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► **To cite this version:**

Joseph de Vilmaest, Olivier Wintenberger. Stochastic Online Optimization using Kalman Recursion. 2020. hal-02468701v1

**HAL Id: hal-02468701**

**<https://hal.science/hal-02468701v1>**

Preprint submitted on 7 Feb 2020 (v1), last revised 23 Jun 2020 (v2)

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# STOCHASTIC ONLINE OPTIMIZATION USING KALMAN RECURSION

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February 7, 2020

## ABSTRACT

We study the Extended Kalman Filter in constant dynamics, offering a bayesian perspective of stochastic optimization. We obtain high probability bounds on the cumulative excess risk in an unconstrained setting. The unconstrained challenge is tackled through a two-phase analysis. First, for linear and logistic regressions, we prove that the algorithm enters a local phase where the estimate stays in a small region around the optimum. We provide explicit bounds with high probability on this convergence time. Second, for generalized linear regressions, we provide a martingale analysis of the excess risk in the local phase, improving existing ones in bounded stochastic optimization. The EKF appears as a parameter-free  $O(d^2)$  online algorithm that optimally solves some unconstrained optimization problems.

**Keywords** extended kalman filter, online learning, stochastic optimization

## 1 Introduction

We consider the online setting where one iteratively estimates the distribution of an observation given explanatory variables. At each time  $t$ , we aim to predict  $y_t \in \mathbb{R}$ , and we have at hand  $X_t \in \mathbb{R}^d$  along with past values  $(X_s, y_s)_{s < t}$ . We present a bayesian perspective, where the search for the best approximation of the distribution is realized inside a set of the form  $\{p_\theta, \theta \in \mathbb{R}^d\}$ , included in the exponential family, with canonical parametrization.

In a non-stationary setting, it leads to a state-space model: the space equation is  $y_t \sim p_{\theta_t}(\cdot | X_t)$  with  $\theta_t \in \mathbb{R}^d$  and the state equation defines the dynamics of  $\theta_t$ , for instance  $\theta_{t+1} - \theta_t \sim \mathcal{N}(0, Q)$  in Kalman Filters and the extended version of it, the EKF (Fahrmeir, 1992). A correspondence has recently been made between the static EKF ( $Q = 0$ ) and Amari's online natural gradient (Ollivier, 2018). This motivates a risk analysis in order to enrich the link between Kalman and the optimization community.

The parameter  $\hat{\theta}_t$  obtained recursively is evaluated by the negative log-likelihood  $-\ln p_\theta(y_t | X_t)$  which we minimize. As it depends only on  $y_t$  and  $\theta^T X_t$ , we denote this loss function by  $\ell(y_t, \theta^T X_t)$ . In the adversarial setting, the aim is to bound the regret

$$\sum_t (\ell(y_t, \hat{\theta}_t^T X_t) - \ell(y_t, \theta^{*T} X_t))$$

with no assumption on  $(X_t, y_t)$  other than boundedness. The optimum  $\theta^*$  is then defined as the minimum of the empirical risk, and strongly depends on the data and the horizon. In the stochastic setting,  $(X_t, y_t)$  is assumed independent and identically distributed (i.i.d.), thus we can define the risk

$$L(\theta) = \mathbb{E}[\ell(y, \theta^T X)]$$

and the objective is to bound the excess risk  $L(\hat{\theta}_t) - L(\theta^*)$  where  $\theta^*$  is the minimum of the risk.

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We focus on the cumulative excess risk  $\sum_t (L(\hat{\theta}_t) - L(\theta^*))$ , and we obtain non-asymptotic bounds holding with high probability. The cumulative risk yields several advantages compared to the risk at a given step. First, this setting paves the way to non-stationary analyses. Indeed, in a well-specified state-space model with  $Q \neq 0$ , replacing  $\theta^*$  by the true parameter, it seems more reasonable to bound the cumulative risk than the risk at a given time, in order to smooth the state variations. Second, our bounds hold simultaneously for any horizon, that is, we control the whole trajectory. Finally, a bound on the cumulative risk leads to a bound on the excess risk at a given step for the averaged version of the algorithm.

The static EKF is very close to the Online Newton Step (Hazan et al., 2007), both are online algorithms close to Newton's method. However the ONS requires the knowledge of the region in which the optimization is realized, it is involved in the choice of the gradient step size and a projection is done at each step to ensure that the search stays under the constraint. On the other hand, the EKF has no gradient step size parameter and thus does not need additional information on the optimal localization, yielding two advantages. First, there is no costly projection step and each recursive update runs in  $\mathcal{O}(d^2)$  operations, consequently our results answer partially the open question of (Koren, 2013). Second, the algorithm is (nearly) parameter-free. Parameter-free is not exactly correct as there are initialization parameters (the prior), but they have no impact on the leading terms of our bounds.

Recent years have seen the emergence of averaged algorithms as solutions for unconstrained stochastic optimization. In Bach and Moulines (2013) the authors provide a sharp bound in expectation on the excess risk for a two step procedure that has been extended to the average of Stochastic Gradient Descent (SGD) with a constant step size by Bach (2014). In this paper we focus on bounds that hold with high probability. We could not reproduce the analysis of Bach (2014) which relies on the fact that the step size is constant. Our martingale analysis is similar to Mahdavi et al. (2015) where the authors derive a bound on the cumulative risk for the ONS.

We believe that bayesian statistics is the reasonable approach in order to obtain (nearly) parameter-free online algorithms. We see the prior on the optimum as a smoothed version of the constraint  $\|\theta^*\| \leq D$  imposed by bounded algorithms such as ONS. This solution is closely related to regularization. Indeed, Kalman Filter in constant dynamics is exactly ridge regression with a varying penalty parameter (see Section 3.2), and similarly the static EKF may be seen as the online approximation of the regularized empirical risk minimization.

We focus in particular on linear regression and logistic regression, two challenging problems in the unconstrained setting. In linear regression, the gradient of the loss is not bounded globally. In logistic regression, the loss is strictly convex, but neither strongly convex nor exp-concave unless the search of  $\theta^*$  is realized in a bounded region. We make the following contributions:

- Our central result is a local analysis of the EKF provided that consecutive steps stay in a small ball around the optimum  $\theta^*$ . We derive local bounds on the cumulative risk with high probability using a martingale analysis. As an intermediate result, we refine a similar bound obtained on the ONS by Mahdavi et al. (2015), see Theorem 3. That is the aim of Section 3.
- In Section 4, we obtain a global bound in the logistic setting. However, in order to use our local result we first obtain the convergence of the algorithm to  $\theta^*$ , and for that matter we need a good control of  $P_t$ . We therefore modify slightly the EKF in the fashion of Bercu et al. (2019). This modification is limited in time and thus our local analysis still applies. This variant of EKF that satisfies a global bound uses a parameter  $\beta$ , contradicting our "parameter-free" claim. But as for the initialization parameters,  $\beta$  can be set to a default value.
- In Section 5, we apply our analysis to the quadratic setting. We rely on (Hsu et al., 2012) to obtain the convergence after exhibiting the correspondence between Kalman Filter and Ridge Regression, and we therefore obtain similarly a global bound using our local analysis.

## 2 Definitions and assumptions

For any  $(X, y) \in \mathcal{X} \times \mathcal{Y}$  for some  $\mathcal{X} \subset \mathbb{R}^d$  and  $\mathcal{Y} \subset \mathbb{R}$ , the loss function is defined as the negative log-likelihood

$$\ell(y, \theta^T X) = -\ln p_\theta(y | X), \quad \theta \in \mathbb{R}^d.$$

The likelihoods we consider are defined by

$$p_\theta(y | X) = h(y) \exp\left(\frac{y\theta^T X - b(\theta^T X)}{a}\right), \quad y \in \mathcal{Y}, X, \theta \in \mathcal{X}, \quad (1)$$

where  $h, a, b$  are the known parameters of the Generalized Linear Model. This setting includes linear and logistic regression, see Sections 4 and 5. In this setting, we display the static EKF.

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**Algorithm 1:** Static Extended Kalman Filter for Generalized Linear Model

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1. *Initialization:*  $P_1$  is any positive definite matrix,  $\hat{\theta}_1$  is any initial parameter in  $\mathbb{R}^d$ .
  2. *Iteration:* at each time step  $t = 1, 2, \dots$ 
    - (a) Update  $P_{t+1} = P_t - \frac{P_t X_t X_t^T P_t}{1 + X_t^T P_t X_t} \alpha_t$  with  $\alpha_t = \frac{b''(\hat{\theta}_t^T X_t)}{a}$ .
    - (b) Update  $\hat{\theta}_{t+1} = \hat{\theta}_t + P_{t+1} \frac{(y_t - b'(\hat{\theta}_t^T X_t)) X_t}{a}$ .
- 

We now present the assumptions we need. The first one is the i.i.d. assumption.

**Assumption 1.** *The observations  $(X_t, y_t)_t$  are i.i.d. copies of the pair  $(X, y) \in \mathcal{X} \times \mathcal{Y}$ ,  $\mathbb{E}[X X^T]$  is positive definite and the diameter (for the Euclidian distance) of  $\mathcal{X}$  is bounded by  $D_X$ .*

Working under Assumption 1, we define the risk function  $L(\theta) = \mathbb{E}[\ell(y, \theta^T X)]$  and  $\Lambda_{\min}$  the smallest eigenvalue of  $\mathbb{E}[X X^T]$ . We notice that the GLM is mis-specified when the distribution of  $(X, y)$  is not of the form (1). In order to obtain a well-defined optimization problem, we assume

**Assumption 2.** *There exists  $\theta^* \in \mathbb{R}^d$  such that  $L(\theta^*) = \inf_{\theta \in \mathbb{R}^d} L(\theta)$ .*

We treat two different settings. First, a bounded setting motivated by logistic regression, with a local exp-concavity assumption along with some regularity on  $\ell''$ . That setting implies  $\mathcal{Y}$  bounded, because  $\ell'$  depends on  $y$  whereas  $\ell''$  doesn't. This is summarized in Assumption 3. Second, we consider the quadratic loss, corresponding to a gaussian model, and in order to include the well-specified model, we assume  $y$  sub-gaussian conditionally to  $X$ , and not too far away from the model as in Assumption 4.

**Assumption 3.** *There exists  $(\kappa_\varepsilon)_{\varepsilon>0}$ ,  $(h_\varepsilon)_{\varepsilon>0}$  and  $\rho_\varepsilon \xrightarrow{\varepsilon \rightarrow 0} 1$  such that for any  $\varepsilon > 0$ ,*

- *For any  $\theta \in \mathbb{R}^d$ ,  $\|\theta - \theta^*\| \leq \varepsilon \implies \ell'(y, \theta^T X)^2 \leq \kappa_\varepsilon \ell''(y, \theta^T X)$  a.s.*
- *For any  $\theta$ ,  $\|\theta - \theta^*\| \leq \varepsilon \implies \ell''(y, \theta^T X) \leq h_\varepsilon$  a.s.*
- *For any  $\theta_1, \theta_2 \in \mathbb{R}^d$ ,  $\|\theta_1 - \theta_2\| \leq \varepsilon \implies \ell''(y, \theta_1^T X) \geq \rho_\varepsilon \ell''(y, \theta_2^T X)$  a.s.*

In logistic regression,  $\mathcal{Y} = \{-1, +1\}$  and Assumption 3 is satisfied for  $\kappa_\varepsilon = e^{D_X(\|\theta^*\| + \varepsilon)}$ ,  $h_\varepsilon = \frac{1}{4}$ ,  $\rho_\varepsilon = e^{-\varepsilon D_X}$ .

**Assumption 4.** *The distribution of  $(X, y) \in \mathcal{X} \times \mathcal{Y}$  satisfies*

- *There exists  $\sigma^2 > 0$  such that for any  $s \in \mathbb{R}$ ,  $\mathbb{E}[e^{s(y - \mathbb{E}[y|X])} | X] \leq e^{\frac{\sigma^2 s^2}{2}}$  a.s.,*
- *There exists  $D_{\text{app}} \geq 0$  such that  $|\mathbb{E}[y | X] - \theta^{*T} X| \leq D_{\text{app}}$  a.s.*

Both conditions of Assumption 4 hold with  $\mathcal{Y} = \mathbb{R}$  and  $D_{\text{app}} = 0$  for the well-specified sub-gaussian linear model with random bounded design. The second condition of Assumption 4 is satisfied for  $D_{\text{app}} > 0$  in misspecified sub-gaussian linear model with a.s. bounded approximation error.

### 3 The algorithm around the optimum

#### 3.1 Main results

In this section, we analyse the cumulative risk under a strong convergence assumption:

**Assumption 5.** *For any  $\delta > 0$ , there exists  $\tau(\varepsilon, \delta) \in \mathbb{N}$  such that it holds for any  $t > \tau(\varepsilon, \delta)$  simultaneously*

$$\|\hat{\theta}_t - \theta^*\| \leq \varepsilon,$$

*with probability at least  $1 - \delta$ .*

Assumption 5 states that with high probability, we have a convergence time after which the algorithm stays trapped in a local region around the optimum. Sections 4 and 5 are devoted to check Assumption 5 in the logistic and linear regression setting by explicitly defining such a convergence time.

**Algorithm 2:** Recursive updates: comparison between the ONS and the static EKF**Online Newton Step**

- $P_{t+1}^{-1} = P_t^{-1} + \ell'(y_t, \hat{\theta}_t^T X_t)^2 X_t X_t^T$ .
- $w_{t+1} = \prod_{\mathcal{K}}^{P_{t+1}^{-1}} \left( w_t - \frac{1}{\gamma} P_{t+1} \nabla_t \right)$ .

**Static Extended Kalman Filter**

- $P_{t+1}^{-1} = P_t^{-1} + \ell''(y_t, \hat{\theta}_t^T X_t) X_t X_t^T$ .
- $\hat{\theta}_{t+1} = \hat{\theta}_t - P_{t+1} \nabla_t$ .

where  $\nabla_t = \ell'(y_t, \hat{\theta}_t^T X_t) X_t$  and  $\prod_{\mathcal{K}}^{P_{t+1}^{-1}}$  is the projection on the convex set  $\mathcal{K}$  for the norm  $\|\cdot\|_{P_{t+1}^{-1}}$ .

We present our result in the bounded and sub-gaussian settings. The results and their proofs are very similar, but two crucial steps are different. First, Assumption 3 yields a bound on the gradient holding almost surely, and we chose to avoid it for the quadratic loss with a relaxed sub-gaussian hypothesis, requiring a specific analysis with larger bounds. Second, our analysis is based on a second-order expansion, and the quadratic loss satisfies an identity with its second-order Taylor expansion, but we need Assumption 5 along with the third point of Assumption 3 otherwise.

The following theorem is our result in the bounded setting. The constant 0.95 may be chosen arbitrarily close to 0.5 with growing constants in the bound on the cumulative risk. There is a hidden trade-off in  $\varepsilon$ : on the one hand, the smaller  $\varepsilon$  the better our upper-bound, but on the other hand  $\tau(\varepsilon, \delta)$  increases when  $\varepsilon$  decreases, and thus our bound applies after a bigger convergence time.

**Theorem 1.** *If Assumptions 1, 2, 3, 5 are satisfied and if  $\rho_\varepsilon > 0.95$ , for any  $\delta > 0$ , it holds for any  $n \geq 1$  simultaneously*

$$\sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} L(\hat{\theta}_t) - L(\theta^*) \leq \frac{5}{2} d \kappa_\varepsilon \ln \left( 1 + n \frac{h_\varepsilon \lambda_{\max}(P_1) D_X^2}{d} \right) + 5 \lambda_{\max} \left( P_{\tau(\varepsilon, \delta)+1}^{-1} \right) \varepsilon^2 \\ + 30 (2\kappa_\varepsilon + h_\varepsilon \varepsilon^2 D_X^2) \ln \delta^{-1},$$

with probability at least  $1 - 3\delta$ .

For the quadratic loss, we obtain the following theorem under the sub-gaussian hypothesis.

**Theorem 2.** *In the quadratic setting, if Assumptions 1, 2, 4 and 5 are satisfied, for any  $\delta > 0$ , it holds for any  $n \geq 1$  simultaneously*

$$\sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} L(\hat{\theta}_t) - L(\theta^*) \leq \frac{15}{2} d (8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \ln \left( 1 + n \frac{\lambda_{\max}(P_1) D_X^2}{d} \right) + 5 \lambda_{\max} \left( P_{\tau(\varepsilon, \delta)+1}^{-1} \right) \varepsilon^2 \\ + 115 \left( \sigma^2 \left( 4 + \frac{\lambda_{\max}(P_1) D_X^2}{4} \right) + D_{\text{app}}^2 + 2\varepsilon^2 D_X^2 \right) \ln \delta^{-1},$$

with probability at least  $1 - 5\delta$ .

We display the parallel between the ONS and the static EKF in Algorithm 2 through their recursive updates. This link motivates a similar analysis, and an intermediate result yields the following refinement on a stochastic bound on the ONS (Mahdavi et al., 2015).

**Theorem 3.** *Let  $(w_t)_t$  be the ONS estimates starting from  $P_1 = \lambda I$  and using a step-size  $\gamma = \frac{1}{2} \min(\frac{1}{4GD}, \alpha)$  with  $\alpha$  the exp-concavity constant. Assume the gradients are bounded by  $G$  and the optimization set  $\mathcal{K}$  has diameter  $D$ . Then for any  $\delta > 0$ , it holds simultaneously*

$$\sum_{t=1}^n L(w_t) - L(\theta^*) \leq \frac{3}{2\gamma} d \ln \left( 1 + \frac{nG^2}{\lambda d} \right) + \frac{\lambda\gamma}{6} D^2 + \left( \frac{12}{\gamma} + \frac{4\gamma G^2 D^2}{3} \right) \ln \delta^{-1}, \quad n \geq 1,$$

with probability at least  $1 - 2\delta$ .

The comparison of this result with Theorem 1 is difficult because we don't control in general  $\tau(\varepsilon, \delta)$ . We obtain similar constants, as  $\kappa_\varepsilon$  is the inverse of the exp-concavity constant  $\alpha$ . However the static EKF is parameter-free whereas  $\alpha$

is an input of the ONS through  $\gamma$ . That is why we argue that the static EKF provides an optimal way to choose the step size as does averaged SGD (Bach, 2014). Indeed, as  $\varepsilon$  is a parameter of the EKF analysis, we can improve the leading constant  $\kappa_\varepsilon$  on local region arbitrarily small around  $\theta^*$ , at a cost for the  $\tau(\varepsilon, \delta)$  first terms, whereas in the ONS the choice of a diameter  $D > \|\theta^*\|$  makes the gradient step-size sub-optimal and impact the leading constant. Similarly to the ONS analysis, the use of second-order methods learns adaptively the pre-conditioning matrix which is crucial in order to improve the leading constant  $D_X^2/\Lambda_{\min}$  to  $d$ . A similar comparison is possible between the result of Theorem 2 and tight risk bounds obtained for the OLS (Hsu et al., 2012). Up to numerical constants, the tight constant  $d(\sigma^2 + D_{\text{app}}^2)$  is achieved by choosing  $\varepsilon$  arbitrarily small, at a cost for the  $\tau(\varepsilon, \delta)$  first terms. Another difference between our bounds in Theorems 1 and 2 and previous ones obtained by Bach (2014) and Hsu et al. (2012) is that EKF is an online algorithm with one-step complexity  $O(d^2)$  and that our bounds hold on the cumulative risk with high probability for any  $n \geq 1$ .

We detail the key ideas of the proofs through intermediate results in Sections 3.2 and 3.3. The detailed proofs are deferred to Appendix A.

### 3.2 Comparison with Online Newton Step and Ridge Regression: a regret analysis

To begin our analysis, we formalize the strong links between the static EKF, the ONS and a Ridge Regression forecaster. For the quadratic loss, the EKF becomes the Kalman Filter: in Algorithm 1 we set  $a = 1, b'(\hat{\theta}_t^T X_t) = \hat{\theta}_t^T X_t, \alpha_t = 1$ .

The parallel with the Ridge Regression forecaster was evoked by Diderrich (1985), and it is crucial that the static Kalman Filter is the Ridge regression estimator for a decaying penalty parameter. It highlights that the static EKF may be seen as an approximation of the regularized empirical risk minimization problem.

**Proposition 4.** *In the quadratic setting, for any sequence  $(X_t, y_t)$ , starting from any  $\hat{\theta}_1 \in \mathbb{R}^d$  and  $P_1 \succ 0$ , we have*

$$\hat{\theta}_t = \arg \min_{\theta \in \mathbb{R}^d} \left( \frac{1}{2} \sum_{s=1}^{t-1} (y_s - \theta^T X_s)^2 + \frac{1}{2} (\theta - \hat{\theta}_1)^T P_1^{-1} (\theta - \hat{\theta}_1) \right), \quad t \geq 1.$$

This proposition and the comparison to ONS (Algorithm 2) motivate similar analyses. The cornerstone of our local analysis is the derivation of a bound on the second-order Taylor expansion of  $\ell$ , from the recursive update formulae.

