$ for arbitrary $R_n \to \infty$, while $\sqrt{n}(\hat{\rho}_n - \rho_0)$ has a non-trivial asymptotic law; e.g. sparse-bridge (Radchenko [6]), the smoothly clipped absolute deviation (SCAD; Fan and Li [2]) and the seamless-L_0 regularization (Dicker et al. [1]). In Section 3, we will refer some asymptotic behaviors of these regularized estimators.

We will prove the moment convergence of the scaled estimator

$$\sqrt{n}(\hat{\theta}_n - \theta_0) = \big(\sqrt{n}\hat{z}_n, \sqrt{n}(\hat{\rho}_n - \rho_0)\big).$$

Let us mention some basic facts concerning the parametric M-estimation. Given a statistical model indexed by a finite-dimensional parameter $\theta \in \Theta \subset \mathbb{R}^p$, we typically estimate the true parameter value $\theta_0 \in \Theta$ by a minimum point $\hat{\theta}_n$ of an appropriate continuous contrast function $Z_n : \Theta \to \mathbb{R}$. In order to assess the asymptotic performance of $\hat{\theta}_n$ quantitatively, when $\sqrt{n}$-consistency is concerned, we look at the statistical random fields

$$\mathbb{M}_n(w; \theta_0) := Z_n\Big(\theta_0 + \frac{w}{\sqrt{n}}\Big) - Z_n(\theta_0), \tag{1.4}$$

where $w \in \mathbb{R}^p$. As is well-known, the weak convergence of $\mathbb{M}_n$ to some $\mathbb{M}_0$ over compact sets, the identifiability condition on $\mathbb{M}_0$, and the tightness of the scaled estimator $\hat{w}_n := \sqrt{n}(\hat{\theta}_n - \theta_0)$ make the "argmin" functional continuous for $\mathbb{M}_n$: $\hat{w}_n \in \operatorname{argmin} \mathbb{M}_n \xrightarrow{\mathcal{L}} \operatorname{argmin} \mathbb{M}_0$. See e.g., van der Vaart [11]. Further, when concerned with moments of $\hat{w}_n$-dependent statistics such as the mean square error, more than the weak convergence is required. Then the *polynomial type large deviation inequality (PLDI)* of Yoshida [12], which estimates the tail of $\mathcal{L}(\hat{w}_n)$ in such a way that

$$\sup_{r>0} \sup_{n>0} r^L P(|\hat{w}_n| \geq r) < \infty \tag{1.5}$$

for a given $L > 0$, plays an important role. When $\hat{w}_n \xrightarrow{\mathcal{L}} \hat{w}_0$ for a random variable $\hat{w}_0$, the moment convergence

$$E[|\hat{w}_n|^q] \to E[|\hat{w}_0|^q], \quad q > 0 \tag{1.6}$$

holds if there exists a $q' > q$ such that $\sup_{n>0} E[|\hat{w}_n|^{q'}] < \infty$. Assume that the PLDI (1.5) holds for some $L > q'$. Then we obtain

$$\sup_{n>0} E[|\hat{w}_n|^{q'}] = \sup_{n>0} \int_0^\infty P(|\hat{w}_n|^{q'} > s) ds < \infty.$$

As the results, the moment convergence (1.6) holds if we can ensure the PLDI (1.5) for some $L > q$.

The main purpose of this paper is to derive the moment convergence of $\hat{w}_n = (\sqrt{n}\hat{z}_n, \sqrt{n}(\hat{\rho}_n - \rho_0))$: if we have the weak convergence $\big(\sqrt{n}\hat{z}_n, \sqrt{n}(\hat{\rho}_n - \rho_0)\big) \xrightarrow{\mathcal{L}} (\hat{u}_0, \hat{v}_0)$ for some random vector $(\hat{u}_0, \hat{v}_0) =: \hat{w}_0$, then for every continuous $f : \mathbb{R}^p \to \mathbb{R}$ of at most polynomial growth we have

$$E[f(\hat{w}_n)] \to E[f(\hat{w}_0)], \tag{1.7}$$

through the PLDI (1.5): for any $L > 0$ there exists a constant $c_L > 0$ for which

$$\sup_{n>0} P(|\hat{w}_n| \geq r) < \frac{c_L}{r^L}, \quad r > 0. \tag{1.8}$$

Let us briefly remark the importance of convergence of moments: asymptotic behavior of expected values of statistics depending on estimators. The PLDI for statistical random fields associated with stochastic process have been studied and applied for example to the information criteria in model selection, the higher-order statistics, as well as the moment convergence for Gaussian quasi-likelihood and Bayes estimators of diffusion processes; see Uchida and Yoshida [9, 10], Sakamoto and Yoshida [8], Yoshida [12] and the references therein for details. See also Masuda [4] for the PLDI associated with the Gaussian quasi-likelihood estimation of a Lévy driven stochastic differential equation, as well as for more related references.

It has been known that the PLDI can be proved under modest conditions when $\mathbb{M}_n$ is smooth and well-integrable, and further admits a *partially locally asymptotically quadratic (PLAQ)* structure (see (1.9) below), which is satisfied for many situations. However in the regularized estimations, the key PLAQ structure may break down; it may happen that $r_n(w;\theta_0)$ diverges in probability. As a matter of fact, most of the existing sparse-estimation procedures belong to this type of asymptotics. Therefore, our results provide a theoretically deeper understanding on the recently highlighted sparse estimation.

This paper is organized as follows. In Section 2, we will derive the PLDI for the regularized-LSE of the linear regression model (1.2). We will look at the PLDI for the random fields only associated with the zero parameter z in Section 2.2. In Section 3, we will give some examples of the regularization term in the contrast function (1.3).

