Self-Concordant Analysis of Generalized Linear Bandits with Forgetting

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Motivations

- **Non-stationary** environments: ubiquitous in real-world applications.
- **Generalized Linear Models**: broader rewards models of considerable practical relevance (**binary**,**categorical**).

↪ **Extension of forgetting strategies** designed for linear bandits to Generalized Linear Models.

Preliminaries

At time t, **time-dependent finite set of arbitrary actions** $\mathscr{A}_t = \{A_{t,1}, \dots, A_{t,K_t}\}$, where $A_{t,k} \in \mathbb{R}^d$. After selection of $a_t \in \mathscr{A}_t$ observation of a reward following:

$$\mathbb{E}[r_{t+1}|a_t] = \mu(a_t^\top \theta_t^\star), \quad \text{with } \mu \text{ the } \textbf{inverse link function},$$

Dynamic Regret:

$$R_T = \sum_{t=1}^{T} \max_{a \in \mathscr{A}_t} \mu(a^\top \theta_t^\star) - \mu(a_t^\top \theta_t^\star)$$

Maximum likelihood estimator: Solution of the convex program:

$$\hat{\theta}_t = \operatorname*{arg\,min}_{\theta \in \mathbb{R}^d} - \sum_{s=1}^{t-1} w_{s,t} \log \mathbb{P}_\theta(r_{s+1}|a_s) + \frac{\lambda}{2}\|\theta\|_2^2 \qquad (1)$$

Forgetting policies: if $w_{s,t} = \gamma^{t-1-s}$ **discounted policy** and if $w_{s,t} = \mathbb{1}(t - s \leq \tau)$ **sliding window policy**.

Assumptions

- Bounded actions and parameters: $\forall t \geq 1, \forall a \in \mathscr{A}_t, \|a\|_2 \leq 1$, $\|\theta_t^\star\|_2 \leq S$.
- Bounded rewards: $\forall t \geq 1, 0 \leq r_t \leq m$.
- **Non-Stationarity:** $\theta_t^\star$ can change in an arbitrary fashion **up to** Γ_T **times**.
- **Self-Concordance**:

$$|\ddot{\mu}| \leq \dot{\mu}$$

- For the inverse link fuction:

$$c_\mu := \inf_{\theta: \|\theta\|_2 \leq S, a: \|a\|_2 \leq 1} \dot{\mu}(a^\top \theta) > 0$$

⚠ $1/c_\mu$ can be **exponentially large in** S!

Challenges and Approach

1) c_μ limitation of the practical interest of Generalized Linear Bandits algorithms. ↪ Reducing **dependency in the** c_μ **in non-stationary environments**
↪ Extension of a Berstein-like inequality of [1] to **weighted self-normalized martingales**.

2) MLE not necessarily bounded, existing algorithms require a complicated projection step or a prohibitively long burn-in phase.
↪ **Finer characterization of the MLE** using self-concordance assumption. Algorithm relying solely on this estimator **without any projection**

Concentration Result

To solve **1)**, **switching from a global analysis** featuring $V_t = \sum_{s=1}^{t} w_{s,t}^2 a_s a_s^\top + \lambda I_d$ **to a local analysis** through $H_t(\theta) = \sum_{s=1}^{t} w_{s,t}^2 \dot{\mu}(a_s^\top \theta) a_s a_s^\top + \lambda I_d$.

↪ How to handle the weights with a local analysis?

Theorem 1.
Let $\widetilde{H}_t = \sum_{s=1}^{t-1} w_s^2 \dot{\mu}(a_s^\top \theta_s^\star) a_s a_s^\top + \lambda_{t-1} I_d$, $\epsilon_{s+1} = r_{s+1} - \mu(a_s^\top \theta_s^\star)$ and $S_t = \sum_{s=1}^{t-1} w_s \epsilon_{s+1} a_s$, then for any $\delta \in (0,1]$,

$$P\left(\|S_t\|_{\widetilde{H}_t^{-1}} \leq \mathcal{O}\left(\sqrt{d \log\left(\frac{t}{\delta}\right)}\right)\right) \geq 1 - \delta\,.$$

↪ High probability upper-bound independent of c_μ thanks to the local analysis!