**Lemma 5.** *For any sequence  $(X_t, y_t)_t$ , starting from  $P_1 \succ 0$  and  $\hat{\theta}_1 \in \mathbb{R}^d$ , it holds for any  $\theta^* \in \mathbb{R}^d$  and  $n \in \mathbb{N}$  that*

$$\begin{aligned} \sum_{t=1}^n \left( \left( \ell'(y_t, \hat{\theta}_t^T X_t) X_t \right)^T (\hat{\theta}_t - \theta^*) - \frac{1}{2} (\hat{\theta}_t - \theta^*)^T \left( \ell''(y_t, \hat{\theta}_t^T X_t) X_t X_t^T \right) (\hat{\theta}_t - \theta^*) \right) \\ \leq \frac{1}{2} \sum_{t=1}^n X_t^T P_{t+1} X_t \ell'(y_t, \hat{\theta}_t^T X_t)^2 + \frac{\|\hat{\theta}_1 - \theta^*\|^2}{\lambda_{\min}(P_1)}. \end{aligned}$$

In the linear setting, as there is equality between the quadratic function and its second-order Taylor expansion, a logarithmic regret bound is therefore obtained for the ridge regression forecaster (Cesa-Bianchi and Lugosi (2006), Theorem 11.7), but the factor before the logarithm is not easily bounded, unless we assume  $(y_t - \hat{\theta}_t^T X_t)^2$  bounded.

In general, we cannot compare the excess loss with the second-order Taylor expansion, and we need a step size parameter. In Hazan et al. (2007), the regret analysis of the ONS is based on a very similar bound on

$$\left( \ell'(y_t, w_t^T X_t) X_t \right)^T (\hat{\theta}_t - \theta^*) - \frac{\gamma}{2} (w_t - \theta^*)^T \left( \ell''(y_t, w_t^T X_t)^2 X_t X_t^T \right) (w_t - \theta^*),$$

where  $\gamma$  is a step size depending on the exp-concavity constant, a bound on the gradients and the diameter of the search region  $\mathcal{K}$ . Then the regret bound follows from the exp-concavity property, bounding the excess loss  $\ell(y_t, w_t^T X_t) - \ell(y_t, \theta^{*T} X_t)$  with the previous quantity.

In general, local exp-concavity and local strong convexity are equivalent to strict convexity (positivity of the second derivative), though exp-concavity and strong convexity constants may be different. Therefore it is very similar to use the ONS or to introduce a step size parameter in the static EKF alongside with a projection step. Indeed, setting a step size parameter  $\zeta$  depending on the diameter considered, we could bound the excess loss at time  $t$  with

$$\left( \ell'(y_t, \hat{\theta}_t^T X_t) X_t \right)^T (\hat{\theta}_t - \theta^*) - \frac{\zeta}{2} (\hat{\theta}_t - \theta^*)^T \left( \ell''(y_t, \hat{\theta}_t^T X_t) X_t X_t^T \right) (\hat{\theta}_t - \theta^*),$$

and a regret bound would follow. But we would pay the exp-concavity constant  $\alpha$  anyway when applying the trick from the proof of Theorem 11.7 in Cesa-Bianchi and Lugosi (2006) to bound the right-hand side of Lemma 5, and the

constant  $1/\gamma$  in the leading term of the bound of the ONS (Theorem 3) would be replaced by  $\alpha/\zeta$ . We would choose  $\zeta$  as the ratio between the minimal and the maximal values of  $l''$ , and that can be considerably smaller than  $\gamma$ .

We follow a very different approach, to stay parameter-free and to avoid any additional cost in the leading constant. In the stochastic setting, we observe that we can upper-bound the excess risk with a second-order expansion, up to a multiplicative factor.

### 3.3 From adversarial to stochastic: the cumulative risk

In order to compare the excess risk with a second-order expansion, we need to compare the first-order term with the second-order one.

**Proposition 6.** *If Assumptions 1, 2 and 3 are satisfied, for any  $\theta \in \mathbb{R}^d$ , it holds*

$$\frac{\partial L^T}{\partial \theta} (\theta - \theta^*) \geq \rho_{\|\theta - \theta^*\|} (\theta - \theta^*)^T \frac{\partial^2 L}{\partial \theta^2} (\theta - \theta^*).$$

This result leads immediately to the following proposition, using the first-order convexity property of  $L$ .

**Proposition 7.** *If Assumptions 1, 2 and 3 are satisfied, for any  $\theta \in \mathbb{R}^d$ ,  $0 < c < \rho_{\|\theta - \theta^*\|}$ , it holds*

$$L(\theta) - L(\theta^*) \leq \frac{\rho_{\|\theta - \theta^*\|}}{\rho_{\|\theta - \theta^*\|} - c} \left( \frac{\partial L^T}{\partial \theta} (\theta - \theta^*) - c(\theta - \theta^*)^T \frac{\partial^2 L}{\partial \theta^2} (\theta - \theta^*) \right).$$

Lemma 5 motivates the use of  $c > \frac{1}{2}$ , thus we need at least  $\rho_{\|\theta - \theta^*\|} > \frac{1}{2}$ . In the linear setting, it holds as an equality with  $\rho = 1$  because the second derivative of the quadratic loss is constant. In the bounded setting we need to control the second derivative in a small range, and we can achieve that only locally. The natural condition becomes the third condition of Assumption 3.

Then we are left to obtain a bound on the cumulative risk from Lemma 5. In order to compare the derivatives of the risk and the losses, we need to control the martingale difference adapted to the natural filtration  $(\mathcal{F}_t)$  and defined by

$$\Delta M_t = \left( \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t} - \nabla_t \right)^T (\hat{\theta}_t - \theta^*), \quad \text{where } \nabla_t = \ell'(y_t, \hat{\theta}_t^T X_t) X_t. \quad (2)$$

That is the objective of the following Lemma, which is a corollary of a martingale inequality from Bercu and Touati (2008) and a stopping time construction of Freedman (1975).

**Lemma 8.** *Let  $k \geq 0$  and  $(\Delta N_t)_{t \geq k}$  be any martingale difference adapted to the filtration  $(\mathcal{F}_t)_{t \geq k}$  such that for any  $t > k$ ,  $\mathbb{E}[\Delta N_t^2 | \mathcal{F}_{t-1}] < \infty$ . For any  $\delta, \lambda > 0$ , we have the simultaneous property*

$$\sum_{t=k+1}^{k+n} \left( \Delta N_t - \frac{\lambda}{2} ((\Delta N_t)^2 + \mathbb{E}[(\Delta N_t)^2 | \mathcal{F}_{t-1}]) \right) \leq \frac{\ln \delta^{-1}}{\lambda}, \quad n \geq 1,$$

with probability at least  $1 - \delta$ .

This lemma yields the refinement of the stochastic bound on the ONS obtained by Mahdavi et al. (2015), formally stated in Theorem 3, whose proof consists in replacing their Theorem 4 by Lemma 8.

Finally we apply Lemma 8 to the martingale difference defined in Equation 2.

**Lemma 9.** *If Assumptions 1 and 2 are satisfied, for any  $k \geq 0$  and  $\delta, \lambda > 0$ , it holds*

$$\sum_{t=k+1}^{k+n} \left( \Delta M_t - \lambda (\hat{\theta}_t - \theta^*)^T \left( \nabla_t \nabla_t^T + \frac{3}{2} \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] \right) (\hat{\theta}_t - \theta^*) \right) \leq \frac{\ln \delta^{-1}}{\lambda}, \quad n \geq 1,$$

with probability at least  $1 - \delta$ .

Summing Lemma 5 and 9, the rest of the proof consists in the following two steps:

- We derive poissonian bounds to control the quadratic terms in  $\hat{\theta}_t - \theta^*$  in terms of the one of the second-order bound of Proposition 7.
- We upper-bound  $\sum_t X_t^T P_{t+1} X_t \ell'(y_t, \hat{\theta}_t^T X_t)^2$  relying on techniques similar to the ridge analysis of the proof of Theorem 11.7 in (Cesa-Bianchi and Lugosi, 2006).

**Algorithm 3:** Truncated Extended Kalman Filter for Logistic Regression

1. *Initialization:*  $P_1$  is any positive definite matrix,  $\hat{\theta}_1$  is any initial parameter in  $\mathbb{R}^d$ .
2. *Iteration:* at each time step  $t = 1, 2, \dots$ 
  - (a) Update  $P_{t+1} = P_t - \frac{P_t X_t X_t^T P_t}{1 + X_t^T P_t X_t} \alpha_t$ , with  $\alpha_t = \max\left(\frac{1}{t^\beta}, \frac{1}{(1 + e^{\hat{\theta}_t^T X_t})(1 + e^{-\hat{\theta}_t^T X_t})}\right)$ .
  - (b) Update  $\hat{\theta}_{t+1} = \hat{\theta}_t + P_{t+1} \frac{y_t X_t}{1 + e^{\hat{\theta}_t^T X_t}}$ .

**4 Logistic setting**

Logistic regression is a statistical model widely used in order to predict a binary random variable  $y \in \mathcal{Y} = \{-1, 1\}$ . It consists in estimating  $\mathcal{L}(y | X)$  with

$$p_\theta(y | X) = \frac{1}{1 + e^{-y\theta^T X}} = \exp\left(\frac{y\theta^T X - (2 \ln(1 + e^{\theta^T X}) - \theta^T X)}{2}\right).$$

In our notations, it yields  $a = 2$  and  $b(\theta^T X) = 2 \ln(1 + e^{\theta^T X}) - \theta^T X$ .

**4.1 The truncated algorithm**

For checking Assumption 5, we follow a trick consisting in changing slightly the update on  $P_t$  (Bercu et al., 2019). Indeed, when they tried to prove the asymptotic convergence of the static EKF (which they named Stochastic Newton Step) using Robbins-Siegmund Theorem, they needed the convergence of  $\sum_t \lambda_{\max}(P_t)^2$ . This seems very likely to hold as we have intuitively  $P_t \propto 1/t$ . However, in order to obtain  $\lambda_{\max}(P_t) = \mathcal{O}(1/t)$ , one needs to lower-bound  $\alpha_t$ , that is, lower-bound  $b''$ , and that is impossible in the logistic global setting. Therefore, the idea is to force a lower-bound on  $\alpha_t$  in its definition. We thus define, for some  $0 < \beta < 1/2$ ,

$$\alpha_t = \max\left(\frac{1}{t^\beta}, \frac{1}{(1 + e^{\hat{\theta}_t^T X_t})(1 + e^{-\hat{\theta}_t^T X_t})}\right), \quad t \geq 1.$$

This modification yields Algorithm 3, where we keep the notations  $\hat{\theta}_t, P_t$  with some abuse. We impose a decreasing threshold on  $\alpha_t$  ( $\beta > 0$ ) so that the recursion coincides with Algorithm 1 after some steps. Then we apply our analysis of Section 3 after slightly changing Assumption 5:

**Assumption 6.** For any  $\delta > 0$ , there exists  $\tau(\varepsilon, \delta) \in \mathbb{N}$  such that it holds for any  $t > \tau(\varepsilon, \delta)$

$$\|\hat{\theta}_t - \theta^*\| \leq \varepsilon \text{ and } \alpha_t = \frac{1}{(1 + e^{\hat{\theta}_t^T X_t})(1 + e^{-\hat{\theta}_t^T X_t})}$$

simultaneously with probability at least  $1 - \delta$ .

The sensitivity of the algorithm to  $\beta$  is discussed at the end of Section 4.2. Also, note that the threshold could be  $c/t^\beta$ ,  $c > 0$ , as in Bercu et al. (2019), it would not change the proofs but it doesn't change the asymptotic result either.

We first state the result with  $\tau(\varepsilon, \delta)$  in our upper-bound, for a particular choice of  $\varepsilon$ . We define its value in the next paragraph, and we discuss its dependence to parameters.

**Theorem 10.** If Assumptions 1, 2 and 6 with  $\varepsilon = 1/(20D_X)$  are satisfied, for any  $\delta > 0$  it holds for any  $n \geq 1$  simultaneously

$$\begin{aligned} \sum_{t=1}^n L(\hat{\theta}_t) - L(\theta^*) &\leq 3de^{D_X \|\theta^*\|} \ln\left(1 + n \frac{\lambda_{\max}(P_1) D_X^2}{4d}\right) + \frac{\lambda_{\max}(P_1^{-1})}{75D_X^2} + 64e^{D_X \|\theta^*\|} \ln \delta^{-1} \\ &\quad + \tau\left(\frac{1}{20D_X}, \delta\right) \left(\frac{1}{300} + D_X \|\hat{\theta}_1 - \theta^*\|\right) + \tau\left(\frac{1}{20D_X}, \delta\right)^2 \frac{\lambda_{\max}(P_1) D_X^2}{2}, \end{aligned}$$

with probability at least  $1 - 4\delta$ .



## 4.2 Definition of $\tau(\varepsilon, \delta)$ in Assumption 6

It is proved that  $\|\hat{\theta}_n - \theta^*\|^2 = \mathcal{O}(\ln n/n)$  almost surely (Bercu et al. (2019), Theorem 4.2). We don't obtain a non-asymptotic version of this rate of convergence, but the aim of this paragraph is to check Assumption 6 with an explicit value of  $\tau(\varepsilon, \delta)$  for any  $\delta, \varepsilon > 0$ .

The truncation introduced in the algorithm improves the control on  $P_t$ . We begin by stating that fact formally.

**Proposition 11.** *If Assumption 1 is satisfied, for any  $\delta > 0$ , it holds simultaneously that*

$$\forall t > \left( \frac{20D_X^4}{\Lambda_{\min}^2} \ln \left( \frac{625dD_X^8}{\Lambda_{\min}^4 \delta} \right) \right)^{1/(1-\beta)}, \quad \lambda_{\max}(P_t) \leq \frac{4}{\Lambda_{\min} t^{1-\beta}},$$

with probability at least  $1 - \delta$ .

The limit  $\beta < 1/2$  thus corresponds to the condition  $\sum_t \lambda_{\max}(P_t)^2 < +\infty$  with high probability. Motivated by Proposition 11, we define, for  $C > 0$ , the event

$$A_C := \bigcap_{t=1}^{\infty} \left( \lambda_{\max}(P_t) \leq \frac{C}{t^{1-\beta}} \right).$$

To obtain a control on  $P_t$  holding for any  $t$ , we use the relation  $\lambda_{\max}(P_t) \leq \lambda_{\max}(P_1)$  holding almost surely. We thus define

$$C_\delta = \max \left( \frac{4}{\Lambda_{\min}}, \lambda_{\max}(P_1) \left( \frac{20D_X^4}{\Lambda_{\min}^2} \ln \left( \frac{625dD_X^8}{\Lambda_{\min}^4 \delta} \right) \right) \right),$$

and we obtain  $\mathbb{P}(A_{C_\delta}) \geq 1 - \delta$ . We obtain the following theorem under that condition.

**Theorem 12.** *Provided that Assumptions 1 and 2 are satisfied, if  $\hat{\theta}_1 = 0$  we have for any  $\varepsilon > 0$  and  $t \geq \exp \left( \frac{2^8 D_X^8 C_\delta^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)^{3/2} \varepsilon^2} \right)$ ,*

$$\begin{aligned} \mathbb{P}(\|\hat{\theta}_t - \theta^*\| > \varepsilon \mid A_{C_\delta}) &\leq (\sqrt{t} + 1) \exp \left( -\frac{\Lambda_{\min}^6 (1-2\beta) \varepsilon^4}{2^{16} D_X^{12} C_\delta^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^6} \ln(t)^2 \right) \\ &\quad + t \exp \left( -\frac{\Lambda_{\min}^2 (1-2\beta) \varepsilon^4}{2^{11} D_X^4 C_\delta^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^2} (\sqrt{t} - 1)^{1-2\beta} \right). \end{aligned}$$

The beginning of our convergence proof is similar to the application of the Robbins-Siegmund Theorem: we obtain a recursive inequality ensuring that  $(L(\hat{\theta}_t))_t$  is decreasing in expectation, up to the addition of a finite sum. In order to obtain a non-asymptotic result, we highlight that the variations of the estimate  $\hat{\theta}_t$  are slow, thus if the algorithm is far from the optimum it means the last estimates were far too. Consequently, we look at the last  $k$  such that  $\|\hat{\theta}_k - \theta^*\| < \varepsilon/2$  if it exists, and we decompose the probability of being outside the local region in two, yielding the two terms in Theorem 12. For  $k < \sqrt{t}$  the recursive decrease in expectation makes it unlikely that the estimate stays far from the optimum for a long period. For  $k > \sqrt{t}$  the control on  $P_t$  allows a control on the probability that the algorithm moves fast away from the optimum.

The following corollary explicitly defines a guarantee for the convergence time.

**Corollary 13.** *Provided that Assumptions 1 and 2 are satisfied, if  $\hat{\theta}_1 = 0$  we check Assumption 6 for any  $\varepsilon > 0$ ,  $\delta > 0$  and*

$$\tau(\varepsilon, \delta) = \max \left( \left( 2(1 + e^{D_X(\|\theta^*\| + \varepsilon)}) \right)^{1/\beta}, \exp \left( \frac{3 \cdot 2^{15} D_X^{12} C_\delta^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^6}{\Lambda_{\min}^6 (1-2\beta)^{3/2} \varepsilon^4} \right), 6\delta^{-1} \right).$$

This definition of  $\tau(\varepsilon, \delta)$  allows a discussion of the dependence of the bound Theorem 10 to the different parameters, as this convergence time has a great impact on the right-hand side.

- First, the truncation has introduced a new parameter  $\beta$ , on which  $\tau(\varepsilon, \delta)$  strongly depends with a trade-off. On the one hand, when  $\beta$  is close to 0, the algorithm is slow to coincide with the true Extended Kalman Filter, for which our fast rate holds. Precisely, we have  $\tau(\varepsilon, \delta) = e^{\mathcal{O}(1)/\beta}$ . On the other hand, the truncation was introduced to control  $P_t$ . The larger  $\beta$ , the larger our control on  $\lambda_{\max}(P_t)$ , and thus we get  $\tau(\varepsilon, \delta) = e^{\mathcal{O}(1)/(1-2\beta)^{3/2}}$ . Practical considerations show that the truncation is artificial and our bound is lousy when  $\beta$  is close to  $\frac{1}{2}$ . Indeed, in Bercu et al. (2019), the authors suggest a threshold as low as possible ( $10^{-10}/t^{0.49}$ ), and the truncation makes no difference in their numerical experiments.

- As Corollary 13 holds for any  $\varepsilon > 0$ , the compromise realized with  $\varepsilon = 1/(20D_X)$ , made for simplifying constants, is totally arbitrary. The dependence of the convergence time is of the order  $\tau(\varepsilon, \delta) = e^{\mathcal{O}(1)/\varepsilon^4}$ , however the  $\log n$  term of the bound has a  $e^{D_X \varepsilon}$  factor. Thus the best compromise should be an  $\varepsilon > 0$  decreasing with  $n$ .
- The dependence to  $\delta$  is complex. The third constraint on  $\tau(\varepsilon, \delta)$  is  $\mathcal{O}(\delta^{-1})$ . Treating the union bound more carefully in the proof of Corollary 13, we claim a control in  $\exp \sqrt{\mathcal{O}(\ln \delta^{-1})}$ . However, we did such an elementary proof because we did not want to hide a dependence through  $C_{\delta/2}$  which implies a  $\Omega(\delta^{-1})$  in the second constraint. To improve this latter dependence, one needs a better control of  $P_t$  which would follow from a specific analysis of the  $\mathcal{O}(\ln \delta^{-1})$  first recursions in order to "initialize" the control on  $P_t$ . However the objective of Corollary 13 was to check Assumption 6 and not to get an optimal value of  $\tau(\varepsilon, \delta)$ .

## 5 Quadratic setting

We state our result for the quadratic loss where Algorithm 1 becomes the standard Kalman Filter. We first state our result with an upper-bound depending on  $\tau(\varepsilon, \delta)$ , then we define  $\tau(\varepsilon, \delta)$  satisfying Assumption 5.

As for the logistic setting, we split the cumulative risk in two sums, the first is roughly bounded in some sort of worst case analysis, and the second with the local analysis (Theorem 2). However, as the loss and its gradient are not bounded we cannot obtain a similar almost sure upper-bound for the first phase, but the sub-gaussian assumption allows for a high probability bound.

**Theorem 14.** *Provided that Assumptions 1, 2, 4 and 5 are satisfied, for any  $\varepsilon, \delta > 0$ , it holds simultaneously*

$$\begin{aligned} \sum_{t=1}^n L(\hat{\theta}_t) - L(\theta^*) &\leq \frac{15}{2}d(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \ln \left( 1 + n \frac{\lambda_{\max}(P_1) D_X^2}{d} \right) + 5\lambda_{\max}(P_1^{-1})\varepsilon^2 \\ &\quad + 115 \left( \sigma^2 \left( 4 + \frac{\lambda_{\max}(P_1) D_X^2}{4} \right) + D_{\text{app}}^2 + 2\varepsilon^2 D_X^2 \right) \ln \delta^{-1} \\ &\quad + D_X^2 \left( 5\varepsilon^2 + 2(\|\hat{\theta}_1 - \theta^*\|^2 + 3\lambda_{\max}(P_1) D_X \sigma \ln \delta^{-1})^2 \right) \tau(\varepsilon, \delta) \\ &\quad + \frac{2\lambda_{\max}(P_1)^2 D_X^4 (3\sigma + D_{\text{app}})^2}{3} \tau(\varepsilon, \delta)^3, \quad n \geq 1, \end{aligned}$$

with probability at least  $1 - 6\delta$ .