For convenience of reference, we end this section with stating Yoshida [12, Theorem 1, Theorem 3(a)], which will play an essential role in our study. We need to introduce some notation. Given a set $K \subset \Theta$, we denote the true value of parameter θ by $\theta_0 \in K$. Define the random function

$$\mathbb{Y}_n(\theta;\theta_0) := -\frac{1}{n}\big(Z_n(\theta) - Z_n(\theta_0)\big).$$

Also, let $\theta \mapsto \mathbb{Y}_0(\theta;\theta_0)$ be a random function. We consider the PLAQ representation of $\mathbb{M}_n$:

$$\mathbb{M}_n(w;\theta_0) = \Delta_n(\theta_0)[w] + \frac{1}{2}\Gamma_0(\theta_0)[w,w] + r_n(w;\theta_0) \tag{1.9}$$

for $w \in \{w \in \mathbb{R}^p : \theta_0 + w/\sqrt{n} \in \Theta\}$, where $\Delta_n(\theta_0) \in \mathbb{R}^p$, $\Gamma_0(\theta_0) \in \mathbb{R}^p \times \mathbb{R}^p$ and $r_n(w;\theta_0) \in \mathbb{R}$ are random variables[1]. Finally, let $\alpha \in (0,1)$, $U_n(r,\theta_0) := \{w \in \mathbb{R}^p : r \leq |w| \leq n^{(1-\alpha)/2}\}$. We now introduce some conditions.

[A1] $\exists \nu_1 > 0,\ \forall L > 0,\ \exists c_L > 0 : \text{constant},\ \forall r > 0,$

$$\sup_{\theta_0 \in K} \sup_{n>0} P\Big(\sup_{w \in U_n(r,\theta_0)} \frac{|r_n(w;\theta_0)|}{1+|w|^2} \geq r^{-\nu_1} \Big) \leq \frac{c_L}{r^L}.$$

[A2] $\Gamma_0(\theta_0)$ is deterministic and positive-definite uniformly in $\theta_0 \in K$.

[A3] $\exists \chi = \chi(\theta_0) > 0 :$ non-random, $\exists \nu = \nu(\theta_0) > 0,\ \forall \theta \in \Theta,$

$$\mathbb{Y}_0(\theta;\theta_0) \leq -\chi|\theta - \theta_0|^\nu.$$

[A4] $\alpha \in (0,1),\ \nu_1 \in (0,1),\ \alpha\nu < \nu_2,\ \beta \in [0,\infty),\ 1 - 2\beta - \nu_2 > 0.$

[A5] $\forall L > 0,\ N_1 := L(1-\nu_1)^{-1},\ N_2 := L(1-2\beta-\nu_2)^{-1},$

$$\sup_{\theta_0 \in K} \sup_{n>0} E\Big[|\Delta_n(\theta_0)|^{N_1}\Big] < \infty;$$

$$\sup_{\theta_0 \in K} \sup_{n>0} E\Big[\Big(\sup_{\theta \in \Theta} n^{1/2-\beta}\big|\mathbb{Y}_n(\theta;\theta_0) - \mathbb{Y}_0(\theta;\theta_0)\big|\Big)^{N_2}\Big] < \infty.$$

Theorem 1.1 (Yoshida [12], Theorems 1 and 3(a)) *Assume [A1]–[A5]. Then, the estimate* (1.8) *holds uniformly in* $\theta_0 \in K$.

2 Moment convergence

In this section we will deduce the PLDI for the regularized-LSE $\hat{\theta}_n = (\hat{z}_n, \hat{\rho}_n)$. In Section 2.1, we will derive the moment convergence of $\hat{w}_n$. Section 2.2 will discuss the partial PLDI for zero parameter z under different conditions, regarding the non-zero parameter ρ as a nuisance parameter.

2.1 Joint PLDI

In this section we discuss the moment convergence of $\hat{w}_n$ by checking the conditions of Theorem 1.1. In particular, if we have the weak convergence $\hat{w}_n \xrightarrow{\mathcal{L}} \hat{w}_0$ for some random vector $\hat{w}_0$, then the moment convergence (1.7) holds. Let $C_n := n^{-1}\sum_{i=1}^n X_i X_i^\top$.

Theorem 2.1 *Assume that the linear regression model is* (1.2) *and the contrast function is* (1.3). *Suppose the following conditions.*

$$\epsilon_1, \epsilon_2, \dots \ \textit{are i.i.d. with}\ E[\epsilon_i] = 0\ \textit{and}\ \forall k > 0,\ E[|\epsilon_i|^k] < \infty; \tag{2.1}$$

[1]The sign in front of the quadratic term $(1/2)\Gamma_0(\theta_0)[w,w]$ is different from the original PLAQ of Yoshida [12] since we consider minimization of (1.4).

$$\exists \delta > 0,\ \exists C_0 > 0,\ \sup_{n>0}\big(n^{\delta}|C_n - C_0|\big) < \infty; \tag{2.2}$$

$$\sup_{n>0}\sup_{i\le n}|X_i| < \infty; \tag{2.3}$$

$$\exists \beta \in \Big(0, \frac{1}{2}\Big),\ \forall a \in \mathbb{R},\ \sup_{n>0}\frac{\mathfrak{p}_n(a)}{n^{1/2+\beta}} < \infty; \tag{2.4}$$

$$\begin{aligned}&\exists \kappa \in (0,2),\ \forall a \neq 0,\ \exists c_a > 0 \text{ constant},\ \forall b \in \mathbb{R},\\ &\limsup_{n\to\infty}\Big|\mathfrak{p}_n\Big(a + \frac{b}{\sqrt{n}}\Big) - \mathfrak{p}_n(a)\Big| \le c_a|b|^{\kappa}.\end{aligned} \tag{2.5}$$

Then the PLDI (1.8) *holds. Additionally if we have the weak convergence $\hat{w}_n \xrightarrow{\mathcal{L}} \hat{w}_0$ for some random vector $\hat{w}_0$, then the moment convergence* (1.7) *holds.*

Proof We will check the conditions of Theorem 1.1 to conclude (1.8). Set $w = (u, v) \in \mathbb{R}^{p_0} \times \mathbb{R}^{p_1}$. We have the statistical random fields

$$\begin{aligned}\mathbb{M}_n(w;\theta_0) &= Z_n\Big(\theta_0 + \frac{w}{\sqrt{n}}\Big) - Z_n(\theta_0)\\ &= \sum_{i=1}^{n}\Big\{\Big(\epsilon_i - \frac{w^{\top}}{\sqrt{n}}X_i\Big)^2 - \epsilon_i^2\Big\} + \sum_{k=1}^{p_0}\mathfrak{p}_n\Big(\frac{u_k}{\sqrt{n}}\Big) + \sum_{l=1}^{p_1}\Big\{\mathfrak{p}_n\Big(\rho_{0l} + \frac{v_l}{\sqrt{n}}\Big) - \mathfrak{p}_n(\rho_{0l})\Big\}\\ &= -\sum_{i=1}^{n}\frac{2}{\sqrt{n}}\epsilon_i X_i[w] + \frac{1}{2}(2C_0)[w,w] + (C_n - C_0)[w,w] + \sum_{k=1}^{p_0}\mathfrak{p}_n\Big(\frac{u_k}{\sqrt{n}}\Big)\\ &\quad + \sum_{l=1}^{p_1}\Big\{\mathfrak{p}_n\Big(\rho_{0l} + \frac{v_l}{\sqrt{n}}\Big) - \mathfrak{p}_n(\rho_{0l})\Big\}.\end{aligned}$$

