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Parametric Graph for Unimodal Ranking Bandit

Supplementary Materials

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The appendix is organized as follows. We first list most of the notations used in the paper in Appendix A. Lemma 1 is proved in Appendix B. In Appendix C, we recall a Lemma from (Combes & Proutière, 2014) used by our own Lemmas and Theorems, and then in Appendices D to F we respectively prove Theorem 2, Lemma 2, and Lemma 3. In Appendix G we define KL-CombUCB and discuss its regret and its relation to GRAB. Finally in Appendix H we introduce and discuss S-GRAB.

A. Notations

The following table summarize the notations used through the paper and the appendix.

SYMBOL	MEANING
T	TIME HORIZON
t	ITERATION
L	NUMBER OF ITEMS
i	INDEX OF AN ITEM
K	NUMBER OF POSITIONS IN A RECOMMENDATION
k	INDEX OF A POSITION
$[n]$	SET OF INTEGERS $\{1, \dots, n\}$
\mathcal{P}_K^L	SET OF PERMUTATIONS OF K DISTINCT ITEMS AMONG L
θ	VECTORS OF PROBABILITIES OF CLICK
θ_i	PROBABILITY OF CLICK ON ITEM i
κ	VECTORS OF PROBABILITIES OF VIEW
κ_k	PROBABILITY OF VIEW AT POSITION k
\mathcal{A}	SET OF BANDIT ARMS
\mathbf{a}	AN ARM IN \mathcal{A}
$\mathbf{a}(t)$	THE ARM CHOSEN AT ITERATION t
$\tilde{\mathbf{a}}(t)$	BEST ARM AT ITERATION t GIVEN THE PREVIOUS CHOICES AND FEEDBACKS (CALLED LEADER)
\mathbf{a}^*	BEST ARM
G	GRAPH CARRYING A PARTIAL ORDER ON \mathcal{A}
γ	MAXIMUM DEGREE OF G
$\mathcal{N}_G(\tilde{\mathbf{a}}(t))$	NEIGHBORHOOD OF $\tilde{\mathbf{a}}(t)$ GIVEN G
$\rho_{i,k}$	PROBABILITY OF CLICK ON ITEM i DISPLAYED AT POSITION k
$\mathbf{c}(t)$	CLICKS VECTOR AT ITERATION t
$r(t)$	REWARD COLLECTED AT ITERATION t , $r(t) = \sum_{k=1}^K c_k(t)$
$\mu_{\mathbf{a}}$	EXPECTATION OF $r(t)$ WHILE RECOMMENDING \mathbf{a} , $\mu_{\mathbf{a}} = \sum_{k=1}^K \rho_{\mathbf{a},k}$
μ^*	HIGHEST EXPECTED REWARD, $\mu^* = \max_{\mathbf{a} \in \mathcal{P}_K^L} \mu_{\mathbf{a}}$
$\Delta_{\mathbf{a}}$	GAP BETWEEN $\mu_{\mathbf{a}}$ AND μ^*
Δ_{min}	MINIMAL VALUE FOR $\Delta_{\mathbf{a}}$
Δ	GENERIC REWARD GAP BETWEEN ONE OF THE SUB-OPTIMAL ARMS AND ONE OF THE BEST ARMS

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Parametric Graph for Unimodal Ranking Bandit (Supplementary Materials)

SYMBOL	MEANING
$R(T)$	CUMULATIVE (PSEUDO-)REGRET, $R(T) = T\mu^* - \mathbb{E} \left[\sum_{t=1}^T \mu_{\mathbf{a}(t)} \right]$
$\Pi_{\rho}(\mathbf{a})$	SET OF PERMUTATIONS IN \mathcal{P}_K^K ORDERING THE POSITIONS S.T. $\rho_{a_{\pi_1}, \pi_1} \geq \rho_{a_{\pi_2}, \pi_2} \geq \dots \geq \rho_{a_{\pi_K}, \pi_K}$
π	ELEMENT OF $\Pi_{\rho}(\mathbf{a})$
$\tilde{\pi}$	ESTIMATION OF π
$\mathbf{a} \circ (\pi_k, \pi_{k+1})$	PERMUTATION SWAPPING ITEMS IN POSITIONS π_k AND π_{k+1}
$\mathbf{a}[\pi_K := i]$	PERMUTATION LEAVING \mathbf{a} THE SAME FOR ANY POSITION EXCEPT π_K FOR WHICH $\mathbf{a}[\pi_K := i]_{\pi_K} = i$
\mathcal{F}	RANKINGS OF POSITIONS RESPECTING Π_{ρ} , $\mathcal{F} = (\pi_{\mathbf{a}})_{\mathbf{a} \in \mathcal{P}_K^K}$ S.T. $\forall \mathbf{a} \in \mathcal{P}_K^K, \pi_{\mathbf{a}} \in \Pi_{\rho}(\mathbf{a})$
$T_{i,k}(t)$	NUMBER OF ITERATIONS S.T. ITEM i HAS BEEN DISPLAYED AT POSITION k , $T_{i,k}(t) = \sum_{s=1}^{t-1} \mathbb{1}\{a_k(s) = i\}$
$\tilde{T}_{\mathbf{a}}(t)$	NUMBER OF ITERATIONS S.T. THE LEADER WAS \mathbf{a} , $\tilde{T}_{\mathbf{a}}(t) \stackrel{def}{=} \sum_{s=1}^{t-1} \mathbb{1}\{\tilde{\mathbf{a}}(s) = \mathbf{a}\}$
$T_{\mathbf{a}}(t)$	NUMBER OF ITERATIONS S.T. THE CHOSEN ARM WAS \mathbf{a} , $T_{\mathbf{a}}(t) = \sum_{s=1}^{t-1} \mathbb{1}\{\mathbf{a}(s) = \mathbf{a}\}$
$T_{\tilde{\mathbf{a}}}^{\mathbf{a}}(t)$	NUMBER OF ITERATIONS S.T. THE LEADER WAS $\tilde{\mathbf{a}}$, THE CHOSEN ARM WAS \mathbf{a} , AND \mathbf{a} WAS CHOSEN BY THE ARGMAX ON $\sum_{k=1}^K b_{a_k, k}(t)$: $T_{\tilde{\mathbf{a}}}^{\mathbf{a}}(t) = \sum_{s=1}^{t-1} \mathbb{1}\{\tilde{\mathbf{a}}(s) = \tilde{\mathbf{a}}, \mathbf{a}(s) = \mathbf{a}, \tilde{T}_{\tilde{\mathbf{a}}}(s)/L \notin \mathbb{N}\}$
$\hat{\rho}_{i,k}(t)$	ESTIMATION OF $\rho_{i,k}$ AT ITERATION t , $\hat{\rho}_{i,k}(t) = \frac{1}{T_{i,k}(t)} \sum_{s=1}^{t-1} \mathbb{1}\{a_k(s) = i\} c_k(s)$
$b_{i,k}(t)$	KULLBACK-LEIBLER INDEX OF $\hat{\rho}_{i,k}(t)$, $b_{i,k}(t) = f(\hat{\rho}_{i,k}(t), T_{i,k}(t), \tilde{T}_{\tilde{\mathbf{a}}}(t) + 1)$
f	KULLBACK-LEIBLER INDEX FUNCTION, $f(\hat{\rho}, s, t) = \sup\{p \in [\hat{\rho}, 1] : s \times \text{kl}(\hat{\rho}, p) \leq \log(t) + 3 \log(\log(t))\}$,
$\text{kl}(p, q)$	KULLBACK-LEIBLER DIVERGENCE FROM A BERNOULLI DISTRIBUTION OF MEAN p TO A BERNOULLI DISTRIBUTION OF MEAN q , $\text{kl}(p, q) = p \log\left(\frac{p}{q}\right) + (1-p) \log\left(\frac{1-p}{1-q}\right)$
$B_{\mathbf{a}}(t)$	PSEUDO-SUM OF INDICES OF \mathbf{a} AT ITERATION t , $B_{\mathbf{a}}(t) = \sum_{k=1}^K b_{a_k, k}(t) - \sum_{k=1}^K b_{\tilde{a}_k(t), k}(t)$
$\mathcal{N}_{\pi^*}(\mathbf{a}^*)$	NEIGHBORHOOD OF THE BEST ARM
$K_{\mathbf{a}}$	(WITH COMBINATORIAL BANDIT SETTING) NUMBER OF ELEMENTS IN \mathbf{a} BUT NOT IN \mathbf{a}^* , $K_{\mathbf{a}} = \min_{\mathbf{a}^* \in \mathcal{A}: \mu_{\mathbf{a}^*} = \mu^*} \mathbf{a} \setminus \mathbf{a}^* $
K_{max}	(WITH COMBINATORIAL BANDIT SETTING) MAXIMAL NUMBER OF ELEMENTS IN A SUB-OPTIMAL ARM \mathbf{a} BUT NOT IN AN OPTIMAL ARM \mathbf{a}^* , $K_{max} = \max_{\mathbf{a} \in \mathcal{A}: \mu_{\mathbf{a}} \neq \mu^*} K_{\mathbf{a}}$
$c^*(\boldsymbol{\theta}, \boldsymbol{\kappa})$	COEFFICIENT IN THE REGRET BOUND OF PMED
c	(IN ε_n -GREEDY) PARAMETER CONTROLLING THE PROBABILITY OF EXPLORATION
c	(IN PB-MHB) PARAMETER CONTROLLING SIZE OF THE STEP IN THE METROPOLIS HASTING INFERENCE
m	(IN PB-MHB) NUMBER OF STEP IN THE METROPOLIS HASTING INFERENCE

References to Theorems

Lemma 1 (PBM Fulfills Assumption 1).

