A Sliding-Window Approach for RL in MDPs with Arbitrarily Changing Rewards and Transitions

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Formalization

Classical Markov Decision Process (MDP)

- MDP : standard model for problems in decision making with uncertainty like RL.
- Classical MDP $M(\mathcal{S}, \mathcal{A}, p, F)$ with state space $\mathcal{S}$, action space $\mathcal{A}$, transition probability p, reward function F.
- Learner selects action a in state s at time $t = 1, \ldots, T$
    - learner receives reward r_t drawn from dist. with mean $\bar{r}(s, a)$.
    - environment transitions into next state $s' \in \mathcal{S}$ according to $p(s' \mid s, a)$.
- In classical MDPs, stochastic state-transition dynamics and reward functions remain fixed.

Switching-MDP

- ➜ Our setting (**Switching-MDP**): transition dynamics and reward functions change a certain number of times (abrupt changes)
  - **Switching-MDP** $\mathbf{M} := (\mathbb{S} = (M_0, \ldots, M_l), c = (c_1, \ldots, c_l))$
  - At $t < c_1$, $\mathbf{M}$ is in its initial configuration $M_0(\mathcal{S}, \mathcal{A}, p_0, F_0)$.
  - At time step $c_i \leq t < c_{i+1}$, $\mathbf{M}$ is in configuration $M_i(\mathcal{S}, \mathcal{A}, p_i, F_i)$.
- ➜ Goal of algorithm $\mathfrak{A}$ starting from an initial state s

  Minimize regret $\Delta(\mathbf{M}, \mathfrak{A}, s, T) = \sum_{t-1}^{T} (\rho^*_{\mathbf{M}}(t) - r_t)$

  $\rho^*_{\mathbf{M}}(t) :=$ Optimal average reward of the active MDP.

Proposed algorithm: SW-UCRL

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- **Key idea:** Modify $\textsc{Ucrl2}$ to use only the last W samples for computing the estimates.
- **Input:** A confidence parameter $\delta \in (0, 1)$ and window size W.
- **Initialization:** Set $t := 1$, and observe the initial state s_1.

SW-UCRL: Episode Initialization

1. Set the start time of episode k, $t_k := t$.
2. For all (s, a) in $\mathcal{S} \times \mathcal{A}$, set $v_k(s, a) := 0$

$$N_k\left(s, a\right) := \#\left\{t_k - W \leq \tau < t_k : s_\tau = s, a_\tau = a\right\}$$

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3. For all $s, s' \in \mathcal{S}$ and $a \in \mathcal{A}$,

$$R_k(s, a) := \sum_{\tau = t_k - W}^{t_k - 1} r_\tau \mathbb{1}\{s_\tau = s, a_\tau = a\}$$

$$P_k(s, a, s') := \#\{t_k - W \leq \tau < t_k : s_\tau = s, a_\tau = a, s_{\tau+1} = s'\}$$

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4. Compute estimates

$$\hat{r}_k\left(s, a\right) := \frac{R_k(s, a)}{\max\{1, N_k(s, a)\}}$$

$$\hat{p}_k\left(s' | s, a\right) := \frac{P_k(s, a, s')}{\max\{1, N_k(s, a)\}}$$

SW-UCRL: Policy Computation

1. Let $\mathcal{M}_k$ be the set of all MDPs with state space $\mathcal{S}$ and action space $\mathcal{A}$, and with transition probabilities $\tilde{p}\left(\cdot|s,a\right)$ close to $\hat{p}_k\left(\cdot|s,a\right)$, and rewards $\tilde{r}(s,a) \in [0,1]$ close to $\hat{r}_k\left(s,a\right)$, that is,

$$\begin{aligned}
\left|\tilde{r}(s,a) - \hat{r}_k\left(s,a\right)\right| &\leq \sqrt{\frac{7\log(2SAt_k/\delta)}{2\max\{1,N_k(s,a)\}}} \quad \text{and} && (1)\\
\left\|\tilde{p}\left(\cdot|s,a\right) - \hat{p}_k\left(\cdot|s,a\right)\right\|_1 &\leq \sqrt{\frac{14S\log(2At_k/\delta)}{\max\{1,N_k(s,a)\}}}\,. && (2)
\end{aligned}$$

2. Use extended value iteration to find a policy near optimal policy $\tilde{\pi}_k$ and an optimistic MDP $\tilde{M}_k \in \mathcal{M}_k$

SW-UCRL: Policy Execution

Episode stopping criterion: number of occurrences of any (s, a) in the episode $(v_k(s, a))$ = number of occurrences of same (s, a) in W observations before episode start$(N_k(s, a))$

While $v_k(s_t, \tilde{\pi}_k(s_t)) < \max\{1, N_k(s_t, \tilde{\pi}_k(s_t))\}$ **do**

- Choose action $a_t = \tilde{\pi}_k(s_t)$, obtain reward r_t.
- Observe next state s_{t+1}.
- Update $v_k(s_t, a_t) := v_k(s_t, a_t) + 1$.
- Set $t := t + 1$.