As Kalman Filter estimator is exactly Ridge estimator for a varying regularization parameter, a much better control in the quadratic setting is obtained than the one we obtain in the logistic setting. Indeed we can use the regularized empirical risk minimization properties instead of the recursive update expression that was the only available property in the logistic setting. In particular, we apply the ridge analysis provided by Hsu et al. (2012), and we check Assumption 5 by providing a non-asymptotic definition of  $\tau(\varepsilon, \delta)$  in Appendix C, Corollary 24. Up to universal constants, and to logarithmic terms in all the constants, we get

$$\begin{aligned} \tau(\varepsilon, \delta) &\lesssim \frac{\varepsilon^{-1}}{\Lambda_{\min}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} + \frac{D_X^2}{\Lambda_{\min}} (1 + D_{\text{app}}^2) \sqrt{\ln \delta^{-1}} + \sigma^2 d \right. \\ &\quad \left. + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{p_1}} + \sigma^2 \right) \ln \delta^{-1} \right). \end{aligned}$$

We obtain a much less dramatic dependence in  $\varepsilon$ . However we cannot avoid a  $\Lambda_{\min}^{-1}$  factor in the definition of  $\tau(\varepsilon, \delta)$  as it implies convergence to  $\theta^*$  and not only risk. Therefore, we could not avoid this extra factor on the bound of the first steps of the cumulative risk as the ridge analysis provided by Hsu et al. (2012) is not valid for small  $t$ .

## 6 Conclusion and future work

This article provides an analysis of the EKF in unconstrained stochastic optimization. It would be interesting to generalize our results to other optimization problems. The local results of Section 3 hold as long as the strictly convex risk can be expressed as a GLM log-likelihood. The hard part is to prove the convergence of the algorithm to this local phase.

A crucial drawback of our analysis is the constant cost in the first phase of convergence of the algorithm to the local region. We used elementary techniques that could be improved and we had to modify the algorithm in order to obtain that convergence guarantee. An objective of future research is to define algorithms coinciding with the EKF after a first phase and converging faster.

Finally this article focuses on i.i.d. data and leads the way to the analysis of the cumulative risk for well-specified non-stationary time series.

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## Organization of the Appendix

The Appendix follows the structure of the article:

- Appendix A contains the proofs of Section 3. Precisely, the intermediate results of Sections 3.2 and 3.3 are proved in Section A.1 and A.2, then Theorem 1 is proved in Section A.3 and Theorem 2 in Section A.4.
- Appendix B contains the proofs of Section 4. We derive the global bound (Theorem 10) in Section B.1, then we obtain the concentration result on  $P_t$  in Section B.2, and finally we prove the convergence of the truncated algorithm in Section B.3.
- Appendix C contains the proofs of Section 5. We prove Theorem 14 in Section C.1 and then in Section C.2 we prove the convergence of the algorithm, and we define an explicit value of  $\tau(\varepsilon, \delta)$  satisfying Assumption 5.

## A Proofs of Section 3

### A.1 Proofs of Sections 3.2

**Proof. of Proposition 4.** The first order condition of the optimum yields

$$\arg \min_{\theta \in \mathbb{R}^d} \sum_{s=1}^{t-1} (y_s - \theta^T X_s)^2 + \frac{1}{2} (\theta - \hat{\theta}_1)^T P_1^{-1} (\theta - \hat{\theta}_1) = \hat{\theta}_1 + P_t \sum_{s=1}^{t-1} (y_s - \hat{\theta}_1^T X_s) X_s.$$

Therefore we prove recursively that  $\hat{\theta}_t - \hat{\theta}_1 = P_t \sum_{s=1}^{t-1} (y_s - \hat{\theta}_1^T X_s) X_s$ . It is clearly true at  $t = 1$ . Assuming it is true for some  $t \geq 1$ , we use the update formula

$$\begin{aligned} \hat{\theta}_{t+1} - \hat{\theta}_1 &= (I - P_{t+1} X_t X_t^T) (\hat{\theta}_t - \hat{\theta}_1) + P_{t+1} y_t X_t - P_{t+1} X_t X_t^T \hat{\theta}_1 \\ &= (I - P_{t+1} X_t X_t^T) P_t \sum_{s=1}^{t-1} (y_s - \hat{\theta}_1^T X_s) X_s + P_{t+1} (y_t - \hat{\theta}_1^T X_t) X_t. \end{aligned}$$

We conclude with the following identity:

$$(I - P_{t+1} X_t X_t^T) P_t = P_t - P_t X_t X_t^T P_t + \frac{P_t X_t X_t^T P_t X_t X_t^T P_t}{X_t^T P_t X_t + 1} = P_t - \frac{P_t X_t X_t^T P_t}{X_t^T P_t X_t + 1} = P_{t+1}.$$

□

**Proof. of Lemma 5.** We start from the update formula  $\hat{\theta}_{t+1} = \hat{\theta}_t + P_{t+1} \frac{(y_t - b'(\hat{\theta}_t^T X_t)) X_t}{a}$  yielding

$$\begin{aligned} (\hat{\theta}_{t+1} - \theta^*)^T P_{t+1}^{-1} (\hat{\theta}_{t+1} - \theta^*) &= (\hat{\theta}_t - \theta^*)^T P_{t+1}^{-1} (\hat{\theta}_t - \theta^*) + 2 \frac{(y_t - b'(\hat{\theta}_t^T X_t)) X_t^T}{a} (\hat{\theta}_t - \theta^*) \\ &\quad + X_t^T P_{t+1} X_t \left( \frac{y_t - b'(\hat{\theta}_t^T X_t)}{a} \right)^2. \end{aligned}$$

With a summation argument, re-arranging terms, we obtain:

$$\begin{aligned} &\sum_{t=1}^n \left( \frac{(b'(\hat{\theta}_t^T X_t) - y_t) X_t^T}{a} (\hat{\theta}_t - \theta^*) - \frac{1}{2} (\hat{\theta}_t - \theta^*)^T (P_{t+1}^{-1} - P_t^{-1}) (\hat{\theta}_t - \theta^*) \right) \\ &= \frac{1}{2} \sum_{t=1}^n X_t^T P_{t+1} X_t \left( \frac{y_t - b'(\hat{\theta}_t^T X_t)}{a} \right)^2 \\ &\quad + \frac{1}{2} \sum_{t=1}^n \left( (\hat{\theta}_t - \theta^*)^T P_t^{-1} (\hat{\theta}_t - \theta^*) - (\hat{\theta}_{t+1} - \theta^*)^T P_{t+1}^{-1} (\hat{\theta}_{t+1} - \theta^*) \right). \end{aligned}$$

We bound the telescopic sum: as  $P_{n+1}^{-1} \succcurlyeq 0$ , we have

$$\begin{aligned} &\sum_{t=\tau+1}^{\tau+n} \left( (\hat{\theta}_t - \theta^*)^T P_t^{-1} (\hat{\theta}_t - \theta^*) - (\hat{\theta}_{t+1} - \theta^*)^T P_{t+1}^{-1} (\hat{\theta}_{t+1} - \theta^*) \right) \\ &\leq (\hat{\theta}_1 - \theta^*)^T P_1^{-1} (\hat{\theta}_1 - \theta^*) \leq \frac{\|\hat{\theta}_1 - \theta^*\|^2}{\lambda_{\min}(P_1)}. \end{aligned}$$

The result follows from the identities

$$\frac{(b'(\hat{\theta}_t^T X_t) - y_t) X_t}{a} = \ell'(y_t, \hat{\theta}_t^T X_t) X_t, \quad P_{t+1}^{-1} - P_t^{-1} = \ell''(y_t, \hat{\theta}_t^T X_t) X_t X_t^T.$$

□

## A.2 Proofs of Section 3.3

**Proof. of Proposition 6.** We recall that  $\mathbb{E}_{y \sim p_{\theta^*}(y|X)}[y] = b'(\theta^{*T}X)$ , therefore

$$\mathbb{E}_{y \sim p_{\theta^*}(y|X)} \left[ \frac{(b'(\theta^T X) - y)(\theta - \theta^*)^T X}{a} \right] = \frac{(\theta - \theta^*)^T X}{a} (b'(\theta^T X) - b'(\theta^{*T} X)).$$

Thus, there exists  $\lambda \in [0, 1]$  such that

$$\mathbb{E}_{y \sim p_{\theta^*}(y|X)} \left[ \frac{(b'(\theta^T X) - y)(\theta - \theta^*)^T X}{a} \right] = \frac{(\theta - \theta^*)^T X}{a} b''(\theta^T X + \lambda(\theta^* - \theta)^T X) (\theta - \theta^*)^T X.$$

Then we use Assumption 3:

$$\frac{b''(\theta^T X + \lambda(\theta^* - \theta)^T X)}{b''(\theta^T X)} = \frac{\ell''(y_t, \theta^T X + \lambda(\theta^* - \theta)^T X)}{\ell''(y_t, \theta^T X)} \geq \rho_{\|\theta - \theta^*\|},$$

yielding

$$\mathbb{E}_{y \sim p_{\theta^*}(y|X)} [\ell'(y, \theta^T X) X]^T (\theta - \theta^*) \geq \rho_{\|\theta - \theta^*\|} (\theta - \theta^*)^T (\ell''(y, \theta^T X) X X^T) (\theta - \theta^*). \quad (3)$$

The first-order condition satisfied by  $\theta^*$  is

$$\mathbb{E} \left[ -\frac{(y - b'(\theta^{*T} X)) X}{a} \right] = 0,$$

which is re-written

$$\mathbb{E}[yX] = \mathbb{E}[b'(\theta^{*T} X) X] = \mathbb{E}[\mathbb{E}_{y \sim p_{\theta^*}(y|X)}[y] X].$$

Plugging it into Equation 3, we obtain

$$\mathbb{E}[\ell'(y, \theta^T X) X]^T (\theta - \theta^*) \geq \rho_{\|\theta - \theta^*\|} (\theta - \theta^*)^T \mathbb{E}[\ell''(y, \theta^T X) X X^T] (\theta - \theta^*).$$

□

**Proof. of Proposition 7.** We first recall that  $L(\theta) - L(\theta^*) \leq \frac{\partial L}{\partial \theta}^T (\theta - \theta^*)$ , then Proposition 6 yields

$$\frac{\partial L}{\partial \theta}^T (\theta - \theta^*) - c(\theta - \theta^*)^T \frac{\partial^2 L}{\partial \theta^2} (\theta - \theta^*) \geq \left(1 - \frac{c}{\rho_{\|\theta - \theta^*\|}}\right) \frac{\partial L}{\partial \theta}^T (\theta - \theta^*),$$

and the result follows. □

We prove the following Lemma, useful in several proofs, inspired by the stopping time technique of Freedman (1975).

**Lemma 15.** *Let  $(\mathcal{F}_n)$  be a filtration, and we consider a sequence of events  $(A_n)$  that is adapted to  $(\mathcal{F}_n)$ . Let  $(V_n)$  be a sequence of random variables adapted to  $(\mathcal{F}_n)$  satisfying  $V_0 = 1$ ,  $V_n \geq 0$  almost surely for any  $n$ , and*

$$\mathbb{E}[V_n | \mathcal{F}_{n-1}, A_{n-1}] \leq V_{n-1}, \quad n \geq 1.$$

Then for any  $\delta > 0$ , it holds

$$\mathbb{P} \left( \left( \bigcup_{n=1}^{\infty} V_n > \delta^{-1} \right) \cup \left( \bigcup_{n=0}^{\infty} \overline{A_n} \right) \right) \leq \delta + \mathbb{P} \left( \bigcup_{n=0}^{\infty} \overline{A_n} \right).$$

A particular case is when  $(V_n)$  is a super-martingale adapted to the filtration  $(\mathcal{F}_n)$  satisfying  $V_0 = 1$  and  $V_n \geq 0$  almost surely, then we have simultaneously  $V_n \leq \delta^{-1}$  for  $n \geq 1$  with probability larger than  $1 - \delta$ .

**Proof. of Lemma 15.** We define

$$E_k = \bigcup_{n=1}^k (V_n > \delta^{-1} \cup \overline{A_{n-1}}).$$

As  $(E_k)$  is increasing, we have, for any  $k \geq 1$ ,

$$\begin{aligned} \mathbb{P}(E_k) &= \sum_{n=1}^k \mathbb{P}(E_n \cap \overline{E_{n-1}}) \\ &= \sum_{n=1}^k \mathbb{P}(\overline{A_{n-1}} \cap \overline{E_{n-1}}) + \sum_{n=1}^k \mathbb{P}(V_n > \delta^{-1} \cap \overline{E_{n-1}} \cap A_{n-1}). \end{aligned}$$

First, we have

$$\sum_{n=1}^k \mathbb{P}(\overline{A_{n-1}} \cap \overline{E_{n-1}}) \leq \mathbb{P}\left(\bigcup_{n=0}^{k-1} \overline{A_n}\right).$$

Second, we apply the Chernoff bound:

$$\begin{aligned} \sum_{n=1}^k \mathbb{P}(V_n > \delta^{-1} \cap \overline{E_{n-1}} \cap A_{n-1}) &= \sum_{n=1}^k \mathbb{E}\left[\frac{V_n}{\delta^{-1}} \mathbb{1}_{E_n \cap \overline{E_{n-1}} \cap A_{n-1}}\right] \\ &\leq \delta \sum_{n=1}^k \mathbb{E}\left[V_n (\mathbb{1}_{\overline{E_{n-1}} \cap A_{n-1}} - \mathbb{1}_{\overline{E_n}})\right] \\ &= \delta \sum_{n=1}^k \left(\mathbb{E}\left[V_n \mathbb{1}_{\overline{E_{n-1}} \cap A_{n-1}}\right] - \mathbb{E}\left[V_n \mathbb{1}_{\overline{E_n}}\right]\right). \end{aligned}$$

The second line is obtained since  $\overline{E_n} \subset (\overline{E_{n-1}} \cap A_{n-1})$ . According to the tower property and the super-martingale assumption,

$$\mathbb{E}\left[V_n \mathbb{1}_{\overline{E_{n-1}} \cap A_{n-1}}\right] = \mathbb{E}\left[\mathbb{E}[V_n \mid \mathcal{F}_{n-1}, A_{n-1}] \mathbb{1}_{\overline{E_{n-1}}}\right] \leq \mathbb{E}\left[V_{n-1} \mathbb{1}_{\overline{E_{n-1}}}\right].$$

Therefore, a telescopic argument along with  $V_0 = 1$  and  $V_k \mathbb{1}_{\overline{E_k}} \geq 0$  yields

$$\sum_{n=1}^k \mathbb{P}(V_n > \delta^{-1} \cap \overline{E_{n-1}} \cap A_{n-1}) \leq \delta.$$

Finally, for any  $k \geq 1$ , we obtain

$$\mathbb{P}(E_k) \leq \mathbb{P}\left(\bigcup_{n=0}^{k-1} \overline{A_n}\right) + \delta$$

and the desired result follows by letting  $k \rightarrow \infty$ .  $\square$

**Proof. of Lemma 8.** Let  $\lambda > 0$ . For any  $n \geq 1$ , we define

$$V_n = \exp\left(\sum_{t=k+1}^{k+n} \left(\lambda \Delta N_t - \frac{\lambda^2}{2} ((\Delta N_t)^2 + \mathbb{E}[(\Delta N_t)^2 \mid \mathcal{F}_{t-1}])\right)\right).$$

Lemma B.1 of Bercu and Touati (2008) states that  $(V_n)$  is a super-martingale adapted to the filtration  $(\mathcal{F}_{k+n})$ . Moreover  $V_0 = 1$  and for any  $n$ , it holds  $V_n \geq 0$  almost surely. Therefore we can apply Lemma 15.  $\square$

**Proof. of Lemma 9.** We first develop  $(\Delta M_t)^2$ :

$$\begin{aligned} (\Delta M_t)^2 &= \left(\mathbb{E}[\nabla_t \mid \mathcal{F}_{t-1}] - \nabla_t\right)^T (\hat{\theta}_t - \theta^*)^2 \\ &= (\hat{\theta}_t - \theta^*)^T \left(\mathbb{E}[\nabla_t \mid \mathcal{F}_{t-1}] \mathbb{E}[\nabla_t \mid \mathcal{F}_{t-1}]^T + \nabla_t \nabla_t^T \right. \\ &\quad \left. - \nabla_t \mathbb{E}[\nabla_t \mid \mathcal{F}_{t-1}]^T - \mathbb{E}[\nabla_t \mid \mathcal{F}_{t-1}] \nabla_t^T\right) (\hat{\theta}_t - \theta^*) \\ &\leq 2(\hat{\theta}_t - \theta^*)^T \left(\mathbb{E}[\nabla_t \mid \mathcal{F}_{t-1}] \mathbb{E}[\nabla_t \mid \mathcal{F}_{t-1}]^T + \nabla_t \nabla_t^T\right) (\hat{\theta}_t - \theta^*) \\ &\leq 2(\hat{\theta}_t - \theta^*)^T \left(\mathbb{E}[\nabla_t \nabla_t^T \mid \mathcal{F}_{t-1}] + \nabla_t \nabla_t^T\right) (\hat{\theta}_t - \theta^*). \end{aligned}$$

The third line holds because if  $U, V \in \mathbb{R}^d$ , it holds  $-UV^T - VU^T \preceq UU^T + VV^T$ . The last one comes from  $\mathbb{E}\left[(\nabla_t - \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}])(\nabla_t - \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}])^T | \mathcal{F}_{t-1}\right] \succeq 0$ .

Also, we have the relation

$$\mathbb{E}[(\Delta M_t)^2 | \mathcal{F}_{t-1}] \leq (\hat{\theta}_t - \theta^*)^T \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] (\hat{\theta}_t - \theta^*).$$

It yields

$$(\Delta M_t)^2 + \mathbb{E}[(\Delta M_t)^2 | \mathcal{F}_{t-1}] \leq (\hat{\theta}_t - \theta^*)^T (3\mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] + 2\nabla_t \nabla_t^T) (\hat{\theta}_t - \theta^*),$$

and the result follows from Lemma 8.  $\square$

We derive the following Lemma in order to control the right-hand side of Lemma 5, in both settings.

**Lemma 16.** *Assume the second point of Assumption 3 holds. For any  $k, n \geq 1$ , if  $\|\hat{\theta}_t - \theta^*\|^2 \leq \varepsilon$  for any  $k < t \leq k+n$  then we have*

$$\sum_{t=k+1}^{k+n} \text{Tr} (P_{t+1}(P_{t+1}^{-1} - P_t^{-1})) \leq d \ln \left( 1 + n \frac{h_\varepsilon \lambda_{\max}(P_{k+1}) D_X^2}{d} \right).$$

**Proof.** We apply Lemma 11.11 of (Cesa-Bianchi and Lugosi, 2006):

$$\begin{aligned} \sum_{t=k+1}^{k+n} \text{Tr} (P_{t+1}(P_{t+1}^{-1} - P_t^{-1})) &= \sum_{t=k+1}^{k+n} \left( 1 - \frac{\det(P_t^{-1})}{\det(P_{t+1}^{-1})} \right) \\ &\leq \sum_{t=k+1}^{k+n} \ln \left( \frac{\det(P_{t+1}^{-1})}{\det(P_t^{-1})} \right) \\ &= \ln \left( \frac{\det(P_{k+n+1}^{-1})}{\det(P_{k+1}^{-1})} \right) \\ &\leq \ln \det \left( I + \sum_{t=k+1}^{k+n} \ell''(y_t, \hat{\theta}_t^T X_t) (P_{k+1}^{1/2} X_t) (P_{k+1}^{1/2} X_t)^T \right) \\ &= \sum_{i=1}^d \ln(1 + \lambda_i), \end{aligned}$$

where  $\lambda_1, \dots, \lambda_d$  are the eigenvalues of  $\sum_{t=k+1}^{k+n} \ell''(y_t, \hat{\theta}_t^T X_t) (P_{k+1}^{1/2} X_t) (P_{k+1}^{1/2} X_t)^T$ . Therefore we have

$$\begin{aligned} \sum_{t=k+1}^{k+n} \text{Tr} (P_{t+1}(P_{t+1}^{-1} - P_t^{-1})) &\leq d \ln \left( 1 + \frac{1}{d} \sum_{i=1}^d \lambda_i \right) \\ &\leq d \ln \left( 1 + \frac{1}{d} n h_\varepsilon \lambda_{\max}(P_{k+1}) D_X^2 \right). \end{aligned}$$

$\square$

### A.3 Bounded setting (Assumption 3)

**Proof. of Theorem 1.** Let  $\delta > 0$ . On the one hand, we sum Lemma 5 and 9. We obtain, for any  $\lambda > 0$ ,

$$\begin{aligned} &\sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left( \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}]^T (\hat{\theta}_t - \theta^*) - \frac{1}{2} Q_t - \lambda (\hat{\theta}_t - \theta^*)^T \left( \nabla_t \nabla_t^T + \frac{3}{2} \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] \right) (\hat{\theta}_t - \theta^*) \right) \\ &\leq \frac{1}{2} \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} X_t^T P_{t+1} X_t \ell'(y_t, \hat{\theta}_t^T X_t)^2 + \frac{\|\hat{\theta}_1 - \theta^*\|^2}{\lambda_{\min}(P_{\tau(\varepsilon, \delta)+1})} + \frac{\ln \delta^{-1}}{\lambda}, \quad n \geq 1, \end{aligned} \quad (4)$$

with probability at least  $1 - \delta$ , where we define  $Q_t = (\hat{\theta}_t - \theta^*)^T \left( \ell''(y_t, \hat{\theta}_t^T X_t) X_t X_t^T \right) (\hat{\theta}_t - \theta^*)$  for any  $t$ .