Theorem 1 (Upper-Bound on the Regret of GRAB).

Theorem 2 (Upper-Bound on the Regret of KL-CombUCB).

Lemma 2 (Upper-Bound on the Number of Iterations of GRAB for which $\tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}} \neq \mathbf{a}^*$).

Lemma 3 (Upper-Bound on the Number of Iterations of GRAB for which $\tilde{\pi}(t) \notin \Pi_{\rho}(\tilde{\mathbf{a}})$).

B. Proof of Lemma 1 (PBM Fulfills Assumption 1)

Proof of Lemma 1. Let $(L, K, (\rho_{i,k})_{(i,k) \in [L] \times [K]})$ be an online learning to rank (OLR) problem with users following PBM, with positive probabilities of looking at a given position. Therefore, there exists $\boldsymbol{\theta} \in [0, 1]^L$ and $\boldsymbol{\kappa} \in (0, 1]^K$ such that for any item i and any position k , $\rho_{i,k} = \theta_i \kappa_k$.

Let $\mathbf{a} \in \mathcal{P}_K^K$ be a recommendation, and let $\pi \in \Pi_{\rho}(\mathbf{a})$ be an appropriate ranking of positions. One of the four following

properties is satisfied:

$$\exists k \in [K-1] \text{ s.t. } \theta_{a_{\pi_k}} < \theta_{a_{\pi_{k+1}}}, \quad (7)$$

$$\exists k \in [K-1] \text{ s.t. } \kappa_{\pi_k} < \kappa_{\pi_{k+1}}, \quad (8)$$

$$\exists i \in [L] \setminus \mathbf{a}([K]) \text{ s.t. } \theta_{a_{\pi_K}} < \theta_i, \quad (9)$$

$$\begin{cases} \forall k \in [K-1], \theta_{a_{\pi_k}} \geq \theta_{a_{\pi_{k+1}}} \\ \forall k \in [K-1], \kappa_{\pi_k} \geq \kappa_{\pi_{k+1}} \\ \forall i \in [L] \setminus \mathbf{a}([K]), \theta_{a_{\pi_K}} \geq \theta_i \end{cases}. \quad (10)$$

Let prove, by considering each of these properties one by one, that \mathbf{a} is either one of the best arms, or \mathbf{a} fulfills either Property (2) or Property (3) of Assumption 1.

If Property (7) is satisfied and $\theta_{a_{\pi_k}} = 0$, then by definition of $\boldsymbol{\pi}$ and $\Pi_{\boldsymbol{\rho}}(\mathbf{a})$, $0 = \theta_{a_{\pi_k}} \kappa_{\pi_k} \geq \theta_{a_{\pi_{k+1}}} \kappa_{\pi_{k+1}} > 0$ which is absurd.

Therefore, If Property (7) is satisfied, $\frac{\theta_{a_{\pi_{k+1}}}}{\theta_{a_{\pi_k}}} > 1$.

Note that by definition of $\boldsymbol{\pi}$ and $\Pi_{\boldsymbol{\rho}}(\mathbf{a})$, and as $\rho_{i,k} = \theta_i \kappa_k$, $\theta_{a_{\pi_k}} \kappa_{\pi_k} \geq \theta_{a_{\pi_{k+1}}} \kappa_{\pi_{k+1}}$.

Hence $\kappa_{\pi_k} \geq \frac{\theta_{a_{\pi_{k+1}}}}{\theta_{a_{\pi_k}}} \kappa_{\pi_{k+1}} > \kappa_{\pi_{k+1}}$, and

$$\begin{aligned} \mu_{\mathbf{a}} - \mu_{\mathbf{a} \circ (\pi_k, \pi_{k+1})} &= \theta_{a_{\pi_k}} \kappa_{\pi_k} + \theta_{a_{\pi_{k+1}}} \kappa_{\pi_{k+1}} - \left(\theta_{a_{\pi_{k+1}}} \kappa_{\pi_k} + \theta_{a_{\pi_k}} \kappa_{\pi_{k+1}} \right) \\ &= \left(\theta_{a_{\pi_k}} - \theta_{a_{\pi_{k+1}}} \right) \left(\kappa_{\pi_k} - \kappa_{\pi_{k+1}} \right) \\ &< 0, \end{aligned}$$

meaning $\mu_{\mathbf{a}} < \mu_{\mathbf{a} \circ (\pi_k, \pi_{k+1})}$, which corresponds to Property (2) of Assumption 1.

Similarly, if Property (8) is satisfied, then Property (2) of Assumption 1 is fulfilled.

If Property (9) is satisfied,

$$\begin{aligned} \mu_{\mathbf{a}} - \mu_{\mathbf{a}[\pi_K := i]} &= \theta_{a_{\pi_K}} \kappa_{\pi_K} - \theta_i \kappa_{\pi_K} \\ &= \left(\theta_{a_{\pi_K}} - \theta_i \right) \kappa_{\pi_K} \\ &< 0. \end{aligned}$$

Hence $\mu_{\mathbf{a}} < \mu_{\mathbf{a}[\pi_K := i]}$, which corresponds to Property (3) of Assumption 1.

Finally, if Property (10) is satisfied, $\mu_{\mathbf{a}} = \mu^*$.

Overall, either \mathbf{a} is one of the best arms, or \mathbf{a} fulfills Property (2) of Assumption 1, or \mathbf{a} fulfills Property (3) of Assumption 1, which concludes the proof. \square

C. Preliminary to the Analysis of GRAB

The analysis of GRAB requires a control of the number of high deviations, as expressed by Lemma B.1 of (Combes & Proutière, 2014). Let us recall this lemma, which we denote Lemma 4 in current paper.

Lemma 4 (Lemma B.1 of (Combes & Proutière, 2014)). *Let $i \in [L]$, $k \in [K]$, $\epsilon > 0$. Define $\mathcal{F}(T)$ the σ -algebra generated by $(\mathbf{c}(t))_{t \in [T]}$. Let $\Lambda \subseteq \mathbb{N}$ be a random set of instants. Assume that there exists a sequence of random sets $(\Lambda(s))_{s \geq 1}$ such that (i) $\Lambda \subseteq \bigcup_{s \geq 1} \Lambda(s)$, (ii) for all $s \geq 1$ and all $t \in \Lambda(s)$, $T_{i,k}(t) \geq \epsilon s$, (iii) $|\Lambda(s)| \leq 1$, and (iv) the event $t \in \Lambda(s)$ is \mathcal{F}_t -measurable. Then for all $\delta > 0$,*

$$\mathbb{E} \left[\sum_{t \geq 1} \mathbb{1}\{t \in \Lambda, |\hat{\rho}_{i,k}(t) - \rho_{i,k}| \geq \delta\} \right] \leq \frac{1}{\epsilon \delta^2}$$

D. Proof of Theorem 2 (Upper-bound on the Regret of KL-CombUCB)

Proof of Theorem 2. Let $\mathbf{a} \in \mathcal{A}$ be a sub-optimal arm. Let $\mathbf{a}^* \in \mathcal{A}$ be an optimal arm such that $|\mathbf{a} \setminus \mathbf{a}^*| = K_{\mathbf{a}}$.

We denote $\bar{K}_{\mathbf{a}} \stackrel{\text{def}}{=} |\mathbf{a}^* \setminus \mathbf{a}|$, $T_{\mathbf{a}}(t) \stackrel{\text{def}}{=} \sum_{s=1}^{t-1} \mathbb{1}\{\mathbf{a}(s) = \mathbf{a}\}$ the number of time the arm \mathbf{a} has been drawn, and $T_e(t) \stackrel{\text{def}}{=} \sum_{s=1}^{t-1} \mathbb{1}\{e \in \mathbf{a}(s)\}$ the number of time the element e was in the drawn arm.