Since $\hat{w}_n$ is a minimum point of $\mathbb{M}_n(w;\theta_0)$ and $\mathfrak{p}_n$ is a non-negative function, we have

$$\begin{aligned}P(|\hat{w}_n| \ge r) &\le P\Big[\sup_{|w|\ge r}\big\{-\mathbb{M}_n(w;\theta_0)\big\} \ge -\mathbb{M}_n(0;\theta_0) = 0\Big]\\ &\le P\Big[\sup_{|w|\ge r}\Big\{\sum_{i=1}^{n}\frac{2}{\sqrt{n}}\epsilon_i X_i[w] - \frac{1}{2}(2C_0)[w,w] - (C_n - C_0)[w,w]\\ &\qquad - \sum_{l=1}^{p_1}\Big(\mathfrak{p}_n\Big(\rho_{0l} + \frac{v_l}{\sqrt{n}}\Big) - \mathfrak{p}_n(\rho_{0l})\Big)\Big\} \ge 0\Big].\end{aligned}$$

Hence, we will establish the PLDI

$$\begin{aligned}&\sup_{n>0}P\Big[\sup_{|w|\ge r}\Big\{\sum_{i=1}^{n}\frac{2}{\sqrt{n}}\epsilon_i X_i[w] - \frac{1}{2}(2C_0)[w,w] - (C_n - C_0)[w,w]\\ &\quad - \sum_{l=1}^{p_1}\Big(\mathfrak{p}_n\Big(\rho_{0l} + \frac{v_l}{\sqrt{n}}\Big) - \mathfrak{p}_n(\rho_{0l})\Big)\Big\} \ge 0\Big] \le \frac{c_L}{r^L}, \quad r > 0\end{aligned} \tag{2.6}$$

for any $L > 0$ to ensure the PLDI (1.8). We have the PLAQ structure with

$$\Delta_n(\theta_0) = \sum_{i=1}^{n} \frac{2}{\sqrt{n}} \epsilon_i X_i; \tag{2.7}$$

$$\Gamma_0(\theta_0) = 2C_0; \tag{2.8}$$

$$r_n(w;\theta_0) = -(C_n - C_0)[w,w] - \sum_{l=1}^{p_1} \Big\{ \mathfrak{p}_n\Big(\rho_{0l} + \frac{v_l}{\sqrt{n}}\Big) - \mathfrak{p}_n(\rho_{0l}) \Big\}. \tag{2.9}$$

According to (2.1)–(2.4), we obtain for any $\theta \in \Theta$

$$\begin{aligned}
\mathbb{Y}_n(\theta;\theta_0) &= -\frac{1}{n}\big(Z_n(\theta) - Z_n(\theta_0)\big) \\
&= -\frac{1}{n}\sum_{i=1}^{n} \Big[\big\{ \epsilon_i - (\theta-\theta_0)^\top X_i \big\}^2 - \epsilon_i^2 \Big] - \frac{1}{n}\sum_{j=1}^{p} \big\{ \mathfrak{p}_n(\theta_j) - \mathfrak{p}_n(\theta_{0j}) \big\} \\
&= \frac{2}{n}\sum_{i=1}^{n} \epsilon_i X_i[\theta-\theta_0] - C_n[\theta-\theta_0, \theta-\theta_0] - \frac{1}{n}\sum_{j=1}^{p} \big\{ \mathfrak{p}_n(\theta_j) - \mathfrak{p}_n(\theta_{0j}) \big\} \\
&\xrightarrow{P} -C_0[\theta-\theta_0, \theta-\theta_0] =: \mathbb{Y}_0(\theta;\theta_0).
\end{aligned}$$

We get $\mathbb{Y}_0(\theta;\theta_0) \le -\lambda_{\min}(C_0)|\theta-\theta_0|^2$ where $\lambda_{\min}(C_0)$ denotes the minimal eigen-value of the matrix C_0. Apparently [A2] holds from (2.2) and (2.8), and also [A3] holds with $\chi = \lambda_{\min}(C_0)$ and $\nu = 2$. Hence it remains to verify [A1], [A4] and [A5].

First, we will verify [A1]. From (2.9), we have

$$\frac{|r_n(w;\theta_0)|}{1+|w|^2} \le \frac{|w|^2}{1+|w|^2}|C_n - C_0| + \frac{1}{1+|w|^2}\Big| \sum_{l=1}^{p_1} \Big\{ \mathfrak{p}_n\Big(\rho_{0l} + \frac{v_l}{\sqrt{n}}\Big) - \mathfrak{p}_n(\rho_{0l}) \Big\} \Big|. \tag{2.10}$$

Let us fix β, ν_2, $\alpha \in (0,1)$ and ξ such that $0 \vee (1/2-\delta) \le \beta < 1/2$, $1-2\beta > \nu_2 > 2\alpha$ and $0 < \xi < \big(2\alpha/(1-\alpha)\big) \wedge 1$. Note that these parameters meet $\beta - 1/2 + (1-\alpha)\xi/2 < 0$. Then for the first term of the right-hand side of (2.10), we get from (2.2)

$$\begin{aligned}
&\sup_{w \in U_n(r,\theta_0)} \Big(\frac{|w|^2}{1+|w|^2}|C_n - C_0| \Big) \\
&= n^{1/2-\beta-\delta}\big(n^{\delta}|C_n - C_0|\big) \sup_{w \in U_n(r,\theta_0)} \Big(\frac{|w|^2}{1+|w|^2} n^{\beta-1/2}|w|^{\xi}|w|^{-\xi} \Big) \\
&\lesssim n^{\beta-1/2} n^{(1-\alpha)\xi/2} r^{-\xi} \lesssim r^{-\xi},
\end{aligned} \tag{2.11}$$

where $A_n \lesssim B_n$ means that $\sup_n (A_n/B_n) < \infty$. Next we will estimate the second term of the right-hand side of (2.10). We obtain from (2.5) that there exists a $\kappa \in (0,2)$ such that