On the other hand, thanks to Assumption 3, we can apply Proposition 7 with  $c = 0.75$  to obtain, for any  $t \geq 1$ ,

$$\begin{aligned} \|\hat{\theta}_t - \theta^*\| \leq \varepsilon &\implies L(\hat{\theta}_t) - L(\theta^*) \leq \frac{\rho_\varepsilon}{\rho_\varepsilon - 0.75} \left( \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}^T (\hat{\theta}_t - \theta^*) - 0.75 (\hat{\theta}_t - \theta^*)^T \frac{\partial^2 L}{\partial \theta^2} \Big|_{\hat{\theta}_t} (\hat{\theta}_t - \theta^*) \right), \\ &\implies L(\hat{\theta}_t) - L(\theta^*) \leq 5 \left( \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}]^T (\hat{\theta}_t - \theta^*) - 0.75 \mathbb{E}[Q_t | \mathcal{F}_{t-1}] \right), \end{aligned} \quad (5)$$

because  $\rho_\varepsilon > 0.95$ .

In order to bridge the gap between Equations (4) and (5), we need to control the quadratic terms of Equation (4) with  $\mathbb{E}[Q_t | \mathcal{F}_{t-1}]$ . First, for any  $t$ , if  $\|\hat{\theta}_t - \theta^*\| \leq \varepsilon$ , we have  $Q_t \in [0, h_\varepsilon \varepsilon^2 D_X^2]$ , and we apply Lemma A.3 of Cesa-Bianchi and Lugosi (2006) to the random variable  $\frac{1}{h_\varepsilon \varepsilon^2 D_X^2} Q_t \in [0, 1]$ : for any  $s > 0$ ,

$$\mathbb{E} \left[ \exp \left( \frac{s}{h_\varepsilon \varepsilon^2 D_X^2} Q_t - \frac{e^s - 1}{h_\varepsilon \varepsilon^2 D_X^2} \mathbb{E}[Q_t | \mathcal{F}_{t-1}] \right) \mid \mathcal{F}_{t-1}, \|\hat{\theta}_t - \theta^*\| \leq \varepsilon \right] \leq 1.$$

We fix  $s = 0.1$  and we define

$$V_n = \exp \left( \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left( \frac{0.1}{h_\varepsilon \varepsilon^2 D_X^2} Q_t - (e^{0.1} - 1) \mathbb{E} \left[ \frac{1}{h_\varepsilon \varepsilon^2 D_X^2} Q_t \mid \mathcal{F}_{t-1} \right] \right) \right).$$

The sequence  $(V_n)$  is adapted to  $(\mathcal{F}_{\tau(\varepsilon, \delta)+n})$ , almost surely we have  $V_0 = 1$  and  $V_n \geq 0$ . Finally,

$$\mathbb{E}[V_n | \mathcal{F}_{\tau(\varepsilon, \delta)+n-1}, \|\hat{\theta}_{\tau(\varepsilon, \delta)+n} - \theta^*\| \leq \varepsilon] \leq V_{n-1},$$

and  $(\|\hat{\theta}_{\tau(\varepsilon, \delta)+n} - \theta^*\| \leq \varepsilon)$  belongs to  $\mathcal{F}_{\tau(\varepsilon, \delta)+n-1}$ . We apply Lemma 15:

$$\mathbb{P} \left( \left( \bigcup_{n=1}^{\infty} V_n > \delta^{-1} \right) \cup \left( \bigcup_{n=1}^{\infty} (\|\hat{\theta}_{\tau(\varepsilon, \delta)+n} - \theta^*\| > \varepsilon) \right) \right) \leq \delta + \mathbb{P} \left( \bigcup_{n=1}^{\infty} (\|\hat{\theta}_{\tau(\varepsilon, \delta)+n} - \theta^*\| > \varepsilon) \right).$$

We define  $A_k^\varepsilon = \bigcap_{n=k+1}^{\infty} (\|\hat{\theta}_n - \theta^*\| \leq \varepsilon)$  for any  $k$ . The last inequality is equivalent to

$$\mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} Q_t > 10(e^{0.1} - 1) \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \mathbb{E}[Q_t | \mathcal{F}_{t-1}] + 10h_\varepsilon \varepsilon^2 D_X^2 \ln \delta^{-1} \right) \cap A_{\tau(\varepsilon, \delta)}^\varepsilon \right) \leq \delta. \quad (6)$$

We then bound the two quadratic terms coming from Lemma 9: using Assumption 3 we have the implications

$$\begin{aligned} \|\hat{\theta}_t - \theta^*\| \leq \varepsilon &\implies (\hat{\theta}_t - \theta^*)^T \nabla_t \nabla_t^T (\hat{\theta}_t - \theta^*) \leq \kappa_\varepsilon Q_t, \\ \|\hat{\theta}_t - \theta^*\| \leq \varepsilon &\implies (\hat{\theta}_t - \theta^*)^T \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] (\hat{\theta}_t - \theta^*) \leq \kappa_\varepsilon \mathbb{E}[Q_t | \mathcal{F}_{t-1}]. \end{aligned}$$

Therefore, we get from (6)

$$\begin{aligned} &\mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left( \frac{1}{2} Q_t + \lambda (\hat{\theta}_t - \theta^*)^T \nabla_t \nabla_t^T (\hat{\theta}_t - \theta^*) + \frac{3}{2} \lambda (\hat{\theta}_t - \theta^*)^T \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] (\hat{\theta}_t - \theta^*) \right) > \right. \right. \\ &\quad \left. \left( 10(e^{0.1} - 1) \left( \frac{1}{2} + \lambda \kappa_\varepsilon \right) + \frac{3}{2} \lambda \kappa_\varepsilon \right) \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \mathbb{E}[Q_t | \mathcal{F}_{t-1}] + 10 \left( \frac{1}{2} + \lambda \kappa_\varepsilon \right) h_\varepsilon \varepsilon^2 D_X^2 \ln \delta^{-1} \right) \cap A_{\tau(\varepsilon, \delta)}^\varepsilon \right) \\ &\leq \delta. \end{aligned}$$

We set  $\lambda = \frac{0.75 - 5(e^{0.1} - 1)}{(10(e^{0.1} - 1) + \frac{3}{2})\kappa_\varepsilon}$ , so that

$$\begin{aligned} 10(e^{0.1} - 1) \left( \frac{1}{2} + \lambda \kappa_\varepsilon \right) + \frac{3}{2} \lambda \kappa_\varepsilon &= 0.75, \\ \frac{1}{2} + \lambda \kappa_\varepsilon &= \frac{1}{2} + \frac{0.75 - 5(e^{0.1} - 1)}{10(e^{0.1} - 1) + \frac{3}{2}} \approx 0.59 \leq 0.6, \end{aligned}$$



and consequently

$$\begin{aligned} & \mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left( \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}]^T (\hat{\theta}_t - \theta^*) - 0.75 \mathbb{E}[Q_t | \mathcal{F}_{t-1}] \right) > 6h_\varepsilon \varepsilon^2 D_X^2 \ln \delta^{-1} \right. \right. \\ & \quad \left. \left. + \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left( \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}]^T (\hat{\theta}_t - \theta^*) - \frac{1}{2} Q_t - \lambda (\hat{\theta}_t - \theta^*)^T \left( \nabla_t \nabla_t^T + \frac{3}{2} \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] \right) (\hat{\theta}_t - \theta^*) \right) \right) \right. \\ & \quad \left. \cap A_{\tau(\varepsilon, \delta)}^\varepsilon \right) \leq \delta. \end{aligned}$$

We plug Equation (5) in the last inequality:

$$\begin{aligned} & \mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} (L(\hat{\theta}_t) - L(\theta^*)) > 30h_\varepsilon \varepsilon^2 D_X^2 \ln \delta^{-1} \right. \right. \\ & \quad \left. \left. + 5 \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left( \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}]^T (\hat{\theta}_t - \theta^*) - \frac{1}{2} Q_t \right. \right. \right. \\ & \quad \left. \left. \left. - \lambda (\hat{\theta}_t - \theta^*)^T \left( \nabla_t \nabla_t^T + \frac{3}{2} \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] \right) (\hat{\theta}_t - \theta^*) \right) \right) \cap A_{\tau(\varepsilon, \delta)}^\varepsilon \right) \leq \delta. \end{aligned}$$

We then use Equation (4) with  $\frac{1}{\lambda} = \frac{10(\varepsilon^{0.1}-1)+\frac{3}{2}\kappa_\varepsilon}{0.75-5(\varepsilon^{0.1}-1)} \approx 11.4\kappa_\varepsilon \leq 12\kappa_\varepsilon$ . It yields

$$\begin{aligned} & \mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} (L(\hat{\theta}_t) - L(\theta^*)) > \frac{5}{2} \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} X_t^T P_{t+1} X_t \ell'(y_t, \hat{\theta}_t^T X_t)^2 \right. \right. \\ & \quad \left. \left. + \frac{5\|\hat{\theta}_1 - \theta^*\|^2}{\lambda_{\min}(P_{\tau(\varepsilon, \delta)+1})} + 30(2\kappa_\varepsilon + h_\varepsilon \varepsilon^2 D_X^2) \ln \delta^{-1} \right) \cap A_{\tau(\varepsilon, \delta)}^\varepsilon \right) \leq 2\delta. \end{aligned}$$

Thanks to Assumption 3, we have

$$X_t^T P_{t+1} X_t \ell'(y_t, \hat{\theta}_t^T X_t)^2 \leq \kappa_\varepsilon \text{Tr} (P_{t+1}(P_{t+1}^{-1} - P_t^{-1})), \quad t > \tau(\varepsilon, \delta),$$

therefore we apply Lemma 16: for any  $n$ , it holds

$$\sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} X_t^T P_{t+1} X_t \ell'(y_t, \hat{\theta}_t^T X_t)^2 \leq d\kappa_\varepsilon \ln \left( 1 + n \frac{h_\varepsilon \lambda_{\max}(P_{\tau(\varepsilon, \delta)+1}) D_X^2}{d} \right).$$

As  $P_{\tau(\varepsilon, \delta)+1} \preceq P_1$ , we obtain

$$\begin{aligned} & \mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} (L(\hat{\theta}_t) - L(\theta^*)) > \frac{5}{2} d\kappa_\varepsilon \ln \left( 1 + n \frac{h_\varepsilon \lambda_{\max}(P_{\tau(\varepsilon, \delta)+1}) D_X^2}{d} \right) \right. \right. \\ & \quad \left. \left. + \frac{5\|\hat{\theta}_1 - \theta^*\|^2}{\lambda_{\min}(P_{\tau(\varepsilon, \delta)+1})} + 30(2\kappa_\varepsilon + h_\varepsilon \varepsilon^2 D_X^2) \ln \delta^{-1} \right) \cap A_{\tau(\varepsilon, \delta)}^\varepsilon \right) \leq 2\delta. \end{aligned}$$

To conclude, we use Assumption 5. □

#### A.4 Quadratic setting (Assumption 4)

We recall two definitions introduced in the previous subsection:

$$\begin{aligned} A_k^\varepsilon &= \bigcap_{n=k+1}^{\infty} (\|\hat{\theta}_n - \theta^*\| \leq \varepsilon), \quad k \geq 1, \\ Q_t &= (\hat{\theta}_t - \theta^*)^T X_t X_t^T (\hat{\theta}_t - \theta^*), \quad t \geq 1. \end{aligned}$$

The sub-gaussian hypothesis requires a different treatment of several steps in the proof. In the following proofs, we use a consequence of the first points of Assumption 4. We apply Lemma 1.4 of Rigollet and Hütter (2015): for any  $X \in \mathbb{R}^d$ ,

$$\mathbb{E}[(y - \mathbb{E}[y | X])^{2i} | X] \leq 2i(2\sigma^2)^i \Gamma(i) = 2(2\sigma^2)^i i!, \quad i \in \mathbb{N}^*. \quad (7)$$

First, we control the quadratic terms in  $\nabla_t = -(y_t - \hat{\theta}_t^T X_t)X_t$  in the following lemma.

**Lemma 17.** *1. For any  $k \in \mathbb{N}$  and  $\delta > 0$ , we have*

$$\begin{aligned} & \mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=k+1}^{k+n} (\hat{\theta}_t - \theta^*)^T \nabla_t \nabla_t^T (\hat{\theta}_t - \theta^*) \right. \right. \\ & \quad \left. \left. > 3(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \sum_{t=k+1}^{k+n} Q_t + 12\varepsilon^2 D_X^2 \sigma^2 \ln \delta^{-1} \right) \cap A_k^{\varepsilon} \right) \leq \delta. \end{aligned}$$

*2. For any  $t$ , it holds almost surely*

$$(\hat{\theta}_t - \theta^*)^T \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] (\hat{\theta}_t - \theta^*) \leq 3(\sigma^2 + D_{\text{app}}^2 + \|\hat{\theta}_t - \theta^*\|^2 D_X^2) \mathbb{E}[Q_t | \mathcal{F}_{t-1}].$$

**Proof.** *1. We recall that for any  $a, b, c$ , we have  $(a + b + c)^2 \leq 3(a^2 + b^2 + c^2)$ . Thus*

$$\begin{aligned} (\hat{\theta}_t - \theta^*)^T \nabla_t \nabla_t^T (\hat{\theta}_t - \theta^*) &= Q_t (y_t - \hat{\theta}_t^T X_t)^2 \\ &\leq 3Q_t \left( (y_t - \mathbb{E}[y_t | X_t])^2 + (\mathbb{E}[y_t | X_t] - \theta^{*T} X_t)^2 + ((\theta^* - \hat{\theta}_t)^T X_t)^2 \right) \\ &\leq 3Q_t \left( (y_t - \mathbb{E}[y_t | X_t])^2 + D_{\text{app}}^2 + \|\hat{\theta}_t - \theta^*\|^2 D_X^2 \right). \end{aligned} \quad (8)$$

To obtain the last inequality, we use the second point of Assumption 4 to bound the middle term. Then we use Taylor series for the exponential, and we apply Equation (7). For any  $t$  and any  $\mu$  satisfying  $0 < \mu \leq \frac{1}{4Q_t \sigma^2}$ , we have

$$\begin{aligned} \mathbb{E} \left[ \exp(\mu Q_t (y_t - \mathbb{E}[y_t | X_t])^2) | \mathcal{F}_{t-1}, X_t \right] &= 1 + \sum_{i \geq 1} \frac{\mu^i Q_t^i \mathbb{E}[(y_t - \mathbb{E}[y_t | X_t])^{2i} | X_t]}{i!} \\ &\leq 1 + 2 \sum_{i \geq 1} \frac{\mu^i Q_t^i i! (2\sigma^2)^i}{i!} \\ &\leq 1 + 2 \sum_{i \geq 1} (2\mu Q_t \sigma^2)^i \\ &\leq 1 + 8\mu Q_t \sigma^2, \quad 2\mu Q_t \sigma^2 \leq \frac{1}{2} \\ &\leq \exp(8\mu Q_t \sigma^2). \end{aligned}$$

Therefore, for any  $t$ ,

$$\mathbb{E} \left[ \exp \left( \frac{1}{4\varepsilon^2 D_X^2 \sigma^2} Q_t ((y_t - \mathbb{E}[y_t | X_t])^2 - 8\sigma^2) \right) | \mathcal{F}_{t-1}, X_t, \|\hat{\theta}_t - \theta^*\| \leq \varepsilon \right] \leq 1.$$

We define the random variable

$$V_n = \exp \left( \frac{1}{4\varepsilon^2 D_X^2 \sigma^2} \sum_{t=k+1}^{k+n} Q_t ((y_t - \mathbb{E}[y_t | X_t])^2 - 8\sigma^2) \right), \quad n \in \mathbb{N}.$$

$(V_n)_n$  is adapted to the filtration  $(\sigma(X_1, y_1, \dots, X_{k+n}, y_{k+n}, X_{k+n+1}))_n$ , moreover  $V_0 = 1$  and  $V_n \geq 0$  almost surely, and

$$\mathbb{E}[V_n | X_1, y_1, \dots, X_{k+n-1}, y_{k+n-1}, X_{k+n}, \|\hat{\theta}_{k+n} - \theta^*\| \leq \varepsilon] \leq V_{n-1}.$$

Therefore we apply Lemma 15: for any  $\delta > 0$ ,

$$\mathbb{P}\left(\bigcup_{n=1}^{\infty} (V_n > \delta^{-1}) \cap A_k^\varepsilon\right) \leq \delta,$$

which is equivalent to

$$\mathbb{P}\left(\bigcup_{n=1}^{\infty} \left(\sum_{t=k+1}^{k+n} Q_t (y_t - \mathbb{E}[y_t | X_t])^2 > 8\sigma^2 \sum_{t=k+1}^{k+n} Q_t + 4\varepsilon^2 D_X^2 \sigma^2 \ln \delta^{-1}\right) \cap A_k^\varepsilon\right) \leq \delta.$$

Substituting in Equation (8), we obtain the desired result.

2. We apply the same decomposition as for Equation 8: for any  $t$ ,

$$\begin{aligned} & (\hat{\theta}_t - \theta^*)^T \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] (\hat{\theta}_t - \theta^*) \\ & \leq 3(\hat{\theta}_t - \theta^*)^T \mathbb{E}\left[X_t X_t^T \left((y_t - \mathbb{E}[y_t | X_t])^2 + D_{\text{app}}^2 + \|\theta^* - \hat{\theta}_t\|^2 D_X^2\right) | \mathcal{F}_{t-1}\right] (\hat{\theta}_t - \theta^*). \end{aligned}$$

Assumption 4 implies that for any  $X_t$ ,  $\mathbb{E}[(y_t - \mathbb{E}[y_t | X_t])^2 | X_t] \leq \sigma^2$ . Thus, the tower property yields

$$\begin{aligned} & (\hat{\theta}_t - \theta^*)^T \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] (\hat{\theta}_t - \theta^*) \\ & \leq 3\left(\sigma^2 + D_{\text{app}}^2 + \|\hat{\theta}_t - \theta^*\|^2 D_X^2\right) (\hat{\theta}_t - \theta^*)^T \mathbb{E}[X_t X_t^T | \mathcal{F}_{t-1}] (\hat{\theta}_t - \theta^*). \end{aligned}$$

□

Second, we bound the right-hand side of Lemma 5, that is the objective of the following lemma.