Let decompose the expected number of iterations at which the permutation \mathbf{a} is recommended:

$$\begin{aligned} \mathbb{E} \left[\sum_{t=1}^T \mathbb{1}\{\mathbf{a}(t) = \mathbf{a}\} \right] &\leq \sum_{e \in \mathbf{a} \setminus \mathbf{a}^*} \mathbb{E} \left[\sum_{t=1}^T \mathbb{1} \left\{ \mathbf{a}(t) = \mathbf{a}, |\hat{\rho}_e(t) - \rho_e| \geq \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}} \right\} \right] \\ &+ \sum_{e \in \mathbf{a}^* \setminus \mathbf{a}} \mathbb{E} \left[\sum_{t=1}^T \mathbb{1}\{b_e(t) \leq \rho_e\} \right] \\ &+ \mathbb{E} \left[\sum_{t=|E|}^T \mathbb{1} \left\{ \mathbf{a}(t) = \mathbf{a}, \forall e \in \mathbf{a} \setminus \mathbf{a}^*, |\hat{\rho}_e(t) - \rho_e| < \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}}, \forall e \in \mathbf{a}^* \setminus \mathbf{a}, b_e(t) > \rho_e \right\} \right] \\ &+ |E|. \end{aligned}$$

The proof consists in upper-bounding each term on the right-hand side.

First Term Let $e \in \mathbf{a} \setminus \mathbf{a}^*$, and denote $A_e = \left\{ t \in [T] : \mathbf{a}(t) = \mathbf{a}, |\hat{\rho}_e(t) - \rho_e| \geq \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}} \right\}$.

$A_e \subseteq \bigcup_{s \in \mathbb{N}} \Lambda_k(s)$, where $\Lambda_k(s) \stackrel{\text{def}}{=} \{t \in A_e : T_{\mathbf{a}}(t) = s\}$. For any integer value s , $|\Lambda_k(s)| \leq 1$ as $T_{\mathbf{a}}(t)$ increases for each $t \in A_e$. Note that for each $s \in \mathbb{N}$ and $n \in \Lambda_k(s)$, $T_e(n) \geq T_{\mathbf{a}}(n) = s$. Then, by Lemma 4

$$\begin{aligned} \mathbb{E}[|A_e|] &\leq \mathbb{E} \left[\sum_{t=1}^T \mathbb{1}\{t \in A_e\} \right] \\ &= \mathbb{E} \left[\sum_{t=1}^T \mathbb{1} \left\{ t \in A_e, |\hat{\rho}_e(t) - \rho_e| \geq \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}} \right\} \right] \\ &\leq \frac{4K_{\mathbf{a}}^2}{\Delta_{\mathbf{a}}^2}. \end{aligned}$$

Hence, $\sum_{e \in \mathbf{a} \setminus \mathbf{a}^*} \mathbb{E} \left[\sum_{t=1}^T \mathbb{1} \left\{ \mathbf{a}(t) = \mathbf{a}, |\hat{\rho}_e(t) - \rho_e| \geq \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}} \right\} \right] = \sum_{e \in \mathbf{a} \setminus \mathbf{a}^*} \mathbb{E}[|A_e|] \leq \frac{4K_{\mathbf{a}}^3}{\Delta_{\mathbf{a}}^2}$.

Second Term Let $e \in \mathbf{a}^* \setminus \mathbf{a}$, and denote $B_e \stackrel{\text{def}}{=} \{t \in [T] : b_e(t) \leq \rho_e\}$.

By Theorem 10 of (Garivier & Cappé, 2011), $\mathbb{E}[|B_e|] = O(\log \log T)$, so $\sum_{e \in \mathbf{a}^* \setminus \mathbf{a}} \mathbb{E} \left[\sum_{t=1}^T \mathbb{1}\{b_e(t) \leq \rho_e\} \right] = \mathcal{O}(\bar{K}_{\mathbf{a}} \log \log T)$.

Third Term Let note $C \stackrel{\text{def}}{=} \left\{ t \in [T] \setminus |E| : \mathbf{a}(t) = \mathbf{a}, \forall e \in \mathbf{a} \setminus \mathbf{a}^*, |\hat{\rho}_e(t) - \rho_e| < \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}}, \forall e \in \mathbf{a}^* \setminus \mathbf{a}, b_e(t) > \rho_e \right\}$.

Let $t \in C$.

At each step of the initialization phase, the algorithm removes at least one element e of the set \tilde{E} of unseen elements. Therefore, the initialization lasts at most $|E|$ iterations. Hence, at iteration t , $\mathbf{a}(t) = \mathbf{a}$ is chosen as $\sum_{e \in \mathbf{a}} b_e(t) = \max_{\mathbf{a}' \in \mathcal{A}} \sum_{e \in \mathbf{a}'} b_e(t)$.

Then, by Pinsker's inequality and the fact that $t \leq T$, and $T_e(t) \geq T_{\mathbf{a}}(t)$ for any e in \mathbf{a} ,

$$\begin{aligned}
 0 &\leq \sum_{e \in \mathbf{a}} b_e(t) - \sum_{e \in \mathbf{a}^*} b_e(t) \\
 &= \sum_{e \in \mathbf{a} \setminus \mathbf{a}^*} b_e(t) - \sum_{e \in \mathbf{a}^* \setminus \mathbf{a}} b_e(t) \\
 &\leq \sum_{e \in \mathbf{a} \setminus \mathbf{a}^*} \hat{\rho}_e(t) + \sqrt{\frac{\log(t) + 3 \log(\log(t))}{2T_e(t)}} - \sum_{e \in \mathbf{a}^* \setminus \mathbf{a}} b_e(t) \\
 &< \sum_{e \in \mathbf{a} \setminus \mathbf{a}^*} \rho_e + \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}} + \sqrt{\frac{\log(T) + 3 \log(\log(T))}{2T_{\mathbf{a}}(t)}} - \sum_{e \in \mathbf{a}^* \setminus \mathbf{a}} \rho_e \\
 &\leq \sum_{e \in \mathbf{a}} \rho_e - \sum_{e \in \mathbf{a}^*} \rho_e + K_{\mathbf{a}} \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}} + K_{\mathbf{a}} \sqrt{\frac{\log(T) + 3 \log(\log(T))}{2T_{\mathbf{a}}(t)}} \\
 &= -\Delta_{\mathbf{a}} + \frac{2\Delta_{\mathbf{a}}}{2} + K_{\mathbf{a}} \sqrt{\frac{\log(T) + 3 \log(\log(T))}{2T_{\mathbf{a}}(t)}}. \\
 &= -\frac{\Delta_{\mathbf{a}}}{2} + K_{\mathbf{a}} \sqrt{\frac{\log(T) + 3 \log(\log(T))}{2T_{\mathbf{a}}(t)}}.
 \end{aligned}$$

Hence, $T_{\mathbf{a}}(t) < K_{\mathbf{a}}^2 \frac{2 \log(T) + 6 \log(\log(T))}{\Delta_{\mathbf{a}}^2}$. Therefore, $C \subseteq \left\{ t \in [T] \setminus [|E|] : \mathbf{a}(t) = \mathbf{a}, T_{\mathbf{a}}(t) < K_{\mathbf{a}}^2 \frac{2 \log(T) + 6 \log(\log(T))}{\Delta_{\mathbf{a}}^2} \right\}$, and

$$\begin{aligned}
 &\mathbb{E} \left[\sum_{t=|E|}^T \mathbb{1} \left\{ \mathbf{a}(t) = \mathbf{a}, \forall e \in \mathbf{a} \setminus \mathbf{a}^*, |\hat{\rho}_e(t) - \rho_e| < \frac{\Delta_{\mathbf{a}}}{2K_{\mathbf{a}}}, \forall e \in \mathbf{a}^* \setminus \mathbf{a}, b_e(t) > \rho_e \right\} \right] \\
 &= \mathbb{E}[|C|] \\
 &\leq \mathbb{E} \left[\left| \left\{ t \in [T] \setminus [|E|] : \mathbf{a}(t) = \mathbf{a}, T_{\mathbf{a}}(t) < K_{\mathbf{a}}^2 \frac{2 \log(T) + 6 \log(\log(T))}{\Delta_{\mathbf{a}}^2} \right\} \right| \right] \\
 &\leq K_{\mathbf{a}}^2 \frac{2 \log(T) + 6 \log(\log(T))}{\Delta_{\mathbf{a}}^2}.
 \end{aligned}$$