$$\frac{1}{1+|w|^2}\Big| \sum_{l=1}^{p_1} \Big\{ \mathfrak{p}_n\Big(\rho_{0l} + \frac{v_l}{\sqrt{n}}\Big) - \mathfrak{p}_n(\rho_{0l}) \Big\} \Big| \lesssim \frac{|v|^{\kappa}}{1+|w|^2} \lesssim |w|^{\kappa-2}, \quad w \in U_n(r,\theta_0);$$

note that $\sup_{w\in U_n(r,\theta_0)}|v_l|/\sqrt{n}\to 0$. Since we can take $\alpha\in(0,1)$ such that $2-\kappa>\xi$ $\big($note that $0<\xi<\big(2\alpha/(1-\alpha)\big)\wedge 1\big)$, we get

$$\sup_{w\in U_n(r,\theta_0)}|w|^{\kappa-2}\lesssim r^{-\xi}. \tag{2.12}$$

Fix a $\nu_1\in(0,\xi)$. Then from (2.10)–(2.12), we have for any $L>0$

$$\sup_{n>0}P\Big(\sup_{w\in U_n(r,\theta_0)}\frac{|r_n(w;\theta_0)|}{1+|w|^2}\gtrsim r^{-\nu_1}\Big)\lesssim\frac{1}{r^L}.$$

This means that [A1] holds, and [A4] also holds with taking the parameters as above.

Second, we will verify [A5]. From (2.7), we define $\Delta_n(\theta_0)=\sum_{i=1}^n(2/\sqrt{n})\epsilon_iX_i=:\sum_{i=1}^n\chi_{ni}$. Then by using Burkholder's inequality and Jensen's inequality we obtain for $N_1=L(1-\nu_1)^{-1}\geq 2$

$$\begin{aligned}\sup_{n>0}E\Big[\big|\Delta_n(\theta_0)\big|^{N_1}\Big]&\leq\sup_{n>0}E\Big[\max_{j\leq n}\Big|\sum_{i=1}^j\chi_{ni}\Big|^{N_1}\Big]\\&\lesssim\sup_{n>0}E\Big[\Big(\sum_{i=1}^n\chi_{ni}^2\Big)^{N_1/2}\Big]\\&\lesssim\sup_{n>0}E\Big[\frac{1}{n}\sum_{i=1}^n\big|\epsilon_iX_i\big|^{2\cdot N_1/2}\Big]\\&\lesssim E\big[|\epsilon_1|^{N_1}\big]\cdot\sup_{n>0}\Big(\frac{1}{n}\sum_{i=1}^n|X_i|^{N_1}\Big)<\infty.\end{aligned}\tag{2.13}$$

The last boundedness of (2.13) follows from (2.1) and (2.3). Moreover, we get for any $\theta\in\Theta$

$$\sum_{i=1}^n\frac{2}{n}\epsilon_iX_i[\theta-\theta_0]-C_n[\theta-\theta_0,\theta-\theta_0]\xrightarrow{P}-C_0[\theta-\theta_0,\theta-\theta_0];$$
$$\frac{1}{n}\sum_{j=1}^p\big\{\mathfrak{p}_n(\theta_j)-\mathfrak{p}_n(\theta_{0j})\big\}\xrightarrow{P}0.$$

Since $(a+b)^{N_2}\lesssim a^{N_2}+b^{N_2}$ for any $a,b\geq 0$ and $N_2=L(1-2\beta-\nu_2)^{-1}\geq 2$, we have

$$\begin{aligned}&\sup_{n>0}E\Big[\sup_{\theta\in\Theta}\Big(n^{1/2-\beta}\Big|\sum_{i=1}^n\frac{2}{n}\epsilon_iX_i[\theta-\theta_0]-C_n[\theta-\theta_0,\theta-\theta_0]+C_0[\theta-\theta_0,\theta-\theta_0]\Big|\Big)^{N_2}\Big]\\&\lesssim\sup_{n>0}\Big(n^{-\beta N_2}E\Big[\Big|\sum_{i=1}^n\frac{1}{\sqrt{n}}\epsilon_iX_i\Big|^{N_2}\Big]\Big)+\Big\{\sup_{n>0}\big(n^{1/2-\beta-\delta}n^{\delta}|C_n-C_0|\big)\Big\}^{N_2}<\infty.\end{aligned}\tag{2.14}$$

Note that the parameter space Θ is a compact set. Further, we obtain

$$\sup_{n>0}\sup_{\theta\in\Theta}\Big[n^{1/2-\beta}\Big|\frac{1}{n}\sum_{j=1}^p\big\{\mathfrak{p}_n(\theta_j)-\mathfrak{p}_n(\theta_{0j})\big\}\Big|\Big]^{N_2}<\infty \tag{2.15}$$

since we have (2.4). From (2.13)–(2.15), we conclude that [A5] holds. Therefore the proof of (1.8) is complete because we established the PLDI (2.6). The latter claim of the theorem is trivial. □

Remark 2.2 We could deal with random design (X_i). Assume for simplicity that (X_i) and (ϵ_j) are independent. Then in order to conclude (1.8), we need to change (2.2) and (2.3) into (2.16) and (2.17), respectively:

$$\exists\delta > 0,\ \exists C_0 > 0 : \text{constant},\ \forall k > 0,\ \sup_{n>0} E\big[\big|n^\delta (C_n - C_0)\big|^k\big] < \infty. \tag{2.16}$$

$$\forall k > 0,\ \sup_{n>0}\sup_{i\leq n} E\big[|X_i|^k\big] < \infty. \tag{2.17}$$

The corresponding proofs are entirely analogous to the case of deterministic X. □

Remark 2.3 Although we have additionally imposed (2.2) (or (2.16) when X is random), they are automatically satisfied as soon as we may standardize the covariates X_i beforehand: just use $\widetilde{X}_i := C_n^{-1/2} X_i$ instead of the original X_i, so that

$$\frac{1}{n}\sum_{i=1}^n \widetilde{X}_i \widetilde{X}_i^\top \equiv I_p \quad (p \times p\text{-identity matrix}).$$

Then (2.2) and (2.16) hold with $C_0 = I_p$. □

2.2 Partial PLDI derivation under different design condition

In this section, we will show that under different set of conditions it is possible to deduce a PLDI for the random fields only associated with the zero parameter z, regarding the non-zero parameter ρ as a nuisance parameter (hence we derived a uniform-in-ρ PLDI) and by utilizing the special nature of the least-squares term. We do not require any information of asymptotic behavior of $n^{-1}\sum_{i=1}^n X_i^{(\rho)} X_i^{(\rho)\top}$, which is the $p_1 \times p_1$ submatrix located in the bottom right corner of C_n, but instead we do a kind of orthogonality between $(X_i^{(z)})$ and $(X_i^{(\rho)})$.