**Lemma 18.** *Let  $k \in \mathbb{N}$ . For any  $\delta > 0$ , we have*

$$\begin{aligned} \mathbb{P}\left(\bigcup_{n=1}^{\infty} \left(\sum_{t=k+1}^{k+n} X_t^T P_{t+1} X_t (y_t - \hat{\theta}_t^T X_t)^2 > 3\left(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2\right) d \ln\left(1 + n \frac{\lambda_{\max}(P_{k+1}) D_X^2}{d}\right) \right. \right. \\ \left. \left. + 12\lambda_{\max}(P_1) D_X^2 \sigma^2 \ln \delta^{-1}\right) \cap A_k^\varepsilon\right) \leq \delta. \end{aligned}$$

**Proof.** We apply a similar analysis as in the proof of Lemma 17 in order to use the sub-gaussian assumption, and then we apply the telescopic argument as in the bounded setting. We decompose  $y_t - \hat{\theta}_t^T X_t$ :

$$\begin{aligned} X_t^T P_{t+1} X_t (y_t - \hat{\theta}_t^T X_t)^2 & \leq 3X_t^T P_{t+1} X_t \left((y_t - \mathbb{E}[y_t | X_t])^2 + (\mathbb{E}[y_t | X_t] - b'(\theta^{*T} X_t))^2 + ((\theta^* - \hat{\theta}_t)^T X_t)^2\right) \\ & \leq 3X_t^T P_{t+1} X_t \left((y_t - \mathbb{E}[y_t | X_t])^2 + D_{\text{app}}^2 + \|\hat{\theta}_t - \theta^*\|^2 D_X^2\right). \end{aligned} \quad (9)$$

To control  $(y_t - \mathbb{E}[y_t | X_t])^2 X_t^T P_{t+1} X_t$ , we use its positivity along with Equation (7). Precisely, for any  $t$  and any  $\mu > 0$  satisfying  $0 < \mu \leq \frac{1}{4X_t^T P_{t+1} X_t \sigma^2}$ , we have

$$\begin{aligned} \mathbb{E}\left[\exp\left(\mu(y_t - \mathbb{E}[y_t | X_t])^2 X_t^T P_{t+1} X_t\right) | \mathcal{F}_{t-1}, X_t\right] & = 1 + \sum_{i \geq 1} \frac{\mu^i (X_t^T P_{t+1} X_t)^i \mathbb{E}\left[(y_t - \mathbb{E}[y_t | X_t])^{2i} | X_t\right]}{i!} \\ & \leq 1 + 2 \sum_{i \geq 1} \frac{\mu^i (X_t^T P_{t+1} X_t)^i i! (2\sigma^2)^i}{i!} \\ & = 1 + 2 \sum_{i \geq 1} (2\mu X_t^T P_{t+1} X_t \sigma^2)^i \\ & \leq 1 + 8\mu X_t^T P_{t+1} X_t \sigma^2, \quad 0 < 2\mu X_t^T P_{t+1} X_t \sigma^2 \leq \frac{1}{2} \\ & \leq \exp\left(8\mu X_t^T P_{t+1} X_t \sigma^2\right). \end{aligned}$$

We apply the previous bound with a uniform  $\mu = \frac{1}{4\lambda_{\max}(P_1)D_X^2\sigma^2}$ , and as  $\lambda_{\max}(P_{t+1}) \leq \lambda_{\max}(P_1)$  for any  $t$ , we get  $\mu \leq \frac{1}{4X_t^T P_{t+1} X_t \sigma^2}$ . Thus, we define

$$V_n = \exp\left(\frac{1}{4\lambda_{\max}(P_1)D_X^2\sigma^2} \sum_{t=k+1}^{k+n} ((y_t - \mathbb{E}[y_t | X_t])^2 - 8\sigma^2) X_t^T P_{t+1} X_t\right), \quad n \in \mathbb{N}.$$

$(V_n)$  is a super-martingale adapted to the filtration  $(\sigma(X_1, y_1, \dots, X_{k+n-1}, y_{k+n-1}, X_{k+n}))_n$  satisfying almost surely  $V_0 = 1, V_n \geq 0$ , thus we apply Lemma 15:

$$\mathbb{P}\left(\bigcup_{n=1}^{\infty} (V_n > \delta^{-1})\right) \leq \delta,$$

or equivalently

$$\mathbb{P}\left(\bigcup_{n=1}^{\infty} \left(\sum_{t=k+1}^{k+n} X_t^T P_{t+1} X_t (y_t - \mathbb{E}[y_t | X_t])^2 > 8\sigma^2 \sum_{t=k+1}^{k+n} X_t^T P_{t+1} X_t + 4\lambda_{\max}(P_1)D_X^2\sigma^2 \ln \delta^{-1}\right)\right) \leq \delta.$$

Combining it with Equation (9), we get

$$\mathbb{P}\left(\bigcup_{n=1}^{\infty} \left(\sum_{t=k+1}^{k+n} X_t^T P_{t+1} X_t (y_t - \hat{\theta}_t^T X_t)^2 > 3(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \sum_{t=k+1}^{k+n} X_t^T P_{t+1} X_t + 12\lambda_{\max}(P_1)D_X^2\sigma^2 \ln \delta^{-1}\right) \cap A_k^\varepsilon\right) \leq \delta.$$

Then we apply Lemma 16: the second point of Assumption 3 holds with  $h_\varepsilon = 1$ , thus

$$\sum_{t=k+1}^{k+n} \text{Tr}(P_{t+1}(P_{t+1}^{-1} - P_t^{-1})) \leq d \ln\left(1 + n \frac{\lambda_{\max}(P_{k+1})D_X^2}{d}\right), \quad n \geq 1.$$

We conclude with  $X_t^T P_{t+1} X_t = \text{Tr}(P_{t+1}(P_{t+1}^{-1} - P_t^{-1}))$ .  $\square$

We sum up our findings and we prove the result for the quadratic loss. The structure of the proof is the same as the one of Theorem 1.

**Proof. of Theorem 2.** On the one hand, we sum Lemma 5 and Lemma 9: for any  $\lambda, \delta > 0$ ,

$$\begin{aligned} & \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left( \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}]^T (\hat{\theta}_t - \theta^*) - \frac{1}{2} Q_t - \lambda (\hat{\theta}_t - \theta^*)^T \left( \nabla_t \nabla_t^T + \frac{3}{2} \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] \right) (\hat{\theta}_t - \theta^*) \right) \\ & \leq \frac{1}{2} \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} X_t^T P_{t+1} X_t (y_t - \hat{\theta}_t^T X_t)^2 + \frac{\|\hat{\theta}_{\tau(\varepsilon, \delta)+1} - \theta^*\|^2}{\lambda_{\min}(P_{\tau(\varepsilon, \delta)+1})} + \frac{\ln \delta^{-1}}{\lambda}, \quad n \geq 1, \end{aligned} \quad (10)$$

with probability at least  $1 - \delta$ . On the other hand, we have

$$\sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} (L(\hat{\theta}_t) - L(\theta^*)) \leq \frac{1}{1-0.8} \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left( \mathbb{E}[\nabla_t | \mathcal{F}_{t-1}]^T (\hat{\theta}_t - \theta^*) - 0.8 \mathbb{E}[Q_t | \mathcal{F}_{t-1}] \right). \quad (11)$$

We aim to relate Equations (10) and (11) as in the proof of Theorem 1. To that end, we apply Lemma 17:

$$\begin{aligned} & \mathbb{P}\left(\bigcup_{n=1}^{\infty} \left(\sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \left(\frac{1}{2} Q_t + \lambda (\hat{\theta}_t - \theta^*)^T \left( \nabla_t \nabla_t^T + \frac{3}{2} \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] \right) (\hat{\theta}_t - \theta^*)\right)\right.\right. \\ & > \left(\frac{1}{2} + 3\lambda(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2)\right) \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} Q_t \\ & \left. \left. + \frac{9}{2} \lambda (\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \sum_{t=\tau(\varepsilon, \delta)+1}^{\tau(\varepsilon, \delta)+n} \mathbb{E}[Q_t | \mathcal{F}_{t-1}] + 12\lambda\varepsilon^2 D_X^2 \sigma^2 \ln \delta^{-1}\right) \cap A_{\tau(\varepsilon, \delta)}^\varepsilon\right) \leq \delta. \end{aligned}$$

As in the proof of Theorem 1 we apply Lemma A.3 of (Cesa-Bianchi and Lugosi, 2006) and Lemma 15: for any  $\delta > 0$ ,

$$\mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=\tau(\varepsilon,\delta)+1}^{\tau(\varepsilon,\delta)+n} Q_t > 10(e^{0.1} - 1) \sum_{t=\tau(\varepsilon,\delta)+1}^{\tau(\varepsilon,\delta)+n} \mathbb{E}[Q_t | \mathcal{F}_{t-1}] + 10\varepsilon^2 D_X^2 \ln \delta^{-1} \right) \cap A_{\tau(\varepsilon,\delta)}^\varepsilon \right) \leq \delta.$$

We combine the last two inequalities:

$$\begin{aligned} & \mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( \sum_{t=\tau(\varepsilon,\delta)+1}^{\tau(\varepsilon,\delta)+n} \left( \frac{1}{2} Q_t + \lambda(\hat{\theta}_t - \theta^*)^T \left( \nabla_t \nabla_t^T + \frac{3}{2} \mathbb{E}[\nabla_t \nabla_t^T | \mathcal{F}_{t-1}] \right) (\hat{\theta}_t - \theta^*) \right) \right. \right. \\ & > \left. \left( 10(e^{0.1} - 1) \left( \frac{1}{2} + 3\lambda(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \right) + \frac{9}{2} \lambda(\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \right) \sum_{t=\tau(\varepsilon,\delta)+1}^{\tau(\varepsilon,\delta)+n} \mathbb{E}[Q_t | \mathcal{F}_{t-1}] \right. \\ & \left. + \left( 10\varepsilon^2 D_X^2 \left( \frac{1}{2} + 3\lambda(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \right) + 12\lambda\varepsilon^2 D_X^2 \sigma^2 \right) \ln \delta^{-1} \right) \cap A_{\tau(\varepsilon,\delta)}^\varepsilon \right) \leq 2\delta. \end{aligned} \quad (12)$$

We set

$$\lambda = (0.8 - 5(e^{0.1} - 1)) \left( 30(e^{0.1} - 1)(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) + \frac{9}{2}(\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \right)^{-1}$$

in order to obtain

$$\begin{aligned} & 10(e^{0.1} - 1) \left( \frac{1}{2} + 3\lambda(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \right) + \frac{9}{2} \lambda(\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) = 0.8, \\ & \frac{1}{109\sigma^2 + 28D_{\text{app}}^2 + 28\varepsilon^2 D_X^2} < \lambda < \frac{1}{108\sigma^2 + 27D_{\text{app}}^2 + 27\varepsilon^2 D_X^2}, \\ & 10\varepsilon^2 D_X^2 \left( \frac{1}{2} + 3\lambda(8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \right) + 12\lambda D_X^2 \varepsilon^2 \sigma^2 \leq 8\varepsilon^2 D_X^2 \\ & \frac{1}{\lambda} \leq 28(4\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2). \end{aligned}$$

Combining Equations (10), (11) and (12), we obtain

$$\begin{aligned} & \mathbb{P} \left( \bigcup_{n=1}^{\infty} \left( 0.2 \sum_{t=\tau(\varepsilon,\delta)+1}^{\tau(\varepsilon,\delta)+n} (L(\hat{\theta}_t) - L(\theta^*)) > \frac{1}{2} \sum_{t=\tau(\varepsilon,\delta)+1}^{\tau(\varepsilon,\delta)+n} X_t^T P_{t+1} X_t (y_t - \hat{\theta}_t^T X_t)^2 + \frac{\varepsilon^2}{\lambda_{\min}(P_{\tau(\varepsilon,\delta)+1})} \right. \right. \\ & \left. \left. + 28(4\sigma^2 + D_{\text{approx}}^2 + \varepsilon^2 D_X^2) \ln \delta^{-1} + 8\varepsilon^2 D_X^2 \ln \delta^{-1} \right) \cap A_{\tau(\varepsilon,\delta)}^\varepsilon \right) \leq 3\delta. \end{aligned}$$

Finally, we apply Lemma 18 with  $P_{\tau(\varepsilon,\delta)+1} \preceq P_1$  and we use Assumption 5: it holds simultaneously

$$\begin{aligned} & \sum_{t=\tau(\varepsilon,\delta)+1}^{\tau(\varepsilon,\delta)+n} L(\hat{\theta}_t) - L(\theta^*) \leq 5 \left( \frac{3}{2} (8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) d \ln \left( 1 + n \frac{\lambda_{\max}(P_1) D_X^2}{d} \right) + \lambda_{\max}(P_{\tau(\varepsilon,\delta)+1}^{-1}) \varepsilon^2 \right. \\ & \quad \left. + 28(4\sigma^2 + D_{\text{approx}}^2 + \varepsilon^2 D_X^2) \ln \delta^{-1} + 8\varepsilon^2 D_X^2 \ln \delta^{-1} \right. \\ & \quad \left. + 6\lambda_{\max}(P_1) D_X^2 \sigma^2 \ln \delta^{-1} \right), \quad n \geq 1, \end{aligned}$$

with probability at least  $1 - 5\delta$ . To conclude, we write

$$28(4\sigma^2 + D_{\text{approx}}^2 + \varepsilon^2 D_X^2) + 8\varepsilon^2 D_X^2 + 6\lambda_{\max}(P_1) D_X^2 \sigma^2 \leq 28 \left( \sigma^2 \left( 4 + \frac{\lambda_{\max}(P_1) D_X^2}{4} \right) + D_{\text{app}}^2 + 2\varepsilon^2 D_X^2 \right).$$

□

## B Proofs of Section 4

### B.1 Proof of Theorem 10

**Proof. of Theorem 10.** For any  $\varepsilon > 0$ , we check Assumption 3 with  $\kappa_\varepsilon = e^{D_X(\|\theta^*\|+\varepsilon)}$ ,  $h_\varepsilon = \frac{1}{4}$ ,  $\rho_\varepsilon = e^{-\varepsilon D_X}$ . In order to apply Theorem 1, we define  $\varepsilon$  such that  $\rho_\varepsilon = 0.95$ , that is  $\varepsilon = \ln(1/0.95)/D_X$ . We can thus apply Theorem

1 with  $\lambda_{\max}(P_{\tau(\varepsilon, \delta)+1}^{-1}) \leq \lambda_{\max}(P_1^{-1}) + \frac{1}{4} \sum_{t=1}^{\tau(\varepsilon, \delta)} \|X_t\|^2$ :

$$\begin{aligned} \sum_{t=\tau(\varepsilon, \delta)+1}^n L(\hat{\theta}_t) - L(\theta^*) &\leq \frac{5de^{D_X(\|\theta^*\|+\varepsilon)}}{2} \ln \left( 1 + (n - \tau(\varepsilon, \delta)) \frac{\lambda_{\max}(P_1)D_X^2}{4d} \right) \\ &\quad + 5 \left( \lambda_{\max}(P_1^{-1}) + \frac{\tau(\varepsilon, \delta)D_X^2}{4} \right) \varepsilon^2 \\ &\quad + 30 \left( 2e^{D_X(\|\theta^*\|+\varepsilon)} + \frac{\varepsilon^2 D_X^2}{4} \right) \ln \delta^{-1}, \quad n \geq 1, \end{aligned}$$

with probability at least  $1 - 3\delta$ . Moreover, we have

$$\frac{5e^{D_X\varepsilon}}{2} < 3, \quad 30 \left( 2e^{D_X\varepsilon} + \frac{\varepsilon^2 D_X^2}{4} \right) < 64, \quad 5\varepsilon^2 D_X^2 \leq 1/75.$$

We then control the first terms. To that end, we use a rough bound at any time  $t \geq 1$ :

$$\begin{aligned} L(\hat{\theta}_t) - L(\theta^*) &\leq \mathbb{E} \left[ \frac{yX}{1 + e^{y\hat{\theta}_t^T X}} \mid \hat{\theta}_t \right]^T (\hat{\theta}_t - \theta^*) \\ &\leq D_X \|\hat{\theta}_t - \theta^*\| \\ &\leq D_X (\|\hat{\theta}_1 - \theta^*\| + (t-1)\lambda_{\max}(P_1)D_X), \end{aligned}$$

because for any  $s \geq 1$ , we have  $P_s \preceq P_1$  and therefore  $\|\hat{\theta}_{s+1} - \hat{\theta}_s\| \leq \lambda_{\max}(P_1)D_X$ . Summing from 1 to  $\tau(\varepsilon, \delta) \leq \tau(\frac{1}{20D_X}, \delta)$  yields the result.  $\square$

### B.2 Concentration of $P_t$

We prove a concentration result based on Tropp (2011), which will be used on the inverse of  $P_t$ .

**Lemma 19.** *If Assumption 1 is satisfied, then for any  $0 \leq \beta < 1$  and  $t \geq 4^{1/(1-\beta)}$ , it holds*

$$\mathbb{P} \left( \lambda_{\min} \left( \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right) < \frac{\Lambda_{\min} t^{1-\beta}}{4(1-\beta)} \right) \leq d \exp \left( -t^{1-\beta} \frac{\Lambda_{\min}^2}{10D_X^4} \right).$$

**Proof.** We wish to center the matrices  $X_s X_s^T$  by subtracting their (common) expected value. We use that if  $A$  and  $B$  are symmetric,  $\lambda_{\min}(A - B) \leq \lambda_{\min}(A) - \lambda_{\min}(B)$ . Indeed, denoting by  $v$  any eigenvector of  $A$  associated with its smallest eigenvalue,

$$\begin{aligned} \lambda_{\min}(A - B) &= \min_x \frac{x^T (A - B)x}{\|x\|^2} \\ &\leq \frac{v^T (A - B)v}{\|v\|^2} \\ &= \lambda_{\min}(A) - \frac{v^T B v}{\|v\|^2} \\ &\leq \lambda_{\min}(A) - \min_x \frac{x^T B x}{\|x\|^2} \\ &= \lambda_{\min}(A) - \lambda_{\min}(B). \end{aligned}$$

We obtain:

$$\begin{aligned}
 \lambda_{\min} \left( \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} - \sum_{s=1}^{t-1} \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] \right) &\leq \lambda_{\min} \left( \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right) - \lambda_{\min} \left( \sum_{s=1}^{t-1} \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] \right) \\
 &= \lambda_{\min} \left( \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right) - \Lambda_{\min} \sum_{s=1}^{t-1} \frac{1}{s^\beta} \\
 &\leq \lambda_{\min} \left( \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right) - \Lambda_{\min} \frac{t^{1-\beta} - 1}{1 - \beta}.
 \end{aligned}$$

Therefore, we obtain

$$\begin{aligned}
 \mathbb{P} \left( \lambda_{\min} \left( \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right) < \frac{\Lambda_{\min}(t^{1-\beta} - 2)}{2(1 - \beta)} \right) \\
 \leq \mathbb{P} \left( \lambda_{\min} \left( \sum_{s=1}^{t-1} \left( \frac{X_s X_s^T}{s^\beta} - \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] \right) \right) < \frac{\Lambda_{\min}(t^{1-\beta} - 2)}{2(1 - \beta)} - \Lambda_{\min} \frac{t^{1-\beta} - 1}{1 - \beta} \right) \\
 = \mathbb{P} \left( \lambda_{\max} \left( \sum_{s=1}^{t-1} \left( \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] - \frac{X_s X_s^T}{s^\beta} \right) \right) > \frac{\Lambda_{\min} t^{1-\beta}}{2(1 - \beta)} \right).
 \end{aligned}$$

We check the assumptions of Theorem 1.4 of Tropp (2011):

- Obviously  $\mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] - \frac{X_s X_s^T}{s^\beta}$  is centered,
- $\lambda_{\max} \left( \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] - \frac{X_s X_s^T}{s^\beta} \right) \leq \lambda_{\max} \left( \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] \right) \leq D_X^2$  almost surely.

As  $0 \preceq \mathbb{E} \left[ \left( \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] - \frac{X_s X_s^T}{s^\beta} \right)^2 \right] \preceq \mathbb{E} \left[ \left( \frac{X_s X_s^T}{s^\beta} \right)^2 \right] \preceq \frac{D_X^4}{s^{2\beta}} I \preceq \frac{D_X^4}{s^\beta} I$ , we get

$$0 \preceq \sum_{s=1}^{t-1} \mathbb{E} \left[ \left( \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] - \frac{X_s X_s^T}{s^\beta} \right)^2 \right] \preceq \left( \sum_{s=1}^{t-1} \frac{D_X^4}{s^\beta} \right) I \preceq \left( D_X^4 \frac{t^{1-\beta}}{1 - \beta} \right) I.$$

Therefore we can apply Theorem 1.4 of Tropp (2011):

$$\begin{aligned}
 \mathbb{P} \left( \lambda_{\max} \left( \sum_{s=1}^{t-1} \left( \mathbb{E} \left[ \frac{X_s X_s^T}{s^\beta} \right] - \frac{X_s X_s^T}{s^\beta} \right) \right) > \frac{\Lambda_{\min} t^{1-\beta}}{2(1 - \beta)} \right) \\
 \leq d \exp \left( - \frac{\Lambda_{\min}^2 t^{2(1-\beta)} / (8(1 - \beta)^2)}{D_X^4 t^{1-\beta} / (1 - \beta) + D_X^2 \Lambda_{\min} t^{1-\beta} / (6(1 - \beta))} \right) \\
 = d \exp \left( - t^{1-\beta} \frac{\Lambda_{\min}^2}{8D_X^4} \frac{1 / (1 - \beta)^2}{1 / (1 - \beta) + \Lambda_{\min} / (6D_X^2 (1 - \beta))} \right) \\
 = d \exp \left( - t^{1-\beta} \frac{\Lambda_{\min}^2}{8D_X^4} \left( 1 - \beta + \frac{\Lambda_{\min} (1 - \beta)}{6D_X^2} \right)^{-1} \right).
 \end{aligned}$$

Using  $\Lambda_{\min} / D_X^2 \leq 1$  and  $\beta \geq 0$ , we obtain  $8(1 - \beta + \frac{\Lambda_{\min}(1-\beta)}{6D_X^2}) \leq 8(1 + 1/6) = 28/3 \leq 10$ , therefore

$$\mathbb{P} \left( \lambda_{\min} \left( \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right) < \frac{\Lambda_{\min}(t^{1-\beta} - 2)}{2(1 - \beta)} \right) \leq d \exp \left( - t^{1-\beta} \frac{\Lambda_{\min}^2}{10D_X^4} \right).$$

The result follows from  $\frac{1}{2}t^{1-\beta} - 2 > 0$  for  $t \geq 4^{1/(1-\beta)}$ . □

We can now do a union bound to obtain Proposition 11.