Regret upper-bound Overall,

$$\begin{aligned}
 \mathbb{E} \left[\sum_{t=1}^T \mathbb{1} \{ \mathbf{a}(t) = \mathbf{a} \} \right] &\leq \frac{4K_{\mathbf{a}}^3}{\Delta_{\mathbf{a}}^2} + \mathcal{O}(\bar{K}_{\mathbf{a}} \log \log T) + K_{\mathbf{a}}^2 \frac{2 \log(T) + 6 \log(\log(T))}{\Delta_{\mathbf{a}}^2} + |E| \\
 &= \frac{2K_{\mathbf{a}}^2}{\Delta_{\mathbf{a}}^2} \log(T) + \mathcal{O} \left(\left(\bar{K}_{\mathbf{a}} + \frac{K_{\mathbf{a}}^2}{\Delta_{\mathbf{a}}^2} \right) \log \log T \right)
 \end{aligned}$$

and

$$\begin{aligned}
 R(T) &= \sum_{\mathbf{a} \in \mathcal{A}: \mu_{\mathbf{a}} \neq \mu^*} \Delta_{\mathbf{a}} \mathbb{E} \left[\sum_{t=1}^T \mathbb{1} \{ \mathbf{a}(t) = \mathbf{a} \} \right] \\
 &\leq \sum_{\mathbf{a} \in \mathcal{A}: \mu_{\mathbf{a}} \neq \mu^*} \frac{2K_{\mathbf{a}}^2}{\Delta_{\mathbf{a}}} \log(T) + \mathcal{O} \left(\left(\bar{K}_{\mathbf{a}} \Delta_{\mathbf{a}} + \frac{K_{\mathbf{a}}^2}{\Delta_{\mathbf{a}}} \right) \log \log T \right) \\
 &= \mathcal{O} \left(\frac{|\mathcal{A}| K_{\max}^2}{\Delta_{\min}} \log T \right),
 \end{aligned}$$

which concludes the proof. □

E. Proof of Lemma 2 (Upper-bound on the Number of Iterations of GRAB for which

$$\tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}} \neq \mathbf{a}^*)$$

Proof of Lemma 2. Let $\tilde{\mathbf{a}} \in \mathcal{P}_K^L \setminus \{\mathbf{a}^*\}$ and prove that $\mathbb{E} \left[\sum_{t=1}^T \mathbb{1}\{\tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}\} \right] = \mathcal{O}(\log \log T)$.

The proof requires notations related to the neighborhood of $\tilde{\mathbf{a}}$. Let $\mathcal{N} \stackrel{def}{=} \bigcup_{\pi \in \mathcal{P}_K^K} \mathcal{N}_\pi(\tilde{\mathbf{a}})$ be the set of all the potential neighbors of $\tilde{\mathbf{a}}$. By definition of the neighborhoods,

$$\mathcal{N} = \{\tilde{\mathbf{a}} \circ (k, k') : k, k' \in [K]^2, k > k'\} \cup \{\tilde{\mathbf{a}}[k := i] : k \in [K], i \in [L] \setminus \tilde{\mathbf{a}}([K])\},$$

and its size is $N = K(2L - K - 1)/2$. As $\tilde{\mathbf{a}}$ is sub-optimal, and due to Assumption 1, for any appropriate ranking of positions $\pi \in \Pi_\rho(\tilde{\mathbf{a}})$, there exists a recommendation \mathbf{a}^+ with a strictly better expected reward than $\tilde{\mathbf{a}}$ in the neighborhood $\mathcal{N}_\pi(\tilde{\mathbf{a}})$. We denote

$$\mathcal{N}^+ \stackrel{def}{=} \bigcup_{\pi \in \Pi_\rho(\tilde{\mathbf{a}})} \left\{ \mathbf{a}^+ \in \mathcal{N}_\pi(\tilde{\mathbf{a}}) : \mu_{\mathbf{a}^+} = \max_{\mathbf{a} \in \mathcal{N}_\pi(\tilde{\mathbf{a}})} \mu_{\mathbf{a}} \right\}$$

the set of such recommendations. We also chose $\epsilon < \min\{1/(2N), 1/L\}$ and note

$$\delta \stackrel{def}{=} \min_{\pi \in \Pi_\rho(\tilde{\mathbf{a}})} \min_{\mathbf{a} \in \mathcal{N}_\pi(\tilde{\mathbf{a}}) \cup \{\tilde{\mathbf{a}}\} \setminus \mathcal{N}^+} \left(\max_{\mathbf{a}' \in \mathcal{N}_\pi(\tilde{\mathbf{a}})} \mu_{\mathbf{a}'} - \mu_{\mathbf{a}} \right).$$

To bound $\mathbb{E}[\mathbb{1}\{\tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}\}]$, we use the decomposition $\{t \in [T] : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}\} \subseteq \bigcup_{\mathbf{a}^+ \in \mathcal{N}^+} A_{\mathbf{a}^+} \cup B$ where for any permutation $\mathbf{a}^+ \in \mathcal{N}^+$,

$$A_{\mathbf{a}^+} = \{t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, T_{\mathbf{a}^+}(t) \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t)\}$$

and

$$B = \{t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \forall \mathbf{a}^+ \in \mathcal{N}^+, T_{\mathbf{a}^+}(t) < \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t)\}.$$

Hence,

$$\mathbb{E}[\mathbb{1}\{\tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}\}] \leq \sum_{\mathbf{a}^+ \in \mathcal{N}^+} \mathbb{E}[|A_{\mathbf{a}^+}|] + \mathbb{E}[|B|].$$

Bound on $\mathbb{E}[|A_{\mathbf{a}^+}|]$ Let \mathbf{a}^+ be a permutation in \mathcal{N}^+ and denote \mathcal{K}^+ the set of positions for which \mathbf{a}^+ and $\tilde{\mathbf{a}}$ disagree: $\mathcal{K}^+ = \{k \in [K] : a_k^+ \neq \tilde{a}_k\}$. The permutation \mathbf{a}^+ is in the neighborhood of $\tilde{\mathbf{a}}$, so either $\mathbf{a}^+ = \tilde{\mathbf{a}} \circ (k, k')$ or $\mathbf{a}^+ = \mathbf{a}[k := i]$, with k and k' in $[K]$, and i in $[L]$. Overall, $|\mathcal{K}^+| \leq 2$.

By the design of the algorithm and by definition of ϵ , we have that $\forall t \in A_{\mathbf{a}^+}, T_{\tilde{\mathbf{a}}}(t) \geq \tilde{T}_{\tilde{\mathbf{a}}}(t)/L > \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t)$. Moreover, at the considered iterations $\tilde{\mathbf{a}}$ is the leader, so

$$\begin{aligned} A_{\mathbf{a}^+} &\subseteq \left\{ t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{T}_{\tilde{\mathbf{a}}}(t) < \frac{1}{\epsilon} \right\} \cup \left\{ t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \min\{T_{\tilde{\mathbf{a}}}(t), T_{\mathbf{a}^+}(t)\} \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) \geq 1, \sum_{\ell} \hat{\rho}_{\tilde{\mathbf{a}}_\ell, \ell}(t) \geq \sum_{\ell} \hat{\rho}_{\mathbf{a}^+_\ell, \ell}(t) \right\} \\ &\subseteq \left\{ t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{T}_{\tilde{\mathbf{a}}}(t) < \frac{1}{\epsilon} \right\} \cup \left\{ t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \min\{T_{\tilde{\mathbf{a}}}(t), T_{\mathbf{a}^+}(t)\} \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t), \sum_{k \in \mathcal{K}^+} \hat{\rho}_{\tilde{\mathbf{a}}_k, k}(t) \geq \sum_{k \in \mathcal{K}^+} \hat{\rho}_{\mathbf{a}^+_k, k}(t) \right\} \\ &\subseteq \left\{ t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{T}_{\tilde{\mathbf{a}}}(t) < \frac{1}{\epsilon} \right\} \\ &\quad \cup \left\{ t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \min\{T_{\tilde{\mathbf{a}}}(t), T_{\mathbf{a}^+}(t)\} \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t), \exists k \in \mathcal{K}^+, |\hat{\rho}_{\tilde{\mathbf{a}}_k, k}(t) - \rho_{\tilde{\mathbf{a}}_k, k}| \geq \frac{\delta}{2|\mathcal{K}^+|} \text{ or } |\hat{\rho}_{\mathbf{a}^+_k, k}(t) - \rho_{\mathbf{a}^+_k, k}| \geq \frac{\delta}{2|\mathcal{K}^+|} \right\} \\ &\subseteq \left\{ t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{T}_{\tilde{\mathbf{a}}}(t) < \frac{1}{\epsilon} \right\} \cup \bigcup_{k \in \mathcal{K}^+} \bigcup_{i \in \{\tilde{\mathbf{a}}_k, \mathbf{a}^+_k\}} \Lambda_{i, k}, \end{aligned}$$

with $\Lambda_{i,k} \stackrel{def}{=} \left\{ t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \min\{T_{\tilde{\mathbf{a}}}(t), T_{\mathbf{a}^+}(t)\} \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t), |\hat{\rho}_{i,k}(t) - \rho_{i,k}| \geq \frac{\delta}{2|\mathcal{K}^+|} \right\}$.