Theorem 2.4 *Assume that the linear regression model is* (1.2) *and the contrast function is* (1.3)*. In addition to* (2.1) *and* (2.3)*, we suppose that*

$$\exists D_0 > 0,\ D_n \to D_0, \tag{2.18}$$

where D_n is the $p_0 \times p_0$ submatrix located in the upper left corner of the matrix C_n. Moreover, we suppose that there exist a positive real sequence (q_n) and a positive function $f(r) \to \infty$ as $r \to \infty$, such that

$$\sup_{n>0}\Big|\frac{1}{\sqrt{nq_n}}\sum_{i=1}^n \big(X_i^{(z)} \otimes X_i^{(\rho)}\big)\Big| < \infty; \tag{2.19}$$

$$\inf_{|u|\ge r}\sum_{k=1}^{p_0}\mathfrak{p}_n\Big(\frac{u_k}{\sqrt{n}}\Big)\ge q_n f(r). \tag{2.20}$$

Then for any $L>0$ there exists a constant $c_L>0$ for which

$$\sup_{n>0}P\big(|\sqrt{n}\hat{z}_n|\ge r\big)\le\frac{c_L}{f(r)^L},\quad r>0. \tag{2.21}$$

Proof We have for $u\in\mathbb{R}^{p_0}$

$$\begin{aligned}
&\mathbb{M}_n(u,\rho;\theta_0)\\
&=Z_n\Big(\frac{u}{\sqrt{n}},\rho\Big)-Z_n(0,\rho)\\
&=\sum_{i=1}^n\Big[\Big\{\epsilon_i-\frac{u^\top}{\sqrt{n}}X_i^{(z)}-(\rho-\rho_0)^\top X_i^{(\rho)}\Big\}^2-\big\{\epsilon_i-(\rho-\rho_0)^\top X_i^{(\rho)}\big\}^2\Big]+\sum_{k=1}^{p_0}\mathfrak{p}_n\Big(\frac{u_k}{\sqrt{n}}\Big)\\
&=-\sum_{i=1}^n\frac{2}{\sqrt{n}}\big\{\epsilon_i-(\rho-\rho_0)^\top X_i^{(\rho)}\big\}X_i^{(z)}[u]+D_n[u,u]+\sum_{k=1}^{p_0}\mathfrak{p}_n\Big(\frac{u_k}{\sqrt{n}}\Big).
\end{aligned}$$

In the present case, we can directly estimate of the tail probability by making use of the special nature of the least-squares term. Let

$$S_n^\rho:=\sum_{i=1}^n\frac{2}{\sqrt{n}}\big\{\epsilon_i-(\rho-\rho_0)^\top X_i^{(\rho)}\big\}X_i^{(z)}.$$

Since $Z_n(z,\rho)\ge Z_n(\hat{z}_n,\hat{\rho}_n)$ for any $(z,\rho)\in\Theta_0\times\Theta_1$, $Z_n(0,\hat{\rho}_n)-Z_n(\hat{z}_n,\hat{\rho}_n)\ge 0$ implies that $\sup_{\rho\in\Theta_1}(1/q_n)\big\{Z_n(0,\rho)-Z_n(\hat{z}_n,\rho)\big\}\ge 0$. Hence we get

$$\begin{aligned}
P\big(|\sqrt{n}\hat{z}_n|\ge r\big)&\le P\Big[\sup_{\rho\in\Theta_1}\sup_{|u|\ge r}\Big\{-\frac{1}{q_n}\mathbb{M}_n(u,\rho;\theta_0)\Big\}\ge 0\Big]\\
&\le P\Big\{\sup_{\rho\in\Theta_1}\sup_{|u|\ge r}\Big(\frac{S_n^\rho}{q_n}[u]-\frac{D_n}{q_n}[u,u]\Big)\ge\frac{1}{q_n}\inf_{|u|\ge r}\sum_{k=1}^{p_0}\mathfrak{p}_n\Big(\frac{u_k}{\sqrt{n}}\Big)\Big\}\\
&\lesssim P\Big\{\sup_{\rho\in\Theta_1}\Big|\frac{1}{\sqrt{q_n}}S_n^\rho\Big|^2\ge\frac{1}{q_n}\inf_{|u|\ge r}\sum_{k=1}^{p_0}\mathfrak{p}_n\Big(\frac{u_k}{\sqrt{n}}\Big)\Big\}
\end{aligned}$$

because we have (2.18) and the quadratic function $S_n^\rho/q_n[u]-D_n/q_n[u,u]$ has the maximum value $(1/4q_n)S_n^{\rho\top}D_n^{-1}S_n^\rho\lesssim|q_n^{-1/2}S_n^\rho|^2$. Therefore, according to (2.19) and (2.20), Markov's inequality and the same argument as (2.13) give us

$$\begin{aligned}
P\big(|\sqrt{n}\hat{z}_n|\ge r\big)&\lesssim P\Big(\sup_{\rho\in\Theta_1}\Big|\frac{1}{\sqrt{q_n}}S_n^\rho\Big|^2\gtrsim f(r)\Big)\\
&\lesssim f(r)^{-L}\Big\{\Big|\sum_{i=1}^n\frac{1}{\sqrt{nq_n}}\big(X_i^{(z)}\otimes X_i^{(\rho)}\big)\Big|^{2L}+q_n^{-L}E\Big[\Big|\sum_{i=1}^n\frac{1}{\sqrt{n}}\epsilon_iX_i^{(z)}\Big|^{2L}\Big]\Big\}\\
&\lesssim f(r)^{-L}.
\end{aligned}$$

Hence we get the PLDI (2.21). □

Remark 2.5 As was mentioned in Remark 2.3, the condition (2.19) is automatic and is not real restrictions if $X_i, \dots, X_n$ are standardized so that $C_n = I_p$ from the beginning. Then (2.19) is never a real restriction. □