**Proof. of Proposition 11.** We reduce our problem to the deviations of a sum of centered independent random matrices:

$$\begin{aligned}\lambda_{\max}(P_t) &= \lambda_{\min} \left( P_1^{-1} + \sum_{s=1}^{t-1} X_s X_s^T \alpha_s \right)^{-1} \\ &\leq \lambda_{\min} \left( P_1^{-1} + \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right)^{-1},\end{aligned}$$

because  $\alpha_s \geq 1/s^\beta$ . Therefore, for  $t \geq 8 \geq 4^{1/(1-\beta)}$ ,

$$\begin{aligned}\mathbb{P} \left( \lambda_{\max}(P_t) > \frac{4}{\Lambda_{\min} t^{1-\beta}} \right) &\leq \mathbb{P} \left( \lambda_{\min} \left( P_1^{-1} + \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right)^{-1} > \frac{4}{\Lambda_{\min} t^{1-\beta}} \right) \\ &= \mathbb{P} \left( \lambda_{\min} \left( P_1^{-1} + \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right) < \frac{\Lambda_{\min} t^{1-\beta}}{4} \right) \\ &\leq \mathbb{P} \left( \lambda_{\min} \left( \sum_{s=1}^{t-1} \frac{X_s X_s^T}{s^\beta} \right) < \frac{\Lambda_{\min} t^{1-\beta}}{4} \right) \\ &\leq d \exp \left( -t^{1-\beta} \frac{\Lambda_{\min}^2}{10D_X^4} \right),\end{aligned}$$

where we applied Lemma 19 to obtain the last line. We take a union bound to obtain, for any  $k \geq 7$ ,

$$\begin{aligned}\mathbb{P} \left( \exists t > k, \lambda_{\max}(P_t) > \frac{4}{\Lambda_{\min} t^{1-\beta}} \right) &\leq \sum_{t>k} d \exp \left( -t^{1-\beta} \frac{\Lambda_{\min}^2}{10D_X^4} \right) \\ &\leq d \sum_{t>k} \exp \left( -\lfloor t^{1-\beta} \rfloor \frac{\Lambda_{\min}^2}{10D_X^4} \right) \\ &= d \sum_{m \geq 1} \exp \left( -m \frac{\Lambda_{\min}^2}{10D_X^4} \right) \sum_{t>k} \mathbb{1}_{\lfloor t^{1-\beta} \rfloor = m}\end{aligned}$$

We bound  $\sum_{t>k} \mathbb{1}_{\lfloor t^{1-\beta} \rfloor = m}$ : for any  $m$

$$\lfloor t^{1-\beta} \rfloor = m \implies m^{1/(1-\beta)} \leq t < (m+1)^{1/(1-\beta)},$$

then using  $e^x \leq 1 + 2x$  for any  $0 \leq x \leq 1$ , we have

$$\begin{aligned}(m+1)^{1/(1-\beta)} &= m^{1/(1-\beta)} (1 + 1/m)^{1/(1-\beta)} \\ &= m^{1/(1-\beta)} \exp(\ln(1 + 1/m)/(1 - \beta)) \\ &\leq m^{1/(1-\beta)} \exp(1/(m(1 - \beta))) \\ &\leq m^{1/(1-\beta)} (1 + 2/(m(1 - \beta))),\end{aligned}$$

as long as  $m \geq 2 \geq 1/(1 - \beta)$ . Therefore

$$(m+1)^{1/(1-\beta)} - m^{1/(1-\beta)} + 1 \leq 2m^{1/(1-\beta)-1}/(1 - \beta) + 1 \leq 4m + 1 \leq 4(m+1),$$

and that is true for  $m = 1$  too. Hence

$$\begin{aligned}\mathbb{P} \left( \exists t > k, \lambda_{\max}(P_t) > \frac{4}{\Lambda_{\min} t^{1-\beta}} \right) &\leq 4d \sum_{m \geq \lfloor k^{1-\beta} \rfloor} (m+1) \exp \left( -m \frac{\Lambda_{\min}^2}{10D_X^4} \right) \\ &= 4d \frac{\exp \left( -\frac{\Lambda_{\min}^2}{10D_X^4} \right)^{\lfloor k^{1-\beta} \rfloor}}{1 - \exp \left( -\frac{\Lambda_{\min}^2}{10D_X^4} \right)} (\lfloor k^{1-\beta} \rfloor + 1 + \frac{\exp \left( -\frac{\Lambda_{\min}^2}{10D_X^4} \right)}{1 - \exp \left( -\frac{\Lambda_{\min}^2}{10D_X^4} \right)}) \\ &\leq 4d \frac{\exp \left( \frac{\Lambda_{\min}^2}{10D_X^4} \right)}{1 - \exp \left( -\frac{\Lambda_{\min}^2}{10D_X^4} \right)} \left( k^{1-\beta} + \frac{1}{1 - \exp \left( -\frac{\Lambda_{\min}^2}{10D_X^4} \right)} \right) \exp \left( -\frac{\Lambda_{\min}^2}{10D_X^4} \right)^{k^{1-\beta}},\end{aligned}$$



where the second line is obtained deriving both sides of  $\sum_{m \geq \lfloor k^{1-\beta} \rfloor} r^{m+1} = \frac{r^{\lfloor k^{1-\beta} \rfloor + 1}}{1-r}$  with respect to  $r$ . Also, as  $1 - e^{-x} \geq xe^{-x}$  for any  $x \in \mathbb{R}$ , we get

$$\begin{aligned} & \mathbb{P} \left( \exists t > k, \lambda_{\max}(P_t) > \frac{4}{\Lambda_{\min} t^{1-\beta}} \right) \\ & \leq 4d \frac{10D_X^4}{\Lambda_{\min}^2} \exp \left( 2 \frac{\Lambda_{\min}^2}{10D_X^4} \right) \left( k^{1-\beta} + \frac{10D_X^4}{\Lambda_{\min}^2} \exp \left( \frac{\Lambda_{\min}^2}{10D_X^4} \right) \right) \exp \left( -\frac{\Lambda_{\min}^2}{10D_X^4} \right)^{k^{1-\beta}}. \end{aligned}$$

Also, as  $xe^{-x} \leq e^{-1}$  for any  $x \geq 0$ , we get for any  $k \geq 7$ :

$$\begin{aligned} \left( k^{1-\beta} + \frac{10D_X^4}{\Lambda_{\min}^2} \exp \left( \frac{\Lambda_{\min}^2}{10D_X^4} \right) \right) \exp \left( -k^{1-\beta} \frac{\Lambda_{\min}^2}{20D_X^4} \right) & \leq \frac{20D_X^4 e^{-1}}{\Lambda_{\min}^2} \exp \left( \frac{10D_X^4}{\Lambda_{\min}^2} \exp \left( \frac{\Lambda_{\min}^2}{10D_X^4} \right) \frac{\Lambda_{\min}^2}{20D_X^4} \right) \\ & = \frac{20D_X^4 e^{-1}}{\Lambda_{\min}^2} \exp \left( \frac{1}{2} \exp \left( \frac{\Lambda_{\min}^2}{10D_X^4} \right) \right). \end{aligned}$$

Combining the last two inequalities, we obtain

$$\begin{aligned} \mathbb{P} \left( \exists t > k, \lambda_{\max}(P_t) > \frac{4}{\Lambda_{\min} t^{1-\beta}} \right) & \leq d \frac{800D_X^8 e^{-1}}{\Lambda_{\min}^4} \exp \left( 2 \frac{\Lambda_{\min}^2}{10D_X^4} + \frac{1}{2} \exp \left( \frac{\Lambda_{\min}^2}{10D_X^4} \right) \right) \exp \left( -k^{1-\beta} \frac{\Lambda_{\min}^2}{20D_X^4} \right) \\ & \leq d \frac{625D_X^8}{\Lambda_{\min}^4} \exp \left( -k^{1-\beta} \frac{\Lambda_{\min}^2}{20D_X^4} \right), \end{aligned}$$

and the result follows. The last line comes from  $\Lambda_{\min} \leq D_X^2$  and consequently

$$800e^{-1} \exp \left( 2 \frac{\Lambda_{\min}^2}{10D_X^4} + \frac{1}{2} \exp \left( \frac{\Lambda_{\min}^2}{10D_X^4} \right) \right) \leq 800e^{-1+0.2+0.5e^{0.1}} \approx 624.7 \leq 625.$$

The condition  $k \geq 7$  is not necessary because

$$\left( \frac{20D_X^4}{\Lambda_{\min}^2} \ln \left( \frac{625dD_X^8}{\Lambda_{\min}^4 \delta} \right) \right)^{1/(1-\beta)} \geq 20 \ln(625\delta^{-1}),$$

and either  $\delta \geq 1$  and the result is trivial, either  $\delta < 1$  and  $20 \ln(625\delta^{-1}) \geq 128$ .  $\square$

### B.3 Convergence of the truncated algorithm

In order to prove Theorem 12, we state and prove an intermediate lemma.

**Lemma 20.** *Let  $\theta \in \mathbb{R}^d$ .*

1. *For any  $\eta > 0$ , we have*

$$L(\theta) - L(\theta^*) > \eta \implies \left\| \frac{\partial L}{\partial \theta} \Big|_{\theta} \right\| \geq D_{\eta}$$

$$\text{for } D_{\eta} = \frac{\Lambda_{\min} \sqrt{\eta}}{\sqrt{2} D_X (1 + e^{D_X (\|\theta^*\| + \sqrt{8\eta/D_X^2})})}.$$

2. *For any  $\varepsilon > 0$ , we have*

$$\|\theta - \theta^*\| > \varepsilon \implies L(\theta) - L(\theta^*) > \frac{\Lambda_{\min}}{4(1 + e^{D_X (\|\theta^*\| + \varepsilon)})} \varepsilon^2.$$

**Proof. of Lemma 20** Both points derive from a second-order identity, turned in an upper-bound in the one case and in a lower-bound in the other. Using  $\frac{\partial L}{\partial \theta}(\theta^*) = 0$ , there exists  $0 \leq \lambda \leq 1$  such that

$$L(\theta) = L(\theta^*) + \frac{1}{2} (\theta - \theta^*)^T \mathbb{E} \left[ \frac{1}{(1 + e^{(\lambda\theta + (1-\lambda)\theta^*)^T X})(1 + e^{-(\lambda\theta + (1-\lambda)\theta^*)^T X})} X X^T \right] (\theta - \theta^*).$$

1. We first have

$$L(\theta) - L(\theta^*) \leq \frac{D_X^2}{8} \|\theta - \theta^*\|^2.$$

Assume  $L(\theta) - L(\theta^*) > \eta$ . Then  $\|\theta - \theta^*\| \geq \sqrt{8\eta/D_X^2}$ . Also, using the Taylor expansion of  $\theta^*$  around some  $\theta_0 \in \mathbb{R}^d$ , we get

$$L(\theta^*) \geq L(\theta_0) + \frac{\partial L}{\partial \theta} \Big|_{\theta_0}^T (\theta^* - \theta_0) + \frac{1}{4(1 + e^{D_X(\|\theta^*\| + \|\theta_0 - \theta^*\|)})} (\theta_0 - \theta^*)^T \mathbb{E}[XX^T] (\theta_0 - \theta^*),$$

and that yields

$$\frac{\partial L}{\partial \theta} \Big|_{\theta_0}^T (\theta_0 - \theta^*) \geq L(\theta_0) - L(\theta^*) + \frac{\Lambda_{\min}}{4(1 + e^{D_X(\|\theta^*\| + \|\theta_0 - \theta^*\|)})} \|\theta_0 - \theta^*\|^2.$$

Therefore, as  $L(\theta_0) - L(\theta^*) \geq 0$ ,

$$\left\| \frac{\partial L}{\partial \theta} \Big|_{\theta_0} \right\| \geq \frac{\Lambda_{\min}}{4(1 + e^{D_X(\|\theta^*\| + \|\theta_0 - \theta^*\|)})} \|\theta_0 - \theta_{\text{true}}\|.$$

Finally, as  $L$  is convex of minimum  $\theta^*$ ,

$$\begin{aligned} \left\| \frac{\partial L}{\partial \theta} \Big|_{\theta} \right\| &\geq \min_{\|\theta_0 - \theta^*\| = \sqrt{8\eta/D_X^2}} \left\| \frac{\partial L}{\partial \theta} \Big|_{\theta_0} \right\| \\ &\geq \frac{\Lambda_{\min}}{4(1 + e^{D_X(\|\theta^*\| + \sqrt{8\eta/D_X^2})})} \sqrt{8\eta/D_X^2} \\ &\geq \frac{\Lambda_{\min}}{\sqrt{2}D_X(1 + e^{D_X(\|\theta^*\| + \sqrt{8\eta/D_X^2})})} \sqrt{\eta}. \end{aligned}$$

2. On the other hand we have

$$L(\theta) \geq L(\theta^*) + \frac{\Lambda_{\min}}{4(1 + e^{D_X(\|\theta^*\| + \|\theta - \theta^*\|)})} \|\theta - \theta^*\|^2.$$

Thus, as  $L$  is convex of minimum  $\theta^*$ , if  $\|\theta - \theta^*\| > \varepsilon$  it holds

$$L(\theta) - L(\theta^*) > \min_{\|\theta_0 - \theta^*\| = \varepsilon} L(\theta_0) - L(\theta^*) \geq \frac{\Lambda_{\min}}{4(1 + e^{D_X(\|\theta^*\| + \varepsilon)})} \varepsilon^2.$$

□

**Proof. of Theorem 12.** We prove the convergence of  $(L(\hat{\theta}_t))_t$  to  $L(\theta^*)$  and then the convergence of  $(\hat{\theta}_t)_t$  to  $\theta^*$  follows. The convergence of  $(L(\hat{\theta}_t))_t$  comes from the first point of Lemma 20. The link between the two convergences is stated in the second point.

To study the evolution of  $L(\hat{\theta}_t)$  we first apply a second-order Taylor expansion: for any  $t \geq 1$  there exists  $0 \leq \alpha_t \leq 1$  such that

$$L(\hat{\theta}_{t+1}) = L(\hat{\theta}_t) + \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}^T (\hat{\theta}_{t+1} - \hat{\theta}_t) + \frac{1}{2} (\hat{\theta}_{t+1} - \hat{\theta}_t)^T \frac{\partial^2 L}{\partial \theta^2} \Big|_{\hat{\theta}_t + \alpha_t (\hat{\theta}_{t+1} - \hat{\theta}_t)} (\hat{\theta}_{t+1} - \hat{\theta}_t). \quad (13)$$

We have  $\frac{\partial^2 L}{\partial \theta^2} \preceq \frac{1}{4} \mathbb{E}[XX^T]$ , therefore, using the update formula on  $\hat{\theta}$ , the second-order term is bounded with

$$\begin{aligned} (\hat{\theta}_{t+1} - \hat{\theta}_t)^T \frac{\partial^2 L}{\partial \theta^2} \Big|_{\hat{\theta}_t + \alpha_t (\hat{\theta}_{t+1} - \hat{\theta}_t)} (\hat{\theta}_{t+1} - \hat{\theta}_t) &\leq \frac{1}{(1 + e^{y_t \hat{\theta}_t^T X_t})^2} X_t^T P_{t+1}^T \frac{\mathbb{E}[XX^T]}{4} P_{t+1} X_t \\ &\leq \frac{1}{4} D_X^4 \lambda_{\max}(P_{t+1})^2 \leq \frac{1}{4} D_X^4 \lambda_{\max}(P_t)^2. \end{aligned}$$

The first-order term is controlled using the definition of the algorithm:

$$\hat{\theta}_{t+1} - \hat{\theta}_t = \left( P_t - \frac{P_t X_t X_t^T P_t}{1 + X_t^T P_t X_t} \alpha_t \right) \frac{y_t X_t}{1 + e^{y_t \hat{\theta}_t^T X_t}},$$

and as  $\alpha_t \leq 1$ ,

$$\left\| -\alpha_t \frac{P_t X_t X_t^T P_t}{1 + X_t^T P_t X_t} \frac{y_t X_t}{1 + e^{y_t \hat{\theta}_t^T X_t}} \right\| \leq D_X^3 \lambda_{\max}(P_t)^2.$$

Also,  $\left\| \frac{\partial L}{\partial \theta} \right\| \leq D_X$ . Substituting our findings in Equation (13), we obtain

$$L(\hat{\theta}_{t+1}) \leq L(\hat{\theta}_t) + \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}^T P_t \frac{y_t X_t}{1 + e^{y_t \hat{\theta}_t^T X_t}} + 2D_X^4 \lambda_{\max}(P_t)^2. \quad (14)$$

We define

$$\begin{aligned} M_t &= \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}^T P_t \frac{y_t X_t}{1 + e^{y_t \hat{\theta}_t^T X_t}} - \mathbb{E} \left[ \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}^T P_t \frac{y_t X_t}{1 + e^{y_t \hat{\theta}_t^T X_t}} \mid X_1, y_1, \dots, X_{t-1}, y_{t-1} \right] \\ &= \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}^T P_t \frac{y_t X_t}{1 + e^{y_t \hat{\theta}_t^T X_t}} + \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}^T P_t \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}. \end{aligned}$$

Hence we have

$$\frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t}^T P_t \frac{y_t X_t}{1 + e^{y_t \hat{\theta}_t^T X_t}} \leq M_t - \lambda_{\min}(P_t) \left\| \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t} \right\|^2 \leq M_t - \frac{1}{tD_X^2} \left\| \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_t} \right\|^2,$$

because  $P_s \succcurlyeq \frac{I}{sD_X^2}$ . Combining it with Equation (14) and summing consecutive terms, we obtain, for any  $k < t$ ,

$$L(\hat{\theta}_t) - L(\hat{\theta}_k) \leq \sum_{s=k}^{t-1} \left( M_s - \frac{1}{sD_X^2} \left\| \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_s} \right\|^2 + 2D_X^4 \lambda_{\max}(P_s)^2 \right). \quad (15)$$

We recall that there exists  $C_\delta$  such that  $\mathbb{P}(A_{C_\delta}) \geq 1 - \delta$  where

$$A_{C_\delta} := \bigcap_{t=1}^{\infty} \left( \lambda_{\max}(P_t) \leq \frac{C_\delta}{t^{1-\beta}} \right).$$

On the previous inequality, we see that the left-hand side is the sum of a martingale and a term which is negative for  $s$  large enough, under the event  $A_{C_\delta}$ .

We are then interested in  $\mathbb{P}((L(\hat{\theta}_t) - L(\theta^*) > \eta) \mid A_{C_\delta})$  for some  $\eta > 0$ . For  $0 \leq k \leq t$ , we define  $B_{k,t}$  be the event  $(\forall k < s < t, L(\hat{\theta}_s) - L(\theta^*) > \eta/2)$ . Then we use the law of total probability:

$$\begin{aligned} \mathbb{P}(L(\hat{\theta}_t) - L(\theta^*) > \eta \mid A_{C_\delta}) &= \mathbb{P} \left( (L(\hat{\theta}_t) - L(\theta^*) > \eta) \cap B_{0,t} \mid A_{C_\delta} \right) \\ &\quad + \sum_{k=1}^{t-1} \mathbb{P} \left( (L(\hat{\theta}_t) - L(\theta^*) > \eta) \cap (L(\hat{\theta}_k) - L(\theta^*) \leq \frac{\eta}{2}) \cap B_{k,t} \mid A_{C_\delta} \right) \\ &\leq \mathbb{P} \left( (L(\hat{\theta}_t) - L(\theta^*) > \eta) \cap B_{0,t} \mid A_{C_\delta} \right) \\ &\quad + \sum_{k=1}^{t-1} \mathbb{P} \left( (L(\hat{\theta}_t) - L(\hat{\theta}_k) > \frac{\eta}{2}) \cap B_{k,t} \mid A_{C_\delta} \right). \end{aligned} \quad (16)$$

Lemma 20 yields

$$L(\hat{\theta}_s) - L(\theta^*) > \frac{\eta}{2} \implies \left\| \frac{\partial L}{\partial \theta} \Big|_{\hat{\theta}_s} \right\| \geq D_\eta.$$

We combine the last equation, along with Equation (15) and the definition of  $A_{C_\delta}$  to get, for any  $1 \leq k < t$ ,

$$\begin{aligned} \mathbb{P} \left( (L(\hat{\theta}_t) - L(\hat{\theta}_k) > \eta/2) \cap B_{k,t} \mid A_{C_\delta} \right) &\leq \mathbb{P} \left( \left( \sum_{s=k}^{t-1} M_s > f(k,t) \right) \cap B_{k,t} \mid A_{C_\delta} \right) \\ &\leq \mathbb{P} \left( \sum_{s=k}^{t-1} M_s > f(k,t) \mid A_{C_\delta} \right), \end{aligned}$$

where  $f(k, t) = \frac{\eta}{2} + \frac{D_\eta^2}{D_X^2} \sum_{s=k}^{t-1} \frac{1}{s} - 2D_X^4 C_\delta^2 \sum_{s=k}^{t-1} \frac{1}{s^{2(1-\beta)}}$  for any  $1 \leq k < t$ .