Fix k in \mathcal{K}^+ and i in $\{\tilde{a}_k, a_k^+\}$. $\Lambda_{i,k} \subseteq \bigcup_{s \in \mathbb{N}} \Lambda_{i,k}(s)$, with $\Lambda_{i,k}(s) \stackrel{def}{=} \{t \in \Lambda_{i,k} : \tilde{T}_{\tilde{\mathbf{a}}}(t) = s\}$. $|\Lambda_{i,k}(s)| \leq 1$ as $\tilde{T}_{\tilde{\mathbf{a}}}(t)$ increases for each $t \in \Lambda_{i,k}$. Note that for each $s \in \mathbb{N}$ and $n \in \Lambda_{i,k}(s)$, $T_{i,k}(n) \geq \min\{T_{\tilde{\mathbf{a}}}(n), T_{\mathbf{a}^+}(n)\} \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(n) = \epsilon s$. Then, by Lemma 4

$$\begin{aligned} \mathbb{E}[|\Lambda_{i,k}|] &= \mathbb{E}\left[\sum_{t=1}^T \mathbb{1}\{t \in \Lambda_{i,k}\}\right] \\ &= \mathbb{E}\left[\sum_{t=1}^T \mathbb{1}\left\{t \in \Lambda_{i,k}, |\hat{\rho}_{i,k}(t) - \rho_{i,k}| > \frac{\delta}{2|\mathcal{K}^+|}\right\}\right] \\ &\leq \frac{4|\mathcal{K}^+|^2}{\epsilon \delta^2} \end{aligned}$$

Hence, $\mathbb{E}[|A_{\mathbf{a}^+}|] \leq \frac{1}{\epsilon} + \sum_{k \in \mathcal{K}^+} \sum_{i \in \{\tilde{a}_k, a_k^+\}} \mathbb{E}[|\Lambda_{i,k}|] \leq \frac{1}{\epsilon} + \frac{8|\mathcal{K}^+|^3}{\epsilon \delta^2}$.

Bound on $\mathbb{E}[|B|]$ We first split B in two parts: $B = B^{t_0} \cup B_{t_0}^T$, where $B^{t_0} \stackrel{def}{=} \{t \in B : \tilde{T}_{\tilde{\mathbf{a}}}(t) \leq t_0\}$, $B_{t_0}^T \stackrel{def}{=} \{t \in B : \tilde{T}_{\tilde{\mathbf{a}}}(t) > t_0\}$, and t_0 is chosen as small as possible to satisfy three constraints required in the rest of the proof.

Namely, $t_0 = \max\left\{\frac{1}{\epsilon}, (1+N)(1 - \frac{1}{L} - \epsilon N)^{-1}, \inf\left\{t : 2\sqrt{\frac{\log(t+1)+3\log(\log(t+1))}{2\epsilon t}} < \frac{\delta}{8}\right\}\right\}$. Note that t_0 only depends on K, L and δ , and that $(1 - \frac{1}{L} - \epsilon N) > 0$ (assuming $L \geq 2$) as $\epsilon < 1/(2N)$.

We also define

- $D \stackrel{def}{=} \bigcup_{(\mathbf{a},k) \in (\mathcal{N} \cup \{\tilde{\mathbf{a}}\}) \times [\mathcal{K}] \setminus \mathcal{N}^+} D_{\mathbf{a},k}$, where $D_{\mathbf{a},k} \stackrel{def}{=} \{t \in [T] : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \mathbf{a}(t) = \mathbf{a}, |\hat{\rho}_{\mathbf{a},k}(t) - \rho_{\mathbf{a},k}| \geq \frac{\delta}{8}\}$,
- $E \stackrel{def}{=} \bigcup_{(\mathbf{a}^+,k) \in \mathcal{N}^+ \times [\mathcal{K}]} E_{\mathbf{a}^+,k}$, where $E_{\mathbf{a}^+,k} \stackrel{def}{=} \{t \in [T] : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, b_{\mathbf{a}^+,k}(t) \leq \rho_{\mathbf{a}^+,k}\}$,
- and $F \stackrel{def}{=} \{t \in [T] : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{\pi}(t) \notin \Pi_{\rho}(\tilde{\mathbf{a}})\}$.

Let $t \in B_{t_0}^T$. By construction, GRAB forces itself to select $\left\lceil \frac{\tilde{T}_{\tilde{\mathbf{a}}}(t)}{L} \right\rceil$ times the leader $\tilde{\mathbf{a}}$ between iterations 1 and $t-1$. So,

$$\tilde{T}_{\tilde{\mathbf{a}}}(t) = \left\lceil \frac{\tilde{T}_{\tilde{\mathbf{a}}}(t)}{L} \right\rceil + \sum_{\mathbf{a} \in \mathcal{N} \cup \{\tilde{\mathbf{a}}\}} T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(t)$$

where $T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(t) = \sum_{s=1}^{t-1} \mathbb{1}\{\tilde{\mathbf{a}}(s) = \tilde{\mathbf{a}}, \mathbf{a}(s) = \mathbf{a}, \tilde{T}_{\tilde{\mathbf{a}}}(s)/L \notin \mathbb{N}\}$ is the number of times arm $\mathbf{a} \in \mathcal{N} \cup \{\tilde{\mathbf{a}}\}$ has been played **normally** (i.e not forced) while $\tilde{\mathbf{a}}$ was leader, up to time $t-1$. Let prove by contradiction that there is at least one recommendation \mathbf{a} that has been selected **normally** more than $\epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) + 1$ times, namely $T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(t) \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) + 1$.

Assume that for each recommendation \mathbf{a} in $\mathcal{N} \cup \{\tilde{\mathbf{a}}\}$, $T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(t) < \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) + 1$. Then

$$\begin{aligned} \tilde{T}_{\tilde{\mathbf{a}}}(t) &= \left\lceil \frac{\tilde{T}_{\tilde{\mathbf{a}}}(t)}{L} \right\rceil + \sum_{\mathbf{a} \in \mathcal{N} \cup \{\tilde{\mathbf{a}}\}} T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(t) \\ &< 1 + \frac{\tilde{T}_{\tilde{\mathbf{a}}}(t)}{L} + N(\epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) + 1). \end{aligned}$$

Therefore $\tilde{T}_{\tilde{\mathbf{a}}}(t)(1 - \frac{1}{L} - N\epsilon) < 1 + N$, which contradicts $t \in B_{t_0}^T$.

So, there exists a recommendation \mathbf{a} such that $T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(t) \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) + 1$. Let denote s' the first iteration such that $T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(s') \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) + 1$. At this iteration, $T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(s') = T_{\mathbf{a}}^{\tilde{\mathbf{a}}}(s' - 1) + 1$, meaning that $\tilde{\mathbf{a}}(s' - 1) = \tilde{\mathbf{a}}, \mathbf{a}(s' - 1) = \mathbf{a}, \tilde{T}_{\tilde{\mathbf{a}}}(s' - 1)/L \notin \mathbb{N}$, and

$T_{\tilde{\mathbf{a}}}^{\tilde{\mathbf{a}}}(s' - 1) \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t)$. Therefore, the set $\{s \in [t] : \tilde{\mathbf{a}}(s) = \tilde{\mathbf{a}}, T_{\tilde{\mathbf{a}}(s)}^{\tilde{\mathbf{a}}}(s) \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t), \tilde{T}_{\tilde{\mathbf{a}}}(s)/L \notin \mathbb{N}\}$ is non-empty. We define $\psi(t)$ as the minimum on this set

$$\psi(t) \stackrel{def}{=} \min \left\{ s \in [t] : \tilde{\mathbf{a}}(s) = \tilde{\mathbf{a}}, T_{\tilde{\mathbf{a}}(s)}^{\tilde{\mathbf{a}}}(s) \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t), \tilde{T}_{\tilde{\mathbf{a}}}(s)/L \notin \mathbb{N} \right\}.$$

We note \mathbf{a} the recommendation $\mathbf{a}(\psi(t))$ at iteration $\psi(t)$. We have $\mathbf{a} \notin \mathcal{N}^+$ since for any recommendation $\mathbf{a}^+ \in \mathcal{N}^+$, $T_{\mathbf{a}^+}^{\tilde{\mathbf{a}}}(\psi(t)) \leq T_{\mathbf{a}^+}^{\tilde{\mathbf{a}}}(t) \leq T_{\mathbf{a}^+}(t) < \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t)$. Let \mathbf{a}^+ be one of the best recommendations in $\mathcal{N}_{\tilde{\pi}(\psi(t))}(\tilde{\mathbf{a}}) \cup \{\tilde{\mathbf{a}}\}$, meaning $\mu_{\mathbf{a}^+} = \max_{\mathbf{a}' \in \mathcal{N}_{\tilde{\pi}(\psi(t))}(\tilde{\mathbf{a}}) \cup \{\tilde{\mathbf{a}}\}} \mu_{\mathbf{a}'}$, and let \mathcal{K} denote the set of positions for which \mathbf{a} and \mathbf{a}^+ disagree. As both recommendations are in $\mathcal{N}_{\tilde{\pi}(\psi(t))}(\tilde{\mathbf{a}}) \cup \{\tilde{\mathbf{a}}\}$, $|\mathcal{K}| \leq 4$.