Remark 2.6 We could drive the PLDI for the random fields only associated with the non-zero parameter ρ, regarding the zero parameter z as a nuisance parameter (hence we derived a uniform-in-z PLDI); in this case, we do not impose any condition on the asymptotic behavior of $D_n = n^{-1}\sum_{i=1}^n X_i^{(z)} X_i^{(z)\top}$. This can be proved by making use of the argument of Yoshida [12] under the conditions including (2.4), (2.5) and the condition stronger than (2.19):

$$\sup_{n>0}\left|\frac{1}{\sqrt{n}}\sum_{i=1}^n (X_i^{(z)} \otimes X_i^{(\rho)})\right| < \infty.$$

□

3 Examples

We will give some examples of the regularization term in (1.3) satisfying the conditions (2.4) and (2.5) in Theorem 2.1: sparse-bridge (Radchenko [6]), the smoothly clipped absolute deviation (SCAD; Fan and Li [2]) and the seamless-L_0 regularization (Dicker et al. [1]). From the previous studies, it is known that these regularized estimators $\hat{\theta}_n = (\hat{z}_n, \hat{\rho}_n)$ have the sparse consistency $P(\hat{z}_n = 0) \to 1$, which concludes the sparse estimation, and the asymptotic laws of $\sqrt{n}(\hat{\rho}_n - \rho_0)$ under some appropriate regularity conditions. Also when the number of variables $p = p_n \to \infty$ as $n \to \infty$, the asymptotic behavior of the SCAD and the seamless-L_0 estimators are known, but once again, note that we consider the case that p is fixed.

3.1 Sparse-bridge

In this section we will focus on the sparse-bridge LSE defined the contrast function to be

$$Z_n(\theta) = Z_n(z, \rho) := \sum_{i=1}^n (Y_i - z^\top X_i^{(z)} - \rho^\top X_i^{(\rho)})^2 + \lambda_n \sum_{j=1}^p |\theta_j|^\gamma, \tag{3.1}$$

where $\lambda_n \geq 0$ denotes the tuning parameter controlling the degree of regularization together with the bridge index $\gamma \in (0, 1)$. This means $\mathfrak{p}_n(\cdot) = \lambda_n |\cdot|^\gamma$. Denote by $\hat{\theta}_n = (\hat{z}_n, \hat{\rho}_n)$ a minimizer of Z_n over a compact parameter space $\Theta = \Theta_0 \times \Theta_1 \subset \mathbb{R}^{p_0} \times \mathbb{R}^{p_1}$. The asymptotic behavior of $\hat{\theta}_n$ is studied by Radchenko [6]. They assumed regularity conditions including that the noises $\epsilon_1, \epsilon_2, \dots$ are i.i.d. with $E[\epsilon_i] = 0$ and $E[\epsilon_i^2] =: \sigma^2 > 0$, $C_n \to C_0$ for some $C_0 > 0$ and that $n^{-1}\max_{i \leq n} |X_i|^2 \to 0$. Note that these conditions are satisfied with (2.1)–(2.3). Then they proved the following results:

- The sparse consistency of $\hat{z}_n$:

$$P(\hat{z}_n = 0) \to 1 \text{ if } \lambda_n / n^{\gamma/2} \to \infty \text{ and } \lambda_n / n \to 0.$$

- The asymptotic laws of $\hat{\rho}_n$:

(i) $\sqrt{n}(\hat{\rho}_n - \rho_0) \xrightarrow{\mathcal{L}} N_{p_1}(-\lambda_0 B_0^{-1}\Upsilon, \sigma^2 B_0^{-1})$ if $\lambda_n/n^{\gamma/2} \to \infty$ and $\lambda_n/\sqrt{n} \to \lambda_0 \geq 0$;

(ii) $n\lambda_n^{-1}(\hat{\rho}_n - \rho_0) \xrightarrow{\mathcal{L}} -B_0^{-1}\Upsilon$ if $\lambda_n/\sqrt{n} \to \infty$ and $\lambda_n/n \to 0$,

where

$$\Upsilon := \frac{\gamma}{2}\{\mathrm{sgn}(\rho_{0,1})|\rho_{0,1}|^{\gamma-1}, \dots, \mathrm{sgn}(\rho_{0,p_1})|\rho_{0,p_1}|^{\gamma-1}\}$$

and B_0 is the $p_1 \times p_1$ submatrix located in the bottom right corner of the matrix C_0. We are concerned here with the moment convergence of $\hat{w}_n$. With regard to the asymptotic law of the non-zero parameter ρ, we only consider the case (i), where the asymptotic distribution is non-degenerate. The following Corollary 3.1 is derived from Theorem 2.1.

Corollary 3.1 *Assume that the linear regression model is* (1.2) *and the contrast function is* (3.1)*, where* $\gamma \in (0,1)$*,* $\lambda_n/n^{\gamma/2} \to \infty$ *and* $\lambda_n/\sqrt{n} \to \lambda_0 \geq 0$*. Suppose that* (2.1)–(2.3)*. Then the PLDI* (1.8) *holds. In particular, the moment convergence* (1.7) *holds with* $\hat{w}_0 = (0, \hat{v}_0)$*, where* $\mathcal{L}(\hat{v}_0) = N_{p_1}(-\lambda_0 B_0^{-1}\Upsilon, \sigma^2 B_0^{-1})$*.*

Proof Apparently, we only need to check the conditions (2.4) and (2.5) in Theorem 2.1 for $\mathfrak{p}_n(\cdot) = \lambda_n|\cdot|^\gamma$. (2.4) follows easily since for any $a \in \mathbb{R}$, we have

$$\frac{\mathfrak{p}_n(a)}{\sqrt{n}} = \frac{\lambda_n}{\sqrt{n}}|a|^\gamma \lesssim 1$$

from $\lambda_n/\sqrt{n} \to \lambda_0 \geq 0$. We will show (2.5). When n is large enough, we have for any $a \neq 0$ and $b \in \mathbb{R}$

$$\begin{aligned}\left|\mathfrak{p}_n\left(a + \frac{b}{\sqrt{n}}\right) - \mathfrak{p}_n(a)\right| &= \lambda_n\left||a + \frac{b}{\sqrt{n}}|^\gamma - |a|^\gamma\right| \\ &\lesssim \frac{\lambda_n}{\sqrt{n}}|b| \lesssim |b|.\end{aligned}$$

This shows that (2.5) holds for $\kappa = 1$, hence we obtain the PLDI (1.8). The latter claim is trivial since we have $(\sqrt{n}\hat{z}_n, \sqrt{n}(\hat{\rho}_n - \rho_0)) \xrightarrow{\mathcal{L}} (0, \hat{v}_0)$, where $\mathcal{L}(\hat{v}_0) = N_{p_1}(-\lambda_0 B_0^{-1}\Upsilon, \sigma^2 B_0^{-1})$. □

In Section 2.2 we considered the PLDI for the random fields only associated with the zero parameter z. In the following Corollary 3.2, we derive this partial PLDI for the sparse-bridge LSE. It is a direct corollary of Theorem 2.4, so we omit the proof.