Similarly, we get

$$\mathbb{P}\left((L(\hat{\theta}_t) - L(\theta^*) > \eta) \cap B_{0,t} \mid A_{C_\delta}\right) \leq \mathbb{P}\left(\sum_{s=1}^{t-1} M_s > f_0(t) \mid A_{C_\delta}\right),$$

with  $f_0(t) = \eta - (L(\hat{\theta}_1) - L(\theta^*)) + \frac{D_\eta^2}{D_X^2} \sum_{s=1}^{t-1} \frac{1}{s} - 2D_X^4 C_\delta^2 \sum_{s=1}^{t-1} \frac{1}{s^{2(1-\beta)}}$  for any  $t \geq 1$ .

We have  $\mathbb{E}[M_s \mid X_1, y_1, \dots, X_{s-1}, y_{s-1}] = 0$ , and almost surely  $|M_s| \leq 2D_X^2 \lambda_{\max}(P_s)$ . We can therefore apply Azuma-Hoeffding inequality: for  $t, k$  such that  $f(k, t) > 0$ ,

$$\mathbb{P}\left(\sum_{s=k}^{t-1} M_s > f(k, t) \mid A_{C_\delta}\right) \leq \exp\left(-f(k, t)^2 \frac{(1-2\beta) \max(1/2, (k-1)^{1-2\beta})}{8D_X^4 C_\delta^2}\right),$$

because  $\sum_{s=k}^{+\infty} \frac{1}{s^{2(1-\beta)}} \leq \frac{1}{(1-2\beta) \max(1/2, (k-1)^{1-2\beta})}$ . Similarly, for  $t$  such that  $f_0(t) > 0$ ,

$$\mathbb{P}\left(\sum_{s=1}^{t-1} M_s > f_0(t) \mid A_{C_\delta}\right) \leq \exp\left(-f_0(t)^2 \frac{1-2\beta}{16D_X^4 C_\delta^2}\right).$$

We need to control  $f(k, t)$ ,  $f_0(t)$ . We see that for  $t$  large enough, when  $k$  is small compared to  $t$ ,  $f(k, t)$  is driven by  $\frac{D_\eta^2}{D_X^2} \ln(t)$  and when  $k \approx t$ ,  $f(k, t)$  is driven by  $\eta/2$ . The following Lemma formally states these approximations as lower-bounds. We prove it right after the end of this proof.

**Lemma 21.** For  $t \geq \max\left(e^{\frac{16D_X^6 C_\delta^2}{D_\eta^2(1-2\beta)}}, \left(1 + \left(\frac{8D_X^4 C_\delta^2}{\eta(1-2\beta)}\right)^{\frac{1}{1-2\beta}}\right)^2\right)$ , it holds

$$\begin{aligned} f(k, t) &\geq \frac{D_\eta^2}{4D_X^2} \ln(t), & 1 \leq k < \sqrt{t}, \\ f(k, t) &\geq \frac{\eta}{4}, & \sqrt{t} \leq k < t. \end{aligned}$$

Similarly, for  $t \geq e^{\frac{2D_X^2}{D_\eta^2} \left(L(\hat{\theta}_1) - L(\theta^*) + \frac{4D_X^4 C_\delta^2}{1-2\beta}\right)}$ , we have

$$f_0(t) \geq \frac{D_\eta^2}{2D_X^2} \ln(t).$$

Then, defining  $C_1 = \frac{D_\eta^4(1-2\beta)}{256D_X^4 C_\delta^2}$  and  $C_2 = \frac{\eta^2(1-2\beta)}{128D_X^4 C_\delta^2}$ , we finally get for  $t$  large enough:

$$\begin{aligned} \mathbb{P}\left((L(\hat{\theta}_t) - L(\theta^*) > \eta) \cap B_{0,t} \mid A_{C_\delta}\right) &\leq \exp(-4C_1 \ln(t)^2), \\ \mathbb{P}\left((L(\hat{\theta}_t) - L(\theta^*) > \eta) \cap (L(\hat{\theta}_k) - L(\theta^*) \leq \frac{\eta}{2}) \cap B_{k,t} \mid A_{C_\delta}\right) &\leq \exp(-C_1 \ln(t)^2), \quad 1 \leq k < \sqrt{t} \\ \mathbb{P}\left((L(\hat{\theta}_t) - L(\theta^*) > \eta) \cap (L(\hat{\theta}_k) - L(\theta^*) \leq \frac{\eta}{2}) \cap B_{k,t} \mid A_{C_\delta}\right) &\leq \exp(-C_2(k-1)^{1-2\beta}), \quad \sqrt{t} \leq k < t \end{aligned}$$

Substituting in Equation (16) yields:

$$\begin{aligned} \mathbb{P}(L(\hat{\theta}_t) - L(\theta^*) > \eta \mid A_{C_\delta}) &\leq \exp(-4C_1 \ln(t)^2) + \sum_{k=1}^{\lceil \sqrt{t} \rceil - 1} \exp(-C_1 \ln(t)^2) + \sum_{k=\lceil \sqrt{t} \rceil}^{t-1} \exp(-C_2(k-1)^{1-2\beta}) \\ &\leq (\sqrt{t} + 1) \exp(-C_1 \ln(t)^2) + t \exp(-C_2(\sqrt{t} - 1)^{1-2\beta}). \end{aligned}$$

Finally, Point 2 of Lemma 20 allows to obtain the result: defining  $\eta = \frac{\Lambda_{\min}\varepsilon^2}{4(1+e^{D_X(\|\theta^*\|+\varepsilon)})}$ , we obtain

$$\begin{aligned} \mathbb{P}(\|\hat{\theta}_t - \theta^*\| > \varepsilon \mid A_{C_\delta}) &\leq \mathbb{P}(L(\hat{\theta}_t) - L(\theta^*) > \eta \mid A_{C_\delta}) \\ &\leq (\sqrt{t} + 1) \exp(-C_1 \ln(t)^2) + t \exp(-C_2(\sqrt{t} - 1)^{1-2\beta}). \end{aligned}$$

In order to obtain the constants involved in the Theorem, we write

$$\begin{aligned} D_\eta &= \frac{\Lambda_{\min} \sqrt{\frac{\Lambda_{\min}\varepsilon^2}{4(1+e^{D_X(\|\theta^*\|+\varepsilon)})}}}{2D_X(1 + \exp(D_X(\|\theta^*\| + \sqrt{\frac{\Lambda_{\min}\varepsilon^2}{D_X^2(1+e^{D_X(\|\theta^*\|+\varepsilon)})}}))} \geq \left( \frac{\Lambda_{\min}}{1 + e^{D_X(\|\theta^*\|+\varepsilon)}} \right)^{3/2} \frac{\varepsilon}{4D_X}, \\ C_1 &\geq \frac{\Lambda_{\min}^6(1-2\beta)\varepsilon^4}{2^{16}D_X^{12}C_\delta^2(1+e^{D_X(\|\theta^*\|+\varepsilon)})^6}, \\ C_2 &\geq \frac{\Lambda_{\min}^2(1-2\beta)\varepsilon^4}{2^{11}D_X^4C_\delta^2(1+e^{D_X(\|\theta^*\|+\varepsilon)})^2}, \end{aligned}$$

and the conditions of Lemma 21 become

$$\begin{aligned} t &\geq \exp\left(\frac{2^8 D_X^8 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)\varepsilon^2}\right), \\ t &\geq \left(1 + \left(\frac{32D_X^4 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})}{(1-2\beta)\Lambda_{\min}\varepsilon^2}\right)^{\frac{1}{1-2\beta}}\right)^2, \\ t &\geq \exp\left(\frac{32D_X^4 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 \varepsilon^2} \left(L(\hat{\theta}_1) - L(\theta^*) + \frac{4D_X^4 C_\delta^2}{1-2\beta}\right)\right). \end{aligned}$$

We would like to obtain a single condition on  $t$ , thus we write

$$\begin{aligned} \left(1 + \left(\frac{32D_X^4 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})}{(1-2\beta)\Lambda_{\min}\varepsilon^2}\right)^{\frac{1}{1-2\beta}}\right)^2 &= \exp\left(2 \ln\left(1 + \left(\frac{32D_X^4 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})}{(1-2\beta)\Lambda_{\min}\varepsilon^2}\right)^{\frac{1}{1-2\beta}}\right)\right) \\ &\leq \exp\left(\frac{2}{1-2\beta} \ln\left(1 + \frac{32D_X^4 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})}{(1-2\beta)\Lambda_{\min}\varepsilon^2}\right)\right) \\ &\leq \exp\left(\frac{2}{1-2\beta} \sqrt{\frac{32D_X^4 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})}{(1-2\beta)\Lambda_{\min}\varepsilon^2}}\right) \\ &\leq \exp\left(\frac{2^8 D_X^8 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)^{3/2} \varepsilon^2}\right), \end{aligned}$$

The third line is obtained with the inequality  $\ln(1+x) \leq \sqrt{x}$  for any  $x > 0$ . Obviously, as  $0 < 1-2\beta < 1$ , the first threshold on  $t$  is bounded by:

$$\exp\left(\frac{2^8 D_X^8 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)\varepsilon^2}\right) \leq \exp\left(\frac{2^8 D_X^8 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)^{3/2} \varepsilon^2}\right).$$

To handle the third one, we use  $D_X^2 C_\delta \geq \frac{4D_X^2}{\Lambda_{\min}} \geq 4$  and as  $\hat{\theta}_1 = 0$  we obtain  $L(\hat{\theta}_1) - L(\theta^*) \leq \ln 2 \leq \frac{4D_X^4 C_\delta^2}{1-2\beta}$ , hence

$$\exp\left(\frac{32D_X^4 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 \varepsilon^2} \left(L(\hat{\theta}_1) - L(\theta^*) + \frac{4D_X^4 C_\delta^2}{1-2\beta}\right)\right) \leq \exp\left(\frac{2^8 D_X^8 C_\delta^2 (1 + e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)^{3/2} \varepsilon^2}\right).$$

□

**Proof. of Lemma 21.** We recall that for any  $k \geq 1$ ,

$$\sum_{s=k}^{t-1} \frac{1}{s} \geq \ln t - \ln k, \quad \sum_{s=k}^{t-1} \frac{1}{s^{2(1-\beta)}} \leq \frac{1}{1-2\beta} \frac{1}{\max(1/2, (k-1)^{1-2\beta})}.$$

Therefore:

$$f(k, t) \geq \frac{\eta}{2} + \frac{D_\eta^2}{D_X^2} (\ln t - \ln k) - \frac{2D_X^4 C_\delta^2}{1-2\beta} \frac{1}{\max(1/2, (k-1)^{1-2\beta})},$$

$$f_0(t) \geq \eta - (L(\hat{\theta}_1) - L(\theta^*)) + \frac{D_\eta^2}{D_X^2} \ln t - \frac{4D_X^4 C_\delta^2}{1-2\beta}.$$

- For any  $1 \leq k < \sqrt{t}$ ,  $\ln k \leq \frac{1}{2} \ln t$ , and we have

$$f(k, t) \geq \frac{D_\eta^2}{2D_X^2} \ln(t) - \frac{4D_X^4 C_\delta^2}{1-2\beta},$$

and taking  $t \geq e^{\frac{16D_X^6 C_\delta^2}{D_\eta^2(1-2\beta)}}$  yields  $f(k, t) \geq \frac{D_\eta^2}{4D_X^2} \ln(t)$ .

- For  $t \geq 2$  and any  $k \geq \sqrt{t}$ , we have

$$f(k, t) \geq \frac{\eta}{2} - \frac{2D_X^4 C_\delta^2}{(1-2\beta)(k-1)^{1-2\beta}} \geq \frac{\eta}{2} - \frac{2D_X^4 C_\delta^2}{(1-2\beta)(\sqrt{t}-1)^{1-2\beta}}.$$

Then if  $t \geq \left(1 + \left(\frac{8D_X^4 C_\delta^2}{\eta(1-2\beta)}\right)^{\frac{1}{1-2\beta}}\right)^2$ , we get  $f(k, t) \geq \frac{\eta}{4}$ .

- Last point comes from  $f_0(t) \geq \frac{D_\eta^2}{D_X^2} \ln t - (L(\hat{\theta}_1) - L(\theta^*)) - \frac{4D_X^4 C_\delta^2}{1-2\beta}$ .

□

**Proof. of Corollary 13.** We apply Theorem 12: for any  $t \geq \exp\left(\frac{2^8 D_X^8 C_{\delta/2}^2 (1+e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)^{3/2} \varepsilon^2}\right)$ ,

$$\mathbb{P}(\|\hat{\theta}_t - \theta^*\| > \varepsilon \mid A_{C_{\delta/2}}) \leq (\sqrt{t} + 1) \exp(-C_1 \ln(t)^2) + t \exp(-C_2(\sqrt{t} - 1)^{1-2\beta}),$$

where

$$C_1 = \frac{\Lambda_{\min}^6 (1-2\beta) \varepsilon^4}{2^{16} D_X^{12} C_{\delta/2}^2 (1+e^{D_X(\|\theta^*\|+\varepsilon)})^6}, \quad C_2 = \frac{\Lambda_{\min}^2 (1-2\beta) \varepsilon^4}{2^{11} D_X^4 C_{\delta/2}^2 (1+e^{D_X(\|\theta^*\|+\varepsilon)})^2}.$$

We use a union bound: for any  $\tau \geq \exp\left(\frac{2^8 D_X^8 C_{\delta/2}^2 (1+e^{D_X(\|\theta^*\|+\varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)^{3/2} \varepsilon^2}\right)$ ,

$$\mathbb{P}\left(\bigcup_{t=\tau+1}^{\infty} (\|\hat{\theta}_t - \theta^*\| > \varepsilon) \mid A_{C_{\delta/2}}\right) \leq \sum_{t>\tau} (\sqrt{t} + 1) \exp(-C_1 \ln(t)^2) + \sum_{t>\tau} t \exp(-C_2(\sqrt{t} - 1)^{1-2\beta}).$$

- If  $\tau \geq e^{\frac{3}{2C_1}}$ , we have

$$\sum_{t>\tau} (\sqrt{t} + 1) \exp(-C_1 \ln(t)^2) \leq \sum_{t>\tau} (\sqrt{t} + 1) \frac{1}{t^{5/2}} \leq 2/\tau,$$

- For  $t \geq 4$ ,  $1 - 1/\sqrt{t} \geq 1/2$ , then for  $t \geq \left(\frac{12}{C_2(1-2\beta)}\right)^{4/(1-2\beta)}$ ,

$$\begin{aligned} t^3 \exp(-C_2(\sqrt{t} - 1)^{1-2\beta}) &\leq \exp\left(3 \ln(t) - \frac{C_2}{2} t^{(1-2\beta)/2}\right) \\ &\leq \exp\left(\frac{12}{1-2\beta} \ln\left(\frac{12}{C_2(1-2\beta)}\right) - \frac{6}{1-2\beta} \left(\frac{12}{C_2(1-2\beta)}\right)\right) \\ &\leq 1, \end{aligned}$$

because for any  $x > 0$ , we have  $\ln x \leq x/2$ .

Thus for  $\tau \geq \left(\frac{12}{C_2(1-2\beta)}\right)^{4/(1-2\beta)}$

$$\sum_{t>\tau} t \exp\left(-C_2(\sqrt{t}-1)^{1-2\beta}\right) \leq 1/\tau.$$

Finally, for  $\tau$  big enough, we obtain

$$\mathbb{P}\left(\bigcup_{t=\tau+1}^{\infty} (\|\hat{\theta}_t - \theta^*\| > \varepsilon) \mid A_{C_{\delta/2}}\right) \leq 3/\tau \leq \delta/2,$$

if  $\tau \geq 6\delta^{-1}$ . We now compare the constants involved. As long as  $\varepsilon D_X \leq 1$ , we have

$$\exp\left(\frac{2^8 D_X^8 C_{\delta/2}^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^3}{\Lambda_{\min}^3 (1-2\beta)^{3/2} \varepsilon^2}\right) \leq \exp\left(\frac{3 \cdot 2^{15} D_X^{12} C_{\delta/2}^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^6}{\Lambda_{\min}^6 (1-2\beta)^{3/2} \varepsilon^4}\right).$$

Furthermore, as  $1 - 2\beta \leq 1$ , we have

$$\exp\left(\frac{3}{2C_1}\right) = \exp\left(\frac{3 \cdot 2^{15} D_X^{12} C_{\delta/2}^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^6}{\Lambda_{\min}^6 (1-2\beta) \varepsilon^4}\right) \leq \exp\left(\frac{3 \cdot 2^{15} D_X^{12} C_{\delta/2}^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^6}{\Lambda_{\min}^6 (1-2\beta)^{3/2} \varepsilon^4}\right).$$

Finally,

$$\begin{aligned} \left(\frac{12}{C_2(1-2\beta)}\right)^{4/(1-2\beta)} &= \exp\left(\frac{4}{1-2\beta} \ln \frac{12}{C_2(1-2\beta)}\right) \\ &= \exp\left(\frac{4}{1-2\beta} \ln \frac{12 \cdot 2^{11} D_X^4 C_{\delta/2}^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^2}{\Lambda_{\min}^2 (1-2\beta)^2 \varepsilon^4}\right) \\ &= \exp\left(\frac{8}{1-2\beta} \ln \frac{12 \cdot 2^{11} D_X^4 C_{\delta/2}^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^2}{\Lambda_{\min}^2 (1-2\beta) \varepsilon^4}\right) \\ &\leq \exp\left(\frac{8}{1-2\beta} \sqrt{\frac{3 \cdot 2^{13} D_X^4 C_{\delta/2}^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^2}{\Lambda_{\min}^2 (1-2\beta) \varepsilon^4}}\right) \\ &= \exp\left(\frac{\sqrt{6} 2^9 D_X^2 C_{\delta/2} (1 + e^{D_X(\|\theta^*\| + \varepsilon)})}{\Lambda_{\min} (1-2\beta)^{3/2} \varepsilon^2}\right) \\ &\leq \exp\left(\frac{3 \cdot 2^{15} D_X^{12} C_{\delta/2}^2 (1 + e^{D_X(\|\theta^*\| + \varepsilon)})^6}{\Lambda_{\min}^6 (1-2\beta)^{3/2} \varepsilon^4}\right). \end{aligned}$$

□

## C Proofs of Section 5

### C.1 Proof of Theorem 14

We first prove a result controlling the first estimates of the algorithm.

**Lemma 22.** *Provided that assumptions 1, 2 and 4 are satisfied, starting from any  $\hat{\theta}_1 \in \mathbb{R}^d$  and  $P_1 \succ 0$ , for any  $\delta > 0$ , it holds simultaneously*

$$\|\hat{\theta}_t - \theta^*\| \leq \|\hat{\theta}_1 - \theta^*\| + \lambda_{\max}(P_1) D_X \left( (3\sigma + D_{\text{approx}})(t-1) + 3\sigma \ln \delta^{-1} \right), \quad t \geq 1,$$

with probability at least  $1 - \delta$ .