Let prove by contradiction that $\psi(t) \in D \cup E \cup F$. Assume that $\psi(t) \notin D \cup E \cup F$.

Since $\psi(t) \notin F$, $\tilde{\pi}(\psi(t))$ belongs to $\Pi_{\rho}(\tilde{\mathbf{a}})$ and hence \mathbf{a}^+ is in \mathcal{N}^+ and $\sum_k \rho_{\mathbf{a}_k^+, k} - \sum_k \rho_{\mathbf{a}_k, k} = \mu_{\mathbf{a}^+} - \mu_{\mathbf{a}} \geq \delta$.

Moreover, since $\psi(t) \notin D \cup E$, for each position $k \in [K]$, $|\hat{\rho}_{\mathbf{a}_k, k}(\psi(t)) - \rho_{\mathbf{a}_k, k}| < \frac{\delta}{8}$, and $b_{\mathbf{a}_k^+, k}(\psi(t)) > \rho_{\mathbf{a}_k^+, k}$.

Finally, $T_{\mathbf{a}}(\psi(t)) \geq T_{\tilde{\mathbf{a}}}^{\tilde{\mathbf{a}}}(\psi(t)) \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) \geq 1$, and therefore $b_{\mathbf{a}_k, k}(\psi(t))$ and $\hat{\rho}_{\mathbf{a}_k, k}(\psi(t))$ are properly defined for any position $k \in [K]$.

Then, by Pinsker's inequality and the fact that $\psi(t) \leq t$, $\tilde{T}_{\tilde{\mathbf{a}}}(s)$ is non-decreasing in s , and $T_{\mathbf{a}}(\psi(t)) \geq \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t)$,

$$\begin{aligned} \sum_k b_{\mathbf{a}_k, k}(\psi(t)) - \sum_k b_{\mathbf{a}_k^+, k}(\psi(t)) &= \sum_{k \in \mathcal{K}} b_{\mathbf{a}_k, k}(\psi(t)) - b_{\mathbf{a}_k^+, k}(\psi(t)) \\ &\leq \sum_{k \in \mathcal{K}} \hat{\rho}_{\mathbf{a}_k, k}(\psi(t)) + \sqrt{\frac{\log(\tilde{T}_{\tilde{\mathbf{a}}}(\psi(t)) + 1) + 3 \log(\log(\tilde{T}_{\tilde{\mathbf{a}}}(\psi(t)) + 1))}{2T_{\mathbf{a}}(\psi(t))}} - b_{\mathbf{a}_k^+, k}(\psi(t)) \\ &< \sum_{k \in \mathcal{K}} \rho_{\mathbf{a}_k, k} + \frac{\delta}{8} + \sqrt{\frac{\log(\tilde{T}_{\tilde{\mathbf{a}}}(t) + 1) + 3 \log(\log(\tilde{T}_{\tilde{\mathbf{a}}}(t) + 1))}{2\epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t)}} - \rho_{\mathbf{a}_k^+, k} \\ &\leq \sum_{k \in \mathcal{K}} \rho_{\mathbf{a}_k, k} + \frac{\delta}{8} + \frac{\delta}{8} - \rho_{\mathbf{a}_k^+, k} \\ &\leq \sum_k \rho_{\mathbf{a}_k, k} - \sum_k \rho_{\mathbf{a}_k^+, k} + |\mathcal{K}| \cdot 2\frac{\delta}{8} \\ &\leq -\delta + 8\frac{\delta}{8} \\ &= 0, \end{aligned}$$

which contradicts the fact that \mathbf{a} is played at iteration $\psi(t)$. So $\psi(t) \in D \cup E \cup F$.

Overall, for any $t \in B_{t_0}^T$, $\psi(t) \in D \cup E \cup F$. So, $B_{t_0}^T \subseteq \bigcup_{n \in D \cup E \cup F} B_{t_0}^T \cap \{t \in [T] : \psi(t) = n\}$. Let n be in $D \cup E \cup F$. For any t in $B_{t_0}^T \cap \{t \in [T] : \psi(t) = n\}$, $T_{\tilde{\mathbf{a}}(n)}^{\tilde{\mathbf{a}}}(n) = \lceil \epsilon \tilde{T}_{\tilde{\mathbf{a}}}(t) \rceil$ and $\tilde{T}_{\tilde{\mathbf{a}}}(t+1) = \tilde{T}_{\tilde{\mathbf{a}}}(t) + 1$. So $|B_{t_0}^T \cap \{t \in [T] : \psi(t) = n\}| < 1/\epsilon + 1$. Overall,

$$\mathbb{E}[|B|] \leq t_0 + \mathbb{E}[|B_{t_0}^T|] \leq t_0 + (1/\epsilon + 1)(\mathbb{E}[|D|] + \mathbb{E}[|E|] + \mathbb{E}[|F|]).$$

It remains to upper-bound $\mathbb{E}[|D|]$, $\mathbb{E}[|E|]$, and $\mathbb{E}[|F|]$ to conclude the proof.

Bound on $\mathbb{E}[|D|]$ The upper-bound on $\mathbb{E}[|D|]$ is obtained with the same strategy as the last step in the proof of the upper-bound on $\mathbb{E}[|A_{\mathbf{a}^+}|]$. Let \mathbf{a} be a recommendation in $\mathcal{N} \cup \{\tilde{\mathbf{a}}\} \setminus \mathcal{N}^+$, and $k \in [K]$ be a position. $D_{\mathbf{a}, k} \subseteq \bigcup_{s \in \mathbb{N}} \Lambda_{\mathbf{a}, k}(s)$, where $\Lambda_{\mathbf{a}, k}(s) \stackrel{def}{=} \{t \in D_{\mathbf{a}, k} : T_{\mathbf{a}}(t) = s\}$. $|\Lambda_{\mathbf{a}, k}(s)| \leq 1$ as $T_{\mathbf{a}}(t)$ increases for each $t \in D_{\mathbf{a}, k}$. Note that for each $s \in \mathbb{N}$ and $n \in \Lambda_{\mathbf{a}, k}(s)$, $T_{\mathbf{a}_k, k}(n) \geq T_{\mathbf{a}}(n) = s$. Then, by Lemma 4

$$\begin{aligned}
 \mathbb{E}[|D_{\mathbf{a},k}|] &\leq \mathbb{E}\left[\sum_{t=1}^T \mathbb{1}\{t \in D_{\mathbf{a},k}\}\right] \\
 &= \mathbb{E}\left[\sum_{t=1}^T \mathbb{1}\left\{t \in D_{\mathbf{a},k}, |\hat{\rho}_{a_k,k}(t) - \rho_{a_k,k}| \geq \frac{\delta}{8}\right\}\right] \\
 &\leq \frac{64}{\delta^2}
 \end{aligned}$$

Hence, $\mathbb{E}[|D|] \leq \sum_{(\mathbf{a},k) \in (\mathcal{N} \cup \{\tilde{\mathbf{a}}\} \setminus \mathcal{N}^+) \times [K]} \mathbb{E}[|D_{\mathbf{a},k}|] \leq \frac{64(N+1)K}{\delta^2}$.

Bound on $\mathbb{E}[|E|]$ By Theorem 10 of (Garivier & Cappé, 2011), $\mathbb{E}[|E_{\mathbf{a}^+,k}|] = O(\log(\log(T)))$, so $\mathbb{E}[|E|] \leq \sum_{(\mathbf{a}^+,k) \in \mathcal{N}^+ \times [K]} \mathbb{E}[|E_{\mathbf{a}^+,k}|] = O(|\mathcal{N}^+|K \log(\log(T)))$.

Bound on $\mathbb{E}[|F|]$ By Lemma 3, $\mathbb{E}[|F|] = \mathbb{E}\left[\sum_{t=1}^T \mathbb{1}\{\tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{\pi}(t) \notin \Pi_{\rho}(\tilde{\mathbf{a}})\}\right] = \mathcal{O}(1)$.

Overall $\mathbb{E}[\mathbb{1}\{\tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}\}] \leq \frac{|\mathcal{K}^+|}{\epsilon} + \frac{8|\mathcal{K}^+|^3|\mathcal{N}^+|}{\epsilon\delta^2} + t_0 + \left(\frac{1}{\epsilon} + 1\right) \frac{64(N+1)K}{\delta^2} + \mathcal{O}\left(\frac{|\mathcal{N}^+|K}{\epsilon} \log \log T\right) + \mathcal{O}(1) = \mathcal{O}\left(\frac{|\mathcal{N}^+|K}{\epsilon} \log \log T\right)$, which concludes the proof. \square

F. Proof of Lemma 3 (Upper-bound on the Number of Iterations of GRAB for which $\tilde{\pi}(t) \notin \Pi_{\rho}(\tilde{\mathbf{a}})$)

Proof of Theorem 3. Let $\tilde{\mathbf{a}}$ be a K -permutation of L items. If $\Pi_{\rho}(\tilde{\mathbf{a}})$ contains all the permutations of K elements, the set $\{t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{\pi}(t) \notin \Pi_{\rho}(\tilde{\mathbf{a}})\}$ is empty.