Corollary 3.2 *Assume that the linear regression model is* (1.2) *and the contrast function is* (3.1)*, where* $\gamma \in (0,1)$*,* $\lambda_n/n^{\gamma/2} \to \infty$ *and* $\lambda_n/n \to 0$*. Suppose that* (2.1)*,* (2.3)*,* (2.18) *and*

$$\sup_{n>0}\left|\left(\lambda_n/n^{\gamma/2}\right)^{-1/2} n^{-1/2}\sum_{i=1}^{n}\left(X_i^{(z)} \otimes X_i^{(\rho)}\right)\right| < \infty.$$

Then the PLDI (2.21) *holds with* $f(r) = r^\gamma$*.*

Remark 3.3 Here, we briefly mention the case of the bridge-LSE $\hat{\theta}_n$ defined as the minimal point of the contrast function

$$Z_n(\theta) := \sum_{i=1}^{n} (Y_i - \theta^\top X_i)^2 + \lambda_n \sum_{j=1}^{p} |\theta_j|^\gamma, \tag{3.2}$$

where $\lambda_n \geq 0$ and $\gamma > 0$ satisfy that $\lambda_n / n^{(1\wedge\gamma)/2} \to \lambda_0 \geq 0$; then, we do not have the sparse consistency. Note that, different from (3.1), in (3.2) we do not divide the true value of parameter θ_0 into the zero part and the non-zero part: jointly estimate all the components. We assume (2.1)–(2.3). Then Knight and Fu [3] proved the following asymptotic behavior of $\hat{\theta}_n$.

- Consistency:

$$\hat{\theta}_n \xrightarrow{P} \theta_0 \text{ if } \lambda_n / n \to 0.$$

- Asymptotic laws:

$$\sqrt{n}(\hat{\theta}_n - \theta_0) \xrightarrow{\mathcal{L}} \operatorname{argmin}(V_0) \text{ if } \lambda_n / n^{(1\wedge\gamma)/2} \to \lambda_0 \geq 0,$$

where for $W \sim N_p(0, \sigma^2 C_0)$,

$$V_0(w) := \begin{cases} -2W[w] + C_0[w,w] + \gamma\lambda_0 \sum_{j=1}^{p} w_j \operatorname{sgn}(\theta_{0j}) |\theta_{0j}|^{\gamma-1} & (\gamma > 1), \\ -2W[w] + C_0[w,w] & \\ \quad +\lambda_0 \sum_{j=1}^{p} \{ w_j \operatorname{sgn}(\theta_{0j}) I(\theta_{0j} \neq 0) + |w_j| I(\theta_{0j} = 0) \} & (\gamma = 1), \\ -2W[w] + C_0[w,w] + \lambda_0 \sum_{j=1}^{p} |w_j|^\gamma I(\theta_{0j} = 0) & (\gamma < 1). \end{cases}$$

Let $\hat{w}_0 = \operatorname{argmin}(V_0)$. We can derive the PLDI for the bridge-LSE by making use of the argument similar to the proof of Theorem 2.1: for any $L > 0$ there exists a constant $c_L > 0$ for which $\sup_{n>0} P(|\hat{w}_n| \geq r) \leq c_L r^{-L}$ $(r > 0)$. In particular, for every continuous $f : \mathbb{R}^p \to \mathbb{R}$ of at most polynomial growth, $E[f(\hat{w}_n)] \to E[f(\hat{w}_0)]$. See Masuda and Shimizu [5, Section 2] for details. □

Remark 3.4 As noted by Knight and Fu [3], the bridge-LSE $\hat{\theta}_n$ is inconsistent when $\lambda_n / n \to \exists\lambda_0 > 0$, and instead tends in probability to

$$\theta_0' := \operatorname*{argmin}_{\theta\in\Theta} \left\{ (\theta - \theta_0)^\top C_0 (\theta - \theta_0) + \lambda_0 \sum_{j=1}^{p} |\theta_j|^\gamma \right\}.$$

Even in this case it is possible to derive the sparse consistency and the associated PLDI for the quasi-zero parameters (whenever exist): specifically, assuming that $\theta_0' = (z_0', \rho_0') = (0, \rho_0') \in \Theta_0' \times \Theta_1' \subset \mathbb{R}^{p_0'} \times \mathbb{R}^{p_1'}$, we could prove the convergence $P(\hat{z}_n' = 0) \to 1$ and the PLDI for $\sqrt{n}\hat{z}_n'$, where $\hat{z}_n'$ denotes the bridge-LSE of z_0', by making use of the same argument as in the proof of Theorem 2.4 and Radchenko [7, Theorem 2]. See Masuda and Shimizu [5, Section 4] for details. □

3.2 SCAD

For simplicity, in this section we assume that the covariates X_i are standardized such that $C_n = I_p$. The SCAD-LSE (Fan and Li [2]) is defined as the minimum point of the contrast function (1.3), where

$$\mathfrak{p}_n(\theta_j) = \begin{cases} n\lambda_n|\theta_j| & (|\theta_j| \le \lambda_n), \\ \dfrac{-n(\theta_j^2 - 2\tau\lambda_n|\theta_j| + \lambda_n^2)}{2(\tau-1)} & (\lambda_n < |\theta_j| \le \tau\lambda_n), \\ \dfrac{n(\tau+1)\lambda_n^2}{2} & (|\theta_j| > \tau\lambda_n). \end{cases}$$

$\tau > 2$ is an additional tuning parameter. Let the minimizer be $\hat{\theta}_n = (\hat{z}_n, \hat{\rho}_n)$ and (2.1) hold. Moreover, Fan and Li [2] assumed that the tuning parameter λ_n satisfied

$$\lambda_n \to 0, \ \sqrt{n}\lambda_n \to \infty. \tag{3.3}$$

Then they proved the sparse consistency and the asymptotic law of ρ_n:

$$\sqrt{n}(\hat{\rho}_n - \rho_0) \xrightarrow{\mathcal{L}} N_{p_1}(0, \mathcal{I}_{p_1}(\rho_0)^{-1}),$$

where $\mathcal{I}_{p_1}(\rho_0) = \mathcal{I}_{p_1}(0, \rho_0)$ denotes the $p_1 \times p_1$ Fisher information matrix knowing $z_0 = 0$.