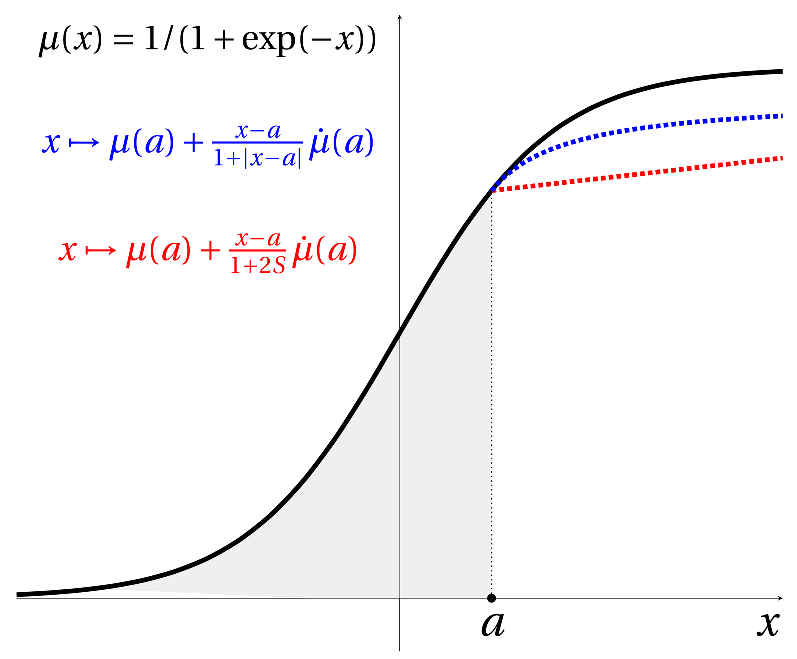
Self-Concordance and MLE

Using a Taylor expansion and the **self-concordance assumption**, the authors in [1] uses:

$$\forall x, \quad \mu(x^\top \theta_t) \geq \mu(x^\top \theta^\star) + \frac{|x^\top(\theta^\star - \theta_t)|}{1 + 2S} \dot{\mu}(x^\top \theta^\star)$$

Here, **tighter bound** to solve **2)**,

$$\forall x, \quad \mu(x^\top \hat{\theta}_t) \geq \mu(x^\top \theta^\star) + \frac{|x^\top(\theta^\star - \hat{\theta}_t)|}{1 + |x^\top(\theta^\star - \hat{\theta}_t)|} \dot{\mu}(x^\top \theta^\star)$$



Comparison with Existing Works

Algorithm	Setting	Projection	Regret Upper Bound
GLM-UCB [2]	Stationary GLM	Non-convex	$\widetilde{\mathcal{O}}\left(c_\mu^{-1} \cdot d \cdot \sqrt{T}\right)$
LogUCB1 [1]	Stationary Logistic	Non-convex	$\widetilde{\mathcal{O}}\left(c_\mu^{-1/2} \cdot d \cdot \sqrt{T}\right)$
D-GLUCB [3]	Non-Stationary GLM	Non-convex	$\widetilde{\mathcal{O}}\left(c_\mu^{-1} \cdot d^{2/3} \cdot \Gamma_T^{1/3} \cdot T^{2/3}\right)$
SC-D-GLUCB	Non-Stationary GLM + Gap Assumption	No projection	$\widetilde{\mathcal{O}}\left(\boldsymbol{c_\mu^{-1/2}} \cdot d \cdot \sqrt{\Gamma_T T}\right)$
SC-D-GLUCB	Non-Stationary GLM	No projection	$\widetilde{\mathcal{O}}\left(\boldsymbol{c_\mu^{-1/3}} \cdot d^{2/3} \cdot \Gamma_T^{1/3} \cdot T^{2/3}\right)$

Tab. 1: Comparison of regret guarantees for different algorithms in the GLM setting

Regret Upper Bound

Theorem 2. Setting $\gamma = 1 - (c_\mu^{1/2}\Gamma_T/(dT))^{2/3}$ and $\lambda = d\log(T)$ leads to,

$$R_T = \mathcal{O}\left(c_\mu^{-1/3} d^{2/3} \Gamma_T^{1/3} T^{2/3}\right)$$

Adding an assumption on the gap, i.e. assuming that for all t and all suboptimal $a \in \mathscr{A}_t$, $\mu(a_{t,\star}^\top \theta_t^\star) - \mu(a^\top \theta^\star) > \Delta$ and setting $\gamma = 1 - \sqrt{\frac{c_\mu \Gamma_T}{d^2 T}}$ leads to,