**Proof.** From Proposition 4, we obtain, for any  $t \geq 1$ ,  $\hat{\theta}_t - \hat{\theta}_1 = P_t \sum_{s=1}^{t-1} (y_s - \hat{\theta}_1^T X_s) X_s$ . Consequently,

$$\begin{aligned} \hat{\theta}_t - \theta^* &= P_t \sum_{s=1}^{t-1} (y_s - \hat{\theta}_1^T X_s) X_s - P_t \left( P_1^{-1} + \sum_{s=1}^{t-1} X_s X_s^T \right) (\theta^* - \hat{\theta}_1) \\ &= P_t \sum_{s=1}^{t-1} (y_s - \theta^{*T} X_s) X_s + P_t P_1^{-1} (\hat{\theta}_1 - \theta^*), \end{aligned}$$

and using  $P_t P_1^{-1} \preceq I$ , we obtain

$$\begin{aligned} \|\hat{\theta}_t - \theta^*\| &\leq \|\hat{\theta}_1 - \theta^*\| + \lambda_{\max}(P_t) D_X \sum_{s=1}^{t-1} |y_s - \theta^{*T} X_s| \\ &\leq \|\hat{\theta}_1 - \theta^*\| + \lambda_{\max}(P_1) D_X \sum_{s=1}^{t-1} (|y_s - \mathbb{E}[y_s | X_s]| + D_{\text{app}}). \end{aligned} \quad (17)$$

We apply Lemma 1.4 of Rigollet and Hütter (2015) in the second line of the following: for any  $\mu$  such that  $0 < \mu < \frac{1}{2\sqrt{2}\sigma}$ ,

$$\begin{aligned} \mathbb{E}[\exp(\mu|y_t - \mathbb{E}[y_t | X_t]|)] &= 1 + \sum_{i \geq 1} \frac{\mu^i \mathbb{E}[|y_t - \mathbb{E}[y_t | X_t]|^i]}{i!} \\ &\leq 1 + \sum_{k \geq 1} \frac{\mu^i (2\sigma^2)^{i/2} i \Gamma(i/2)}{i!} \\ &\leq 1 + \sum_{i \geq 1} \left( \sqrt{2}\mu\sigma \right)^i, \quad \text{because } \Gamma(i/2) \leq \Gamma(i) = (i-1)! \\ &\leq 1 + 2\sqrt{2}\mu\sigma, \quad \text{because } 0 < \sqrt{2}\mu\sigma \leq \frac{1}{2} \\ &\leq \exp\left(2\sqrt{2}\mu\sigma\right). \end{aligned}$$

Thus we can apply Lemma 15 to the super-martingale  $\left( \exp\left(\frac{1}{2\sqrt{2}\sigma} \sum_{s=1}^t (|y_s - \mathbb{E}[y_s | X_s]| - 2\sqrt{2}\sigma)\right) \right)_t$  in order to obtain, for any  $\delta > 0$ ,

$$\sum_{s=1}^{t-1} |y_t - \mathbb{E}[y_t | X_t]| \leq 2\sqrt{2}(t-1)\sigma + 2\sqrt{2}\sigma \ln \delta^{-1}, \quad t \geq 1,$$

with probability at least  $1 - \delta$ . The result follows from Equation (17) and  $2\sqrt{2} \leq 3$ .  $\square$

**Proof. of Theorem 14.** We first apply Theorem 2: with probability at least  $1 - 5\delta$ , it holds simultaneously

$$\begin{aligned} \sum_{t=\tau(\varepsilon, \delta)+1}^n L(\hat{\theta}_t) - L(\theta^*) &\leq \frac{15}{2} d (8\sigma^2 + D_{\text{app}}^2 + \varepsilon^2 D_X^2) \ln \left( 1 + (n - \tau(\varepsilon, \delta)) \frac{\lambda_{\max}(P_1) D_X^2}{d} \right) \\ &\quad + 5\lambda_{\max}(P_{\tau(\varepsilon, \delta)+1}^{-1}) \varepsilon^2 \\ &\quad + 115 \left( \sigma^2 \left( 4 + \frac{\lambda_{\max}(P_1) D_X^2}{4} \right) + D_{\text{app}}^2 + 2\varepsilon^2 D_X^2 \right) \ln \delta^{-1}, \quad n \geq \tau(\varepsilon, \delta). \end{aligned}$$

Moreover,  $\lambda_{\max}(P_{\tau(\varepsilon, \delta)+1}^{-1}) \leq \lambda_{\max}(P_1^{-1}) + \tau(\varepsilon, \delta) D_X^2$ .

Then we derive a bound on the first  $\tau(\varepsilon, \delta)$  terms. For any  $t \geq 1$ , we have  $L(\hat{\theta}_t) - L(\theta^*) \leq D_X^2 \|\hat{\theta}_t - \theta^*\|^2$ , thus, using  $(a+b)^2 \leq 2(a^2 + b^2)$  and applying Lemma 22 we obtain the simultaneous property

$$\begin{aligned} L(\hat{\theta}_t) - L(\theta^*) &\leq 2D_X^2 (\|\hat{\theta}_1 - \theta^*\| + 3\lambda_{\max}(P_1) D_X \sigma \ln \delta^{-1})^2 \\ &\quad + 2\lambda_{\max}(P_1)^2 D_X^4 (3\sigma + D_{\text{app}})^2 (t-1)^2, \quad t \geq 1, \end{aligned}$$



with probability at least  $1 - \delta$ .

Thus, a summation argument yields, for any  $\delta > 0$ ,

$$\begin{aligned} \sum_{t=1}^{\tau(\varepsilon, \delta)} L(\hat{\theta}_t) - L(\theta^*) &\leq 2D_X^2(\|\hat{\theta}_1 - \theta^*\| + 3\lambda_{\max}(P_1)D_X\sigma \ln \delta^{-1})^2\tau(\varepsilon, \delta) \\ &\quad + \lambda_{\max}(P_1)^2D_X^4(3\sigma + D_{\text{app}})^2 \frac{(\tau(\varepsilon, \delta) - 1)\tau(\varepsilon, \delta)(2\tau(\varepsilon, \delta) - 1)}{3}, \end{aligned}$$

with probability at least  $1 - \delta$ . □

## C.2 Definition of $\tau(\varepsilon, \delta)$

We now focus on the definition of  $\tau(\varepsilon, \delta)$ . We first transcript the result of Hsu et al. (2012) to our notations in the following lemma.

**Lemma 23.** *Provided that Assumptions 1, 2 and 4 are satisfied, starting from any  $\hat{\theta}_1 \in \mathbb{R}^d$  and  $P_1 = p_1I, p_1 > 0$ , we have, for any  $0 < \delta < e^{-2.6}$  and  $t \geq 6\frac{D_X^2}{\Lambda_{\min}}(\ln d + \ln \delta^{-1})$ ,*

$$\begin{aligned} \|\hat{\theta}_{t+1} - \theta^*\|_{\Sigma}^2 &\leq \frac{3}{t} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{2p_1} + \frac{D_X^2}{\Lambda_{\min}}D_{\text{app}}^2 \frac{4(1 + \sqrt{8 \ln \delta^{-1}})}{0.07^2} + \frac{3\sigma^2(d/0.035 + \ln \delta^{-1})}{0.07} \right) \\ &\quad + \frac{12}{0.07^2t^2} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} \frac{D_X^2}{\Lambda_{\min}}(1 + \sqrt{8 \ln \delta^{-1}}) \right. \\ &\quad \left. + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}}(D_{\text{app}} + D_X\|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{2p_1}} \right)^2 (\ln \delta^{-1})^2 \right), \end{aligned}$$

with probability at least  $1 - 4\delta$ .

**Proof.** We first observe that

$$\arg \min_{w \in \mathbb{R}^d} \frac{1}{t} \sum_{s=1}^t (y_s - w^T X_s)^2 + \lambda \|w - \hat{\beta}_1\|^2 = \arg \min_{w \in \mathbb{R}^d} \frac{1}{t} \sum_{s=1}^t (y_s - \hat{\beta}_1^T X_s - w^T X_s)^2 + \lambda \|w\|^2,$$

therefore we apply ridge analysis of Hsu et al. (2012) to  $(X_s, y_s - \hat{\beta}_1^T X_s)$ . We note that  $(y_s - \hat{\beta}_1^T X_s)$  has the same variance proxy and the same approximation error, it only amounts to translate the optimal  $w$ , that is denoted by  $\beta$ .

For any  $\lambda > 0$ , we observe that  $d_{2,\lambda} \leq d_{1,\lambda} \leq d$ ,  $\rho_\lambda \leq \frac{D_X}{\sqrt{d_{1,\lambda}\Lambda_{\min}}}$  and  $b_\lambda \leq \rho_\lambda(D_{\text{app}} + D_X\|\beta - \hat{\beta}_1\|)$ . Therefore we can apply Theorem 16 of Hsu et al. (2012): for  $0 < \delta < e^{-2.6}$  and  $t \geq 6\frac{D_X}{\sqrt{\Lambda_{\min}}}(\ln(d) + \ln \delta^{-1})$ , the following holds with probability  $1 - 4\delta$ :  $\|\hat{\beta}_{t+1,\lambda} - \beta\|_{\Sigma}^2 = 3(\|\beta_\lambda - \beta\|_{\Sigma}^2 + \varepsilon_{\text{bs}} + \varepsilon_{\text{vr}})$ , with

$$\begin{aligned} \varepsilon_{\text{bs}} &\leq \frac{4}{0.07^2} \left( \frac{\frac{D_X^2}{\Lambda_{\min}} \mathbb{E}[(\mathbb{E}[y | X] - \beta^T X)^2]}{t} + (1 + \frac{D_X^2}{\Lambda_{\min}}) \|\beta_\lambda - \beta\|_{\Sigma}^2 (1 + \sqrt{8 \ln \delta^{-1}}) \right. \\ &\quad \left. + \frac{(\frac{D_X}{\sqrt{\Lambda_{\min}}}(D_{\text{app}} + D_X\|\beta - \hat{\beta}_1\|) + \|\beta_\lambda - \beta\|_{\Sigma})^2}{t^2} (\ln \delta^{-1})^2 \right), \\ \delta_f &\leq \frac{1}{\sqrt{t}} \frac{D_X}{\sqrt{\Lambda_{\min}}} (1 + \sqrt{8 \ln \delta^{-1}}) + \frac{1}{t} \frac{4\sqrt{\frac{D_X^4}{\Lambda_{\min}^2 d} + 1}}{3} \ln \delta^{-1}, \\ \varepsilon_{\text{vr}} &\leq \frac{\sigma^2 d(1 + \delta_f)}{0.07^2 t} + \frac{2\sigma^2 \sqrt{d(1 + \delta_f)} \ln \delta^{-1}}{0.07^{3/2} t} + \frac{2\sigma^2 \ln \delta^{-1}}{0.07 t}. \end{aligned}$$

Moreover  $\mathbb{E}[(\mathbb{E}[y | X] - \beta^T X)^2] \leq D_{\text{app}}^2$  and  $\Lambda_{\min} \leq D_X^2$ , hence, using  $\|\beta_\lambda - \beta\|_{\Sigma} \leq \lambda \|\beta - \hat{\beta}_1\|$  we transfer the result in our KF notations, that is,  $\hat{\theta}_t = \hat{\beta}_{t,p_1^{-1}/2(t-1)}$ ,  $\hat{\beta}_1 = \hat{\theta}_1$ ,  $\beta = \theta^*$ . We obtain, for any  $0 < \delta < e^{-2.6}$  and

$$t \geq 6 \frac{D_X}{\sqrt{\Lambda_{\min}}} (\ln(d) + \ln \delta^{-1}),$$

$$\begin{aligned} \varepsilon_{\text{bs}} &\leq \frac{4}{0.07^2} \left( \frac{\frac{D_X^2}{\Lambda_{\min}} D_{\text{app}}^2 + \frac{D_X^2}{\Lambda_{\min}} \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1 t}}{t} (1 + \sqrt{8 \ln \delta^{-1}}) \right. \\ &\quad \left. + \frac{\left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{2p_1 t}} \right)^2}{t^2} (\ln \delta^{-1})^2 \right), \\ \delta_f &\leq \frac{1}{\sqrt{t}} \frac{D_X}{\sqrt{\Lambda_{\min}}} (1 + \sqrt{8 \ln \delta^{-1}}) + \frac{1}{t} \frac{4 \sqrt{\frac{D_X^4}{\Lambda_{\min}^2 d} + 1}}{3} \ln \delta^{-1}, \\ \varepsilon_{\text{vr}} &\leq \frac{\sigma^2 d (1 + \delta_f)}{0.07^2 t} + \frac{2\sigma^2 \sqrt{d(1 + \delta_f)} \ln \delta^{-1}}{0.07^{3/2} t} + \frac{2\sigma^2 \ln \delta^{-1}}{0.07 t}, \\ \|\hat{\theta}_{t+1} - \theta^*\|_{\Sigma}^2 &\leq 3 \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{2p_1 t} + \varepsilon_{\text{bs}} + \varepsilon_{\text{vr}} \right), \end{aligned}$$

with probability at least  $1 - 4\delta$ . For  $t \geq \frac{D_X^2}{\Lambda_{\min}} \ln \delta^{-1}$ , as  $\ln \delta^{-1} \geq 1$ , we get

$$\delta_f \leq \frac{1}{\sqrt{6 \ln \delta^{-1}}} (1 + \sqrt{8 \ln \delta^{-1}}) + \frac{1}{6} \frac{4}{3} \sqrt{\frac{1}{d} + 1} \leq \frac{1 + \sqrt{8}}{\sqrt{6}} + \frac{2\sqrt{2}}{9} \approx 1.9 \leq 2.$$

Thus, as  $\sqrt{ab} \leq \frac{a+b}{2}$  for any  $a, b > 0$ , we have

$$\begin{aligned} \varepsilon_{\text{vr}} &\leq \frac{\sigma^2}{0.07 t} \left( \frac{3d}{0.07} + 2 \sqrt{\frac{3d \ln \delta^{-1}}{0.07}} + 2 \ln \delta^{-1} \right) \\ &\leq \frac{\sigma^2}{0.07 t} \left( \frac{6d}{0.07} + 3 \ln \delta^{-1} \right) \\ &\leq \frac{3\sigma^2 (d/0.035 + \ln \delta^{-1})}{0.07 t}. \end{aligned}$$

It yields the result. □

Lemma 23 allows the definition of an explicit value for  $\tau(\varepsilon, \delta)$ , as displayed in the following Corollary.

**Corollary 24.** *Assumption 5 is satisfied for  $\tau(\varepsilon, \delta) = \max(\tau_1(\delta), \tau_2(\varepsilon, \delta), \tau_3(\varepsilon, \delta))$  where we define*

$$\begin{aligned} \tau_1(\delta) &= \max \left( 12 \frac{D_X^2}{\Lambda_{\min}} (\ln d + \ln \delta^{-1}), \frac{48 D_X^2}{\Lambda_{\min}} \ln \frac{24 D_X^2}{\Lambda_{\min}} \right), \\ \tau_2(\varepsilon, \delta) &= \frac{24 \varepsilon^{-1}}{\Lambda_{\min}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{2p_1} + \frac{D_X^2}{\Lambda_{\min}} D_{\text{app}}^2 \frac{4(1 + \sqrt{8 \ln \delta^{-1}})}{0.07^2} + \frac{3\sigma^2 (d/0.035 + \ln \delta^{-1})}{0.07} \right) \\ &\quad \ln \frac{12 \varepsilon^{-1}}{\Lambda_{\min}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{2p_1} + \frac{D_X^2}{\Lambda_{\min}} D_{\text{app}}^2 \frac{4(1 + \sqrt{8 \ln \delta^{-1}})}{0.07^2} + \frac{3\sigma^2 (d/0.035 + \ln \delta^{-1})}{0.07} \right), \\ \tau_3(\varepsilon, \delta) &= \sqrt{\frac{96 \varepsilon^{-1}}{0.07^2 \Lambda_{\min}}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} \frac{D_X^2}{\Lambda_{\min}} (1 + \sqrt{8 \ln \delta^{-1}}) \right. \\ &\quad \left. + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{2p_1}} \right)^2 (\ln \delta^{-1})^2 \right)^{1/2} \\ &\quad \ln \frac{96 \varepsilon^{-1}}{0.07^2 \Lambda_{\min}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{2p_1} \left( 1 + \frac{D_X^2}{\Lambda_{\min}} \right) (1 + \sqrt{8 \ln \delta^{-1}}) \right. \\ &\quad \left. + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{2p_1}} \right)^2 (\ln \delta^{-1})^2 \right). \end{aligned}$$

We recall that for any  $\eta \leq 1$ , we have  $\frac{\ln t}{t} \leq \eta$  for  $t \geq 2\eta^{-1} \ln(\eta^{-1})$ , and we use it in the following proof.

**Proof. of Corollary 24.** We define  $\delta_t = \delta/t^2$  for any  $t \geq 1$ . In order to apply Lemma 23 with a union bound, we need  $t \geq 6\frac{D_X^2}{\Lambda_{\min}}(\ln d + \ln \delta_t^{-1})$ . If  $t \geq 12\frac{D_X^2}{\Lambda_{\min}}(\ln d + \ln \delta^{-1})$  and  $t \geq \frac{48D_X^2}{\Lambda_{\min}} \ln \frac{24D_X^2}{\Lambda_{\min}}$ , we obtain

$$\begin{aligned} t &\geq \frac{t}{2} + \frac{\sqrt{t}}{2}\sqrt{t} \\ &\geq 6\frac{D_X^2}{\Lambda_{\min}}(\ln d + \ln \delta^{-1}) + \frac{12D_X^2}{\Lambda_{\min}} \ln t, \quad \text{as } \ln t \leq \sqrt{t} \\ &= 6\frac{D_X^2}{\Lambda_{\min}}(\ln d + \ln \delta_t^{-1}). \end{aligned}$$

Therefore, we define  $\tau_1(\delta) = \max\left(12\frac{D_X^2}{\Lambda_{\min}}(\ln d + \ln \delta^{-1}), \frac{48D_X^2}{\Lambda_{\min}} \ln \frac{24D_X^2}{\Lambda_{\min}}\right)$ , and we apply Lemma 23. We get the simultaneous property

$$\begin{aligned} \|\hat{\theta}_{t+1} - \theta^*\|_{\Sigma}^2 &\leq \frac{3}{t} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{2p_1} + \frac{D_X^2}{\Lambda_{\min}} D_{\text{app}}^2 \frac{4(1 + \sqrt{8 \ln \delta_t^{-1}})}{0.07^2} + \frac{3\sigma^2(d/0.035 + \ln \delta_t^{-1})}{0.07} \right) \\ &\quad + \frac{12}{0.07^2 t^2} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} \frac{D_X^2}{\Lambda_{\min}} (1 + \sqrt{8 \ln \delta_t^{-1}}) \right. \\ &\quad \left. + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{2p_1}} \right)^2 (\ln \delta_t^{-1})^2 \right), \quad t \geq \tau_1(\delta), \end{aligned}$$

with probability at least  $1 - 4\delta \sum_{t \geq \tau_1(\delta)} t^{-2} \geq 1 - \delta$  because  $\tau_1(\delta) > 4$ .

Thus, as  $\ln t \geq 1$  for  $t \geq \tau_1(\delta)$  and  $\|\hat{\theta}_{t+1} - \theta^*\|_{\Sigma}^2 \geq \Lambda_{\min} \|\hat{\theta}_{t+1} - \theta^*\|^2$ , we obtain

$$\begin{aligned} \|\hat{\theta}_{t+1} - \theta^*\| &\leq \frac{6 \ln t}{\Lambda_{\min} t} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{2p_1} + \frac{D_X^2}{\Lambda_{\min}} D_{\text{app}}^2 \frac{4(1 + \sqrt{8 \ln \delta^{-1}})}{0.07^2} + \frac{3\sigma^2(d/0.035 + \ln \delta^{-1})}{0.07} \right) \\ &\quad + \frac{48(\ln t)^2}{0.07^2 \Lambda_{\min} t^2} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} \frac{D_X^2}{\Lambda_{\min}} (1 + \sqrt{8 \ln \delta^{-1}}) \right. \\ &\quad \left. + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{2p_1}} \right)^2 (\ln \delta^{-1})^2 \right), \quad t \geq \tau_1(\delta), \end{aligned}$$

with probability at least  $1 - \delta$ . Finally, both terms of the last inequality are bounded by  $\varepsilon/2$ .  $\square$

From Corollary 24, we obtain the asymptotic rate by comparing  $\tau_2(\delta)$  and  $\tau_3(\delta)$ . We write  $\tau_2(\delta) = 2A_2(\delta) \ln A_2(\delta)$ ,  $\tau_3(\delta) = 2A_3(\delta) \ln A_3(\delta)$  with

$$\begin{aligned} A_2(\delta) &\lesssim \frac{\varepsilon^{-1}}{\Lambda_{\min}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} + \frac{D_X^2}{\Lambda_{\min}} D_{\text{app}}^2 \sqrt{\ln \delta^{-1}} + \sigma^2(d + \ln \delta^{-1}) \right) \\ A_3(\delta) &\lesssim \sqrt{\frac{\varepsilon^{-1}}{\Lambda_{\min}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} \frac{D_X^2}{\Lambda_{\min}} \sqrt{\ln \delta^{-1}} + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{p_1}} \right)^2 (\ln \delta^{-1})^2 \right)}. \end{aligned}$$

where the symbol  $\lesssim$  means less than up to universal constants. As  $\sqrt{a+b} \lesssim \sqrt{a} + \sqrt{b}$  and  $\sqrt{ab} \lesssim a+b$ , we obtain

$$\begin{aligned} A_3(\delta) &\lesssim \sqrt{\frac{\varepsilon^{-1}}{\Lambda_{\min}} \left( \sqrt{\frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} \frac{D_X^2}{\Lambda_{\min}} \sqrt{\ln \delta^{-1}}} + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{p_1}} \right) \ln \delta^{-1} \right)} \\ &\lesssim \sqrt{\frac{\varepsilon^{-1}}{\Lambda_{\min}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} + \frac{D_X^2}{\Lambda_{\min}} \sqrt{\ln \delta^{-1}} + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{p_1}} \right) \ln \delta^{-1} \right)}. \end{aligned}$$

Thus, as long as  $\frac{\varepsilon^{-1}}{\Lambda_{\min}} \leq 1$ , we get

$$A_2(\delta), A_3(\delta) \lesssim \frac{\varepsilon^{-1}}{\Lambda_{\min}} \left( \frac{\|\hat{\theta}_1 - \theta^*\|^2}{p_1} + \frac{D_X^2}{\Lambda_{\min}} (1 + D_{\text{app}}^2) \sqrt{\ln \delta^{-1}} + \sigma^2 d \right. \\ \left. + \left( \frac{D_X}{\sqrt{\Lambda_{\min}}} (D_{\text{app}} + D_X \|\theta^*\|) + \frac{\|\hat{\theta}_1 - \theta^*\|}{\sqrt{p_1}} + \sigma^2 \right) \ln \delta^{-1} \right).$$