Otherwise, let denote δ the smallest non-zero gap between the probability of click at position k and the probability of click at position $k' \neq k$: $\delta \stackrel{def}{=} \min\{\rho_{\tilde{a}_k,k} - \rho_{\tilde{a}_{k'},k'} : (k, k') \in [K]^2, \rho_{\tilde{a}_k,k} - \rho_{\tilde{a}_{k'},k'} > 0\}$. The gap δ is the minimum on a finite set, so $\delta > 0$.

By definition of $\tilde{\pi}(t)$, $\hat{\rho}_{\tilde{a}_{\tilde{\pi}_1(t)}, \tilde{\pi}_1(t)}(t) \geq \hat{\rho}_{\tilde{a}_{\tilde{\pi}_2(t)}, \tilde{\pi}_2(t)}(t) \geq \dots \geq \hat{\rho}_{\tilde{a}_{\tilde{\pi}_K(t)}, \tilde{\pi}_K(t)}(t)$, so,

$$\begin{aligned}
 \{t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{\pi}(t) \notin \Pi_{\rho}(\tilde{\mathbf{a}})\} &= \bigcup_{\tilde{\pi} \in \mathcal{P}_K^K} \bigcup_{k \in [K-1]} \left\{t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{\pi}(t) = \tilde{\pi}, \rho_{\tilde{a}_{\tilde{\pi}_k}, \tilde{\pi}_k} < \rho_{\tilde{a}_{\tilde{\pi}_{k+1}}, \tilde{\pi}_{k+1}}\right\} \\
 &\subseteq \bigcup_{\tilde{\pi} \in \mathcal{P}_K^K} \bigcup_{k \in [K-1]} \left\{t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{\pi}(t) = \tilde{\pi}, \text{ or } |\hat{\rho}_{\tilde{a}_{\tilde{\pi}_k}, \tilde{\pi}_k}(t) - \rho_{\tilde{a}_{\tilde{\pi}_k}, \tilde{\pi}_k}| > \frac{\delta}{2}, \text{ or } |\hat{\rho}_{\tilde{a}_{\tilde{\pi}_{k+1}}, \tilde{\pi}_{k+1}}(t) - \rho_{\tilde{a}_{\tilde{\pi}_{k+1}}, \tilde{\pi}_{k+1}}| > \frac{\delta}{2}\right\} \\
 &= \bigcup_{\tilde{\pi} \in \mathcal{P}_K^K} \bigcup_{k \in [K]} \Lambda_{\tilde{\pi},k},
 \end{aligned}$$

with $\Lambda_{\tilde{\pi},k} \stackrel{def}{=} \left\{t : \tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{\pi}(t) = \tilde{\pi}, |\hat{\rho}_{\tilde{a}_{\tilde{\pi}_k}, \tilde{\pi}_k}(t) - \rho_{\tilde{a}_{\tilde{\pi}_k}, \tilde{\pi}_k}| > \frac{\delta}{2}\right\}$, for any ranking of positions $\tilde{\pi} \in \mathcal{P}_K^K$ and any rank $k \in [K]$.

Let $\tilde{\pi} \in \mathcal{P}_K^K$ be a ranking of positions, and $k \in [K]$ be a rank. $\Lambda_{\tilde{\pi},k} \subseteq \bigcup_{s \in \mathbb{N}} \Lambda_{\tilde{\pi},k}(s)$, with $\Lambda_{\tilde{\pi},k}(s) \stackrel{def}{=} \{t \in \Lambda_{\tilde{\pi},k} : \tilde{T}_{\tilde{\mathbf{a}}}(t) = s\}$. $|\Lambda_{\tilde{\pi},k}(s)| \leq 1$ as $\tilde{T}_{\tilde{\mathbf{a}}}(t)$ increases for each $t \in \Lambda_{\tilde{\pi},k}$. Note that for each $s \in \mathbb{N}$ and $n \in \Lambda_{\tilde{\pi},k}(s)$, $T_{\tilde{a}_{\tilde{\pi}_k}, \tilde{\pi}_k}(n) \geq$

Algorithm 2 KL-ComUCB1 (generic version)

Input: set of elements E , set of arms \mathcal{A}
 $t \leftarrow 1$
while $\{e \in E : T_e(t) = 0\} \neq \emptyset$ **do**
 $\tilde{E} \leftarrow \{e \in E : T_e(t) = 0\}$
 $\tilde{\mathcal{A}} \leftarrow \{\mathbf{a} \in \mathcal{A} : \mathbf{a} \cap \tilde{E} \neq \emptyset\}$

 recommend $\mathbf{a}(t) = \operatorname{argmax}_{\mathbf{a} \in \tilde{\mathcal{A}}} \sum_{e \in \mathbf{a}} b_e(t)$

 observe the weights $[w_e(t) : e \in \mathbf{a}]$
 $t \leftarrow t + 1$
end while
 $t_0 \leftarrow t$
for $t = t_0, t_0 + 1, \dots$ **do**

 recommend $\mathbf{a}(t) = \operatorname{argmax}_{\mathbf{a} \in \mathcal{A}} \sum_{e \in \mathbf{a}} b_e(t)$

 observe the weights $[w_e(t) : e \in \mathbf{a}]$
end for
 $T_{\tilde{\mathbf{a}}}(n) \geq \tilde{T}_{\tilde{\mathbf{a}}}(n)/L = s/L$. Then, by Lemma 4

$$\begin{aligned} \mathbb{E} [|\Lambda_{\tilde{\pi}, k}|] &= \mathbb{E} \left[\sum_{t=1}^T \mathbb{1}\{t \in \Lambda_{\tilde{\pi}, k}\} \right] \\ &= \mathbb{E} \left[\sum_{t=1}^T \mathbb{1} \left\{ t \in \Lambda_{\tilde{\pi}, k}, |\hat{\rho}_{\tilde{\mathbf{a}}_{\tilde{\pi}, k}, \tilde{\pi}_k}(t) - \rho_{\tilde{\mathbf{a}}_{\tilde{\pi}, k}, \tilde{\pi}_k}| > \frac{\delta}{2} \right\} \right] \\ &\leq \frac{4L}{\delta^2} \end{aligned}$$

Hence,

$$\begin{aligned} \mathbb{E} \left[\sum_{t=1}^T \mathbb{1}\{\tilde{\mathbf{a}}(t) = \tilde{\mathbf{a}}, \tilde{\pi}(t) \notin \Pi_{\rho}(\tilde{\mathbf{a}})\} \right] &\leq \sum_{\tilde{\pi} \in \mathcal{P}_K^K} \sum_{k \in [K]} \mathbb{E} [|\Lambda_{\tilde{\pi}, k}|] \\ &\leq \frac{4LKK!}{\delta^2} \\ &= \mathcal{O}(LKK!), \end{aligned}$$

 which concludes the proof. □

G. KL-CombUCB and its Application to PBM Setting

In this section we first define the generic combinatorial semi-bandit algorithm KL-CombUCB and we compare two upper-bounds on its regret. Then, we present the application of KL-CombUCB to PBM setting and discuss its relation to GRAB.

G.1. KL-CombUCB for Generic Setting

CombUCB1 (Kveton et al., 2015) is a bandit algorithm handling the following combinatorial setting. Let E be a set of elements and $\mathcal{A} \subseteq \{0, 1\}^E$ be a set of arms, where each arm \mathbf{a} is a subset of E . Following the terminology used in (Kveton et al., 2015), E is the *ground set* and \mathcal{A} the *feasible set*. At each iteration, the bandit algorithm chooses a subset of elements $\mathbf{a} \in \mathcal{A}$ and receives the reward $\sum_{e \in \mathbf{a}} w_e$, where \mathbf{w} is an independent draw of a distribution ν on $[0, 1]^E$. Given these assumptions, CombUCB1 chooses an arm $\mathbf{a}(t)$ at each iteration, aiming at minimizing the total regret defined as usual.