$$R_T = \mathcal{O}\left(\Delta^{-1} c_\mu^{-1/2} d \sqrt{\Gamma_T T}\right)$$

Algorithm

Algorithm 1: SC-SW-GLUCB

Input: Probability δ, dimension d, regularization λ, upper bound for parameters S, sliding window length τ.
Initialization: $V = \lambda / c_\mu I_d$, $\hat{\theta} = 0_{\mathbb{R}^d}$
for $t \geq 1$ **do**
  Receive $\mathscr{A}_t$, compute $\hat{\theta}_t$ according to Eq. (1) and β_t according to Eq. (**??**)
  Play action $a_t = \arg\max_{a \in \mathscr{A}_t} \mu(a^\top \hat{\theta}_t) + \frac{\beta_t^\delta}{\sqrt{c_\mu}} \|a\|_{V_t^{-1}}$
  Receive reward r_{t+1}
  Updating phase:
  if $t < \tau$ **then**
    $V_{t+1} \leftarrow a_t a_t^\top + V_t$
  else
    $V_{t+1} \leftarrow a_t a_t^\top - a_{t-\tau} a_{t-\tau}^\top + V_t$

Experiments in Abruptly Changing Environments

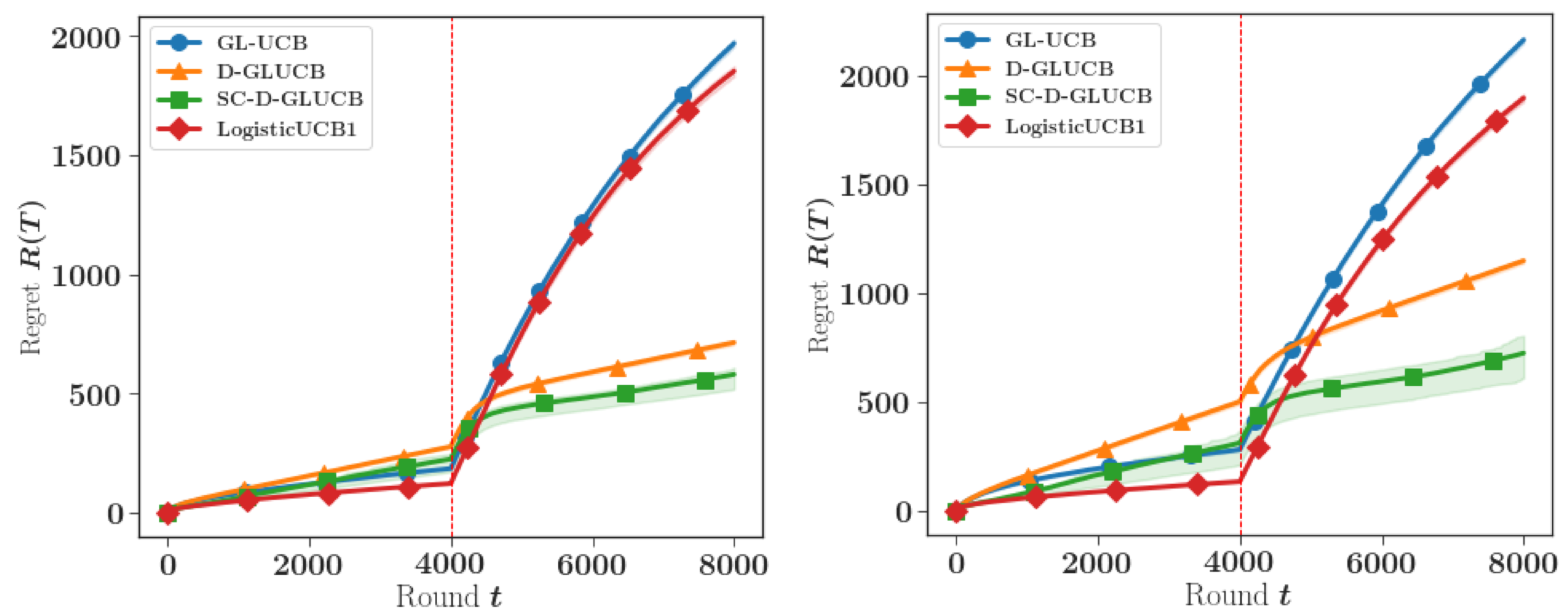


Fig. 1: Regret of the different algorithms in a 2D abruptly changing environment averaged on 200 independent experiments and the 25% associated quantiles. *(left)* $c_\mu^{-1} = 400$, *(right)* $c_\mu^{-1} = 1000$

References

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