Performance Bounds

Theorem (Regret Upper Bound)

Given a switching-MDP with l changes, the regret of SW-UCRL *using window size W is upper-bounded with probability at least $1-\delta$ by*

$$2lW + 66.12\left\lceil \frac{T}{\sqrt{W}} \right\rceil DS\sqrt{A\log\left(\frac{T}{\delta}\right)},$$

where $D =$ max of diameters of constituent MDPs.

- Optimal value of W:

$$W^* = \left(\frac{16.53}{l} TDS\sqrt{A\log\left(\frac{T}{\delta}\right)}\right)^{2/3}$$

Performance Bounds

Corollary (Regert Upper Bound using W^*)

Given a switching-MDP with l changes, the regret of SW-UCRL *using* $W^* = \left(\frac{16.53}{l} TDS \sqrt{A \log\left(\frac{T}{\delta}\right)} \right)^{2/3}$ *is upper-bounded with probability at least* $1 - \delta$ *by*

$$38.94 \cdot l^{1/3} T^{2/3} D^{2/3} S^{2/3} \left(A \log\left(\frac{T}{\delta} \right) \right)^{1/3}.$$

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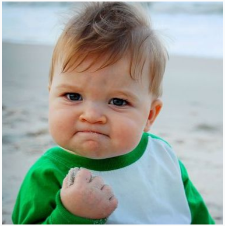


Contribution: Improves upon the regret bound for UCRL2 with restarts (Jaksch et al.(2010) [2]) in terms of D, S and A.

Performance Bounds

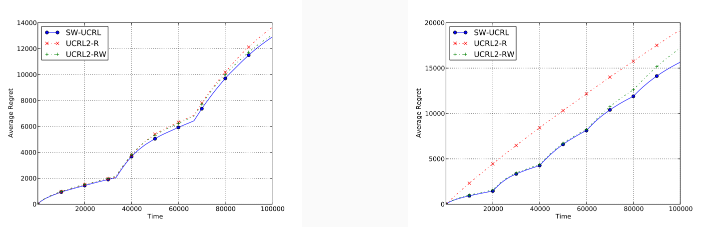
Corollary (Sample Complexity Bound)

Given a switching-MDP problem with l changes, the average per-step regret of SW-UCRL *using W^* is at most ϵ with probability at least $1-\delta$ after any T steps with*

$$T \geq 2 \cdot (38.94)^3 \cdot \frac{lD^2S^2A}{\epsilon^3} \log\left(\frac{(38.94)^3 lD^2S^2A}{\epsilon^3\delta}\right).$$

Experiments

Experiments



(a) Average regret plot for 2 changes **(b)** Average regret plot for 4 changes

Figure 1: Average regret plots for switching-MDPs

- Switching-MDPs with $S = 5, A = 3$, and $T = 100000$.
- l changes happen at every $\lceil \frac{T}{l} \rceil$ time steps.
- SW-UCRL with optimum window size W^*
- For comparison : UCRL2 with restarts (UCRL2-R) and UCRL2 with restarts after every W^* time steps (UCRL2-RW)

Summary and Future Directions

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- SW-UCRL: a competent solution for regret-minimization on switching-MDPS.
- Variation-dependent regret bound?
- Link between allowable variation in rewards and transition probabilities and minimal achievable regret? (like Besbes et al. (2014) [1] for bandits)
- Refine episode-stopping criterion?

Thank you all.

References

[1] Omar Besbes, Yonatan Gur, and Assaf Zeevi. Stochastic multi-armed-bandit problem with non-stationary rewards. In Z. Ghahramani, M. Welling, C. Cortes, N. D. Lawrence, and K. Q. Weinberger, editors, *Advances in Neural Information Processing Systems 27*, pages 199–207. Curran Associates, Inc., 2014.

[2] Thomas Jaksch, Ronald Ortner, and Peter Auer. Near-optimal regret bounds for reinforcement learning. *J. Mach. Learn. Res.*, 11:1563–1600, August 2010.

SW-UCRL: Policy computation

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2. Use extended value iteration to find a policy near optimal policy $\tilde{\pi}_k$ and an optimistic MDP $\tilde{M}_k \in \mathcal{M}_k$ such that

$$\tilde{\rho}_k := \min_s \rho(\tilde{M}_k, \tilde{\pi}_k, s) \geq \max_{M' \in \mathcal{M}_k, \pi, s'} \rho(M', \pi, s') - \frac{1}{\sqrt{t_k}}.$$