Supplementary Material for Adaptive Smoothed Online Multi-Task Learning

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Theoretical Proofs

Proof of Theorem 1

Proof. Define $\Delta_k^{(t)} \stackrel{def}{=} \|w_k^{(t)} - w_k^*\|^2 - \|w_k^{(t+1)} - w_k^*\|^2$.

We can first upper bound $\sum_{t\in T} \Delta_k^{(t)}$ via $\sum_{t\in[T]} \Delta_k^{(t)} = \sum_{t\in[T]} \|w_k^{(t)} - w_k^*\|^2 - \|w_k^{(t+1)} - w_k^*\|^2 = \|w_k^{(0)} - w_k^*\|^2 - \|w_k^{(T+1)} - w_k^*\|^2 \le \|w_k^*\|^2$.

We further notice any non-zero $\Delta_k^{(t)}$ can be lower-bounded via

$$\begin{aligned}
\Delta_k^{(t)} =& \|w_k^{(t)} - w_k^*\|^2 - \|w_k^{(t)} - C\sum_{j\in[K]^+} \eta_{kj}^{(t)} {\ell_{kj}^{(t)}}' - w_k^*\|^2 && (1)\\
=& 2Cw_k^{(t)} \sum_{j\in[K]^+} \eta_{kj}^{(t)} {\ell_{kj}^{(t)}}' - 2Cw_k^* \sum_{j\in[K]^+} \eta_{kj}^{(t)} {\ell_{kj}^{(t)}}' - C^2 \| \sum_{j\in[K]^+} \eta_{kj}^{(t)} {\ell_{kj}^{(t)}}' \|_2^2 && (2)\\
\ge& 2C \sum_{j\in[K]^+} \eta_{kj}^{(t)} \big(\ell_{kj}^{(t)} - 1\big) - 2C \sum_{j\in[K]^+} \eta_{kj}^{(t)} \big(\ell_{kj}^{(t)*} - 1\big) - C^2 \| \sum_{j\in[K]^+} \eta_{kj}^{(t)} y_j^{(t)} x_j^{(t)} \|_2^2 && (3)\\
=& 2C \sum_{j\in[K]^+} \eta_{kj}^{(t)} \ell_{kj}^{(t)} - 2C \sum_{j\in[K]^+} \eta_{kj}^{(t)} \ell_{kj}^{(t)*} - C^2 \| \sum_{j\in[K]^+} \eta_{kj}^{(t)} y_j^{(t)} x_j^{(t)} \|_2^2 && (4)\\
\ge& 2C\eta_{kk}^{(t)} \ell_{kk}^{(t)} - 2C \sum_{j\in[K]^+} \eta_{kj}^{(t)} \ell_{kj}^{(t)*} - C^2 \Big(\sum_{j\in[K]^+} \eta_{kj}^{(t)} \|x_j^{(t)}\|_2 \Big)^2 && (5)\\
\ge& 2C\eta_{kk}^{(t)} \big(\ell_{kk}^{(t)} - \ell_{kk}^{(t)*}\big) - 2C \sum_{j\in[K]^+, j\neq k} \eta_{kj}^{(t)} \ell_{kj}^{(t)*} - C^2R^2 && (6)\\
\ge& 2C\alpha \big(\ell_{kk}^{(t)} - \ell_{kk}^{(t)*}\big) - 2C(1-\alpha)\ell_{kk}^{(t)*} - 2C \sum_{j\in[K]^+, j\neq k} \eta_{kj}^{(t)} \ell_{kj}^{(t)*} - C^2R^2 && (7)\\
=& 2C\alpha \big(\ell_{kk}^{(t)} - \ell_{kk}^{(t)*}\big) - 2C(1-\alpha)\Big(\ell_{kk}^{(t)*} + \sum_{j\in[K]^+, j\neq k} \eta_{kj}^{(t)} \ell_{kj}^{(t)*}\Big) - C^2R^2 && (8)\\
\ge& 2C\alpha \big(\ell_{kk}^{(t)} - \ell_{kk}^{(t)*}\big) - 2C(1-\alpha)\Big(\ell_{kk}^{(t)*} + \max_{j\in[K]^+, j\neq k} \ell_{kj}^{(t)*}\Big) - C^2R^2 && (9)
\end{aligned}$$

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Combining the aforementioned upper and lower bound over $\sum_{t\in[T]} \Delta_k^{(t)}$, we have

$$\sum_{t\in[T]} (\ell_{kk}^{(t)} - \ell_{kk}^{(t)*}) \leq \frac{1}{2C\alpha}\|w_k^*\|^2 + \frac{(1-\alpha)T}{\alpha}\Big(\ell_{kk}^{(t)*} + \max_{j\in[K]^+, j\neq k} \ell_{kj}^{(t)*}\Big) + \frac{CR^2T}{2\alpha} \tag{10}$$

□

Proof of Corollary 2

Proof. By setting $\alpha = \frac{\sqrt{T}}{1+\sqrt{T}}$ and $C = \frac{1+\sqrt{T}}{T}$, we have

$$\sum_{t\in[T]} (\ell_{kk}^{(t)} - \ell_{kk}^{(t)*}) \leq \frac{\sqrt{T}}{2}\|w_k^*\|^2 + \sqrt{T}\Big(\ell_{kk}^{(t)*} + \max_{j\in[K]^+, j\neq k} \ell_{kj}^{(t)*}\Big) + \frac{(1+\sqrt{T})^2}{2\sqrt{T}}R^2 \tag{11}$$

$$\leq \frac{\sqrt{T}}{2}\|w_k^*\|^2 + \sqrt{T}\Big(\ell_{kk}^{(t)*} + \max_{j\in[K]^+, j\neq k} \ell_{kj}^{(t)*}\Big) + 2\sqrt{T}R^2 \tag{12}$$

$$= \sqrt{T}\left(\frac{1}{2}\|w_k^*\|^2 + \ell_{kk}^{(t)*} + \max_{j\in[K]^+, j\neq k} \ell_{kj}^{(t)*} + 2R^2\right) \tag{13}$$

Asymptotically, the average regret of our algorithm w.r.t the best predictor w^* in hindsight goes to 0. Since our algorithm depends on C and α, our algorithm needs to know the value of T. We can get rid of the dependence of our regret bound on T using the *doubling trick*. □

Relationship to Domain Adaptation and Life-long Learning

Multi-task learning has been studied in part under a related research topic, *Domain Adaptation* (DA) [1] under different assumptions. There are several key differences between those methods and ours: i) While DA tries to find a *single* hypothesis that works well for both the source and the target data, this paper finds a hypothesis for each task by adaptively leveraging related tasks. ii) It is a typical assumption in DA that the source domains are label-rich and the target domains are label-scarce. However, we are more interested in the scenario where there is a large number of tasks with very few examples available for each task. iii) DA uses predefined uniform weights or weights induced from VC-convergence theory during training, while our method allows cross-task weights to dynamically evolve in an adaptive manner.

The proposed online method is significantly different from lifelong learning (*ELLA* [2]). Unlike our online learning setting where the data from each task arrives in an online fashion, in lifelong learning, task arrives sequentially. At any time-step, the online learner either receives a subset of data for previously solved task or a completely new task.

References

[1] Shai Ben-David, John Blitzer, Koby Crammer, Alex Kulesza, Fernando Pereira, and Jennifer Wortman Vaughan. A theory of learning from different domains. *Machine learning*, 79(1-2):151–175, 2010.

[2] Paul Ruvolo and Eric Eaton. Ella: An efficient lifelong learning algorithm. *International Conference on Machine Learning*, 28:507–515, 2013.