Let us take $\lambda_n \sim n^{\beta-1/2}$, where β is the same as in the proof of Theorem 2.1. This meets (3.3). Now, we will show (2.4) and (2.5). First we establish (2.4). Obviously, we only need to consider the case $\lambda_n < |\theta_j| \le \tau\lambda_n$. When n is large enough, we have $n\theta_j^2/n^{\beta+1/2} \lesssim n\lambda_n^2/n^{\beta+1/2} \sim n^{1+2\beta-1-\beta-1/2} = n^{\beta-1/2} \lesssim 1$, hence (2.4) holds. In order to ensure (2.5), we use

$$\mathfrak{p}_n'(\theta_j) = \lambda_n n\Big\{I(\theta_j \le \lambda_n) + \frac{(\tau\lambda_n - \theta_j)_+}{(\tau-1)\lambda_n} I(\theta_j > \lambda_n)\Big\}, \quad \theta_j > 0.$$

When n is large enough, for any $a > 0$ and $b \in \mathbb{R}$

$$\begin{aligned} \Big|\mathfrak{p}_n\Big(a + \frac{b}{\sqrt{n}}\Big) - \mathfrak{p}_n(a)\Big| &\le \frac{|b|}{\sqrt{n}} \int_0^1 \Big|\mathfrak{p}_n'\Big(a + \frac{b}{\sqrt{n}}t\Big)\Big| dt \\ &\sim \lambda_n\sqrt{n}|b| \int_0^1 I\Big(a + \frac{b}{\sqrt{n}}t \le \lambda_n\Big) dt \\ &\quad + \sqrt{n}|b| \int_0^1 \frac{[\tau\lambda_n - \{a + (b/\sqrt{n})t\}]_+}{\tau - 1} I\Big(a + \frac{b}{\sqrt{n}}t > \lambda_n\Big) dt \\ &\lesssim |b|. \end{aligned}$$

Similarly, we get the same estimate for $a < 0$. As the results, it is possible to take λ_n ensuring (1.7), where $\hat{w}_0 = (0, \hat{v}_0)$ and $\mathcal{L}(\hat{v}_0) = N_{p_1}(0, \mathcal{I}_{p_1}(\rho_0)^{-1})$.

3.3 seamless-L_0

The seamless-L_0 regularization (Dicker et al. [1]), which approximates the (technically unpleasant due to its discontinuity at the origin) L_0-loss, is given by

$$Z_n(\theta) = Z_n(z, \rho) := \sum_{i=1}^n (Y_i - z^\top X_i^{(z)} - \rho^\top X_i^{(\rho)})^2 + \frac{2n\lambda_n}{\log 2} \sum_{j=1}^p \log\Big(\frac{|\theta_j|}{|\theta_j| + \tau_n} + 1\Big),$$

where $\tau_n > 0$ is an additional tuning parameter. Let the minimizer be $\hat{\theta}_n = (\hat{z}_n, \hat{\rho}_n)$ and (2.1)–(2.3) hold. Moreover, Dicker et al. [1] assumed that the tuning parameters satisfied

$$\lambda_n = O(1),\ \lambda_n\sqrt{n} \to \infty,\ \tau_n = O(n^{-3/2}). \tag{3.4}$$

Then they proved the sparse consistency and the asymptotic law of $\hat{\rho}_n$:

$$\sqrt{n}(\hat{\rho}_n - \rho_0) \xrightarrow{\mathcal{L}} N_{p_1}(0, \sigma^2 B_0^{-1}),$$

where B_0 is the same as in Section 3.1.

Let us take $\lambda_n \sim n^{\beta-1/2}$ and $\tau_n \sim n^{-3/2}$, where β is the same as in the proof of Theorem 2.1. This meets (3.4). Now, we will show (2.4) and (2.5) for $\mathfrak{p}_n(\cdot) = (2n\lambda_n/\log 2)\log\{|\cdot|/(|\cdot|+\tau_n)+1\}$. (2.4) follows easily since $\mathfrak{p}_n/n^{1/2+\beta} \lesssim n^{1+\beta-1/2-1/2-\beta} = 1$. In order to ensure (2.5), we make use of the equation

$$|\log(1+x) - \log(1+x')| = \left|\int_0^1 \frac{ds}{1+x'+(x-x')s}(x-x')\right|$$

where $x, x' > 0$. When n is large enough, for any $a > 0$ and $b \in \mathbb{R}$

$$\begin{aligned}
\left|\mathfrak{p}_n\Big(a + \frac{b}{\sqrt{n}}\Big) - \mathfrak{p}_n(a)\right| &= \frac{2n\lambda_n}{\log 2}\left|\log\Big(\frac{|a+b/\sqrt{n}|}{|a+b/\sqrt{n}|+\tau_n}+1\Big) - \log\Big(\frac{|a|}{|a|+\tau_n}+1\Big)\right| \\
&\lesssim n\lambda_n\left|\frac{a+\delta}{a+\delta+\tau_n} - \frac{a}{a+\tau_n}\right| \quad (\delta := b/\sqrt{n}) \\
&= n\lambda_n\frac{|(a+\delta)(a+\tau_n) - a(a+\delta+\tau_n)|}{(a+\delta+\tau_n)(a+\tau_n)} \\
&= n\lambda_n\frac{\tau_n|\delta|}{(a+\delta+\tau_n)(a+\tau_n)} \\
&\sim n^{\beta-3/2}|b| \lesssim |b|.
\end{aligned}$$

Similarly, we get the same estimate for $a < 0$. As the results, it is possible to take the tuning parameters ensuring (1.7), where $\hat{w}_0 = (0, \hat{v}_0)$ and $\mathcal{L}(\hat{v}_0) = N_{p_1}(0, \sigma^2 B_0^{-1})$.

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