Algorithm 3 KL-ComUCB1 (applied to PBM)

Input: number of items L , number of positions K

for $t = 1, 2, \dots, L$ **do**

recommend $\mathbf{a}(t) = (((t-1)\%L) + 1, (t\%L) + 1, \dots, ((t+K-2)\%L) + 1)$

observe the clicks-vector $\mathbf{c}(t)$

end for

for $t = L+1, L+2, \dots$ **do**

recommend $\mathbf{a}(t) = \operatorname{argmax}_{\mathbf{a} \in \mathcal{P}_K^L} \sum_{k=1}^K b_{a_k, k}(t)$

observe the clicks-vector $\mathbf{c}(t)$

end for

We denote $\rho_e \stackrel{def}{=} \mathbb{E}_{\mathbf{w} \sim \nu} [w_e]$ the expected reward associated to element e , $\mu_{\mathbf{a}} \stackrel{def}{=} \mathbb{E}_{\mathbf{w} \sim \nu} [\sum_{e \in \mathbf{a}} w_e] = \sum_{e \in \mathbf{a}} \rho_e$ the expected reward when choosing the arm $\mathbf{a} \in \mathcal{A}$, and $\mu^* \stackrel{def}{=} \max_{\mathbf{a} \in \mathcal{A}} \mu_{\mathbf{a}}$ the best expected reward. We also denote $\Delta_{\mathbf{a}} \stackrel{def}{=} \mu^* - \mu_{\mathbf{a}}$ the gap between the best expected reward and the reward of an arm \mathbf{a} , and $\Delta_{min} \stackrel{def}{=} \min_{\mathbf{a} \in \mathcal{A}: \Delta_{\mathbf{a}} > 0} \Delta_{\mathbf{a}}$ the smallest gap of a suboptimal arm. Finally, $K \stackrel{def}{=} \max_{\mathbf{a} \in \mathcal{A}} |\mathbf{a}|$ denotes the maximum size of an arm (meaning the maximum number of chosen elements), $K_{\mathbf{a}} \stackrel{def}{=} \min_{\mathbf{a}^* \in \mathcal{A}: \mu_{\mathbf{a}^*} = \mu^*} |\mathbf{a} \setminus \mathbf{a}^*|$ is the smallest number of elements to remove from \mathbf{a} to get an optimal arm, and $K_{max} \stackrel{def}{=} \max_{\mathbf{a} \in \mathcal{A}: \mu_{\mathbf{a}} \neq \mu^*} K_{\mathbf{a}}$ is its larger value.

In our paper, we use the Kullback-Leibler variation of CombUCB1 which chooses the arm based on the index $b_e(t)$ (defined hereafter) instead of the usual confidence upper-bound derived from the Hoeffding's inequality. The corresponding algorithm (KL-CombUCB) also assumes that the weight-vector $\mathbf{w}(t)$ is in $\{0, 1\}^E$. KL-CombUCB is depicted by Algorithm 2 which uses the following notations. At each iteration t , we denote

$$\hat{\rho}_e(t) \stackrel{def}{=} \frac{1}{T_e(t)} \sum_{s=1}^{t-1} \mathbb{1}\{e \in \mathbf{a}(s)\} w_e(s)$$

the average number of clicks obtained by the element e , where

$$T_e(t) \stackrel{def}{=} \sum_{s=1}^{t-1} \mathbb{1}\{e \in \mathbf{a}(s)\}$$

is the number of times element e has been selected; $\hat{\rho}_e(t) \stackrel{def}{=} 0$ when $T_e(t) = 0$. The statistics $\hat{\rho}_e(t)$ are paired with their respective *indices*

$$b_e(t) \stackrel{def}{=} f(\hat{\rho}_e(t), T_e(t), t),$$

where $f(\hat{\rho}, s, t)$ stands for

$$\sup\{p \in [\hat{\rho}, 1] : s \times \text{kl}(\hat{\rho}, p) \leq \log(t) + 3 \log(\log(t))\},$$

with

$$\text{kl}(p, q) \stackrel{def}{=} p \log\left(\frac{p}{q}\right) + (1-p) \log\left(\frac{1-p}{1-q}\right)$$

the *Kullback-Leibler divergence* from a Bernoulli distribution of mean p to a Bernoulli distribution of mean q ; $f(\hat{\rho}, s, t) \stackrel{def}{=} 1$ when $\hat{\rho} = 1$, $s = 0$, or $t = 0$.

Kveton et al. prove that the regret of CombUCB1 is upper-bounded by $\mathcal{O}(|E|K/\Delta_{min} \log T)$, and a similar proof would lead to the same upper-bound for KL-CombUCB. In our paper we prove in Theorem 2 a completely different regret upper-bound for KL-CombUCB: $\mathcal{O}(|\mathcal{A}|K_{max}^2/\Delta_{min} \log T)$. For most combinatorial bandit settings, this new bound is useless since $|\mathcal{A}| \gg |E|$, and $K_{max} \approx K$. However, the analysis of GRAB involves an application of KL-CombUCB to a setting where the new bound is smaller than the standard one as $|\mathcal{A}| = |E| - 1$ and $K_{max} = 2$.

Algorithm 4 S-GRAB: Static Graph for unimodal RAnking Bandit

Input: number of items L , number of positions K

$$\gamma \leftarrow K(2L - K - 1)/2$$

for $t = 1, 2, \dots$ **do**

$$\tilde{\mathbf{a}}(t) \leftarrow \operatorname{argmax}_{\mathbf{a} \in \mathcal{P}_K^L} \sum_{k=1}^K \hat{\rho}_{a_k, k}(t)$$

$$\text{recommend } \mathbf{a}(t) = \begin{cases} \tilde{\mathbf{a}}(t) & , \text{ if } \frac{\tilde{T}_{\tilde{\mathbf{a}}(t)}(t)}{\gamma+1} \in \mathbb{N}, \\ \operatorname{argmax}_{\mathbf{a} \in \{\tilde{\mathbf{a}}(t)\} \cup \mathcal{N}_G(\tilde{\mathbf{a}}(t))} \sum_{k=1}^K b_{a_k, k}(t) & , \text{ otherwise} \end{cases}$$

where $\mathcal{N}_G(\mathbf{a}) = \{\mathbf{a} \circ (k, k') : k, k' \in [K]^2, k > k'\} \cup \{\mathbf{a}[k := i] : k \in [K], i \in [L] \setminus \mathbf{a}([K])\}$
 observe the clicks vector $\mathbf{c}(t)$

end for

G.2. KL-CombUCB Applied to PBM Setting

In the experiments (Section 6), we apply KL-CombUCB to PBM bandit setting by choosing the *ground set* $E = [L] \times [K]$, the *feasible set* $\Theta = \{(a_k, k) : k \in [K]\} : \mathbf{a} \in \mathcal{P}_K^L$, and the *expected weights* $\rho_{(i,k)} = \theta_i \kappa_k$ for any “element” $(i, k) \in E$. Note that the observed weights of the generic setting correspond to the clicks-vector in the PBM setting.

The corresponding algorithm, depicted by Algorithm 3, recommends at each iteration t the best permutation given the indices $b_{i,k}(t)$ defined for GRAB. This optimization problem is a *linear sum assignment problem* which is solvable in $\mathcal{O}(K^2(L + \log K))$ time (Ramshaw & Tarjan, 2012). Note the close relationship with GRAB:

- both algorithms solve a linear sum assignment problem, they only differ from the metric to optimize: $\sum_{k=1}^K \hat{\rho}_{a_k, k}(t)$ for GRAB vs. $\sum_{k=1}^K b_{a_k, k}(t)$ for KL-CombUCB;
- both algorithms recommend the best permutation \mathbf{a} regarding $\sum_{k=1}^K b_{a_k, k}(t)$, they only differ from the considered set of permutations: $\{\tilde{\mathbf{a}}(t)\} \cup \mathcal{N}_{\tilde{\pi}(t)}(\tilde{\mathbf{a}}(t))$ for GRAB vs. \mathcal{P}_K^L for KL-CombUCB.

By considering a larger set of permutations, KL-ComUCB1 suffers a $\mathcal{O}(LK^2/\Delta_{\min} \log T)$ regret (by applying (Kveton et al., 2015) bound), which is higher than the upper-bound on the regret of GRAB by a factor K^2 .

H. S-GRAB: OSUB on a Static Graph

The algorithm S-GRAB, depicted in Algorithm 4, is similar to GRAB except that it explores a static graph $G = (E, V)$ defined by

$$V \stackrel{\text{def}}{=} \mathcal{P}_K^L,$$

$$E \stackrel{\text{def}}{=} \{(\mathbf{a}, \mathbf{a} \circ (k, k')) : k, k' \in [K]^2, k > k'\} \cup \{(\mathbf{a}, \mathbf{a}[k := i]) : k \in [K], i \in [L] \setminus \mathbf{a}([K])\}.$$

This graph is chosen to ensure that with PBM setting any sub-optimal recommendation has a strictly better recommendation in its neighborhood given G . This graph is fixed and does not require the knowledge of a mapping \mathcal{P} , but its degree is also about K times larger than the degree of the graphs handled by GRAB.

As for GRAB, any recommendation in the neighborhood of the leader given G differs with the leader at, at most two positions. Therefore a proof similar to the one of Theorem 1 ensures that S-GRAB’s regret is upper-bounded by $\mathcal{O}(LK/\Delta_{\min} \log T)$. This regret upper-bound is higher than GRAB’s one by a factor K due to the larger size of the considered neighborhoods. However, this regret remains smaller than KL-CombUCB’s one by a factor K thanks to the bounded number of differences between the leader and the arm played.

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