

PROOF OF LEMMA 7

The vector $\bar{\mathbf{w}}^{t+1}$ can be rewritten as in the following.

$$\begin{aligned}\bar{\mathbf{w}}^{t+1} &= \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} \mathbf{w}^{L,m,u,t}, \\ &= \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} (\mathbf{w}^{L-1,m,u,t} - \eta_t \tilde{\nabla} f_{m,u}(\mathbf{w}^{L-1,m,u,t})),\end{aligned}\tag{36a}$$

$$= \mathbf{w}^t - \eta_t \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} \sum_{l=0}^{L-1} \tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) \right],\tag{36b}$$

$$\begin{aligned}&= \mathbf{w}^t - \eta_t \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} \sum_{l=0}^{L-1} (\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t}) + \nabla f(\mathbf{b}^{l,t})) \right], \\ &= \mathbf{w}^t - \eta_t [\mathbf{e}^{0,t} + \nabla f(\mathbf{b}^{0,t}) + \dots + \mathbf{e}^{L-1,t} + \nabla f(\mathbf{b}^{L-1,t})], \\ &= \mathbf{w}^t - \eta_t (\mathbf{g}^t + \mathbf{e}^t).\end{aligned}\tag{36c}$$

where (36a) comes from Step 8 of Algorithm 1 and (36b) is due to the fact that

$$\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} = 1.$$

From (36c), the following holds

$$\begin{aligned}\mathbb{E}[\|\bar{\mathbf{w}}^{t+1} - \mathbf{w}^*\|_2^2] &= \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^* - \eta_t \mathbf{e}^t\|_2^2], \\ &= \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*\|_2^2] - 2\eta_t \langle \mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*, \mathbf{e}^t \rangle + \eta_t^2 \mathbb{E}[\|\mathbf{e}^t\|_2^2], \\ &\leq \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*\|_2^2] + K\eta_t^2 \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*\|_2^2] + \frac{1}{K} \mathbb{E}[\|\mathbf{e}^t\|_2^2] + \eta_t^2 \mathbb{E}[\|\mathbf{e}^t\|_2^2], \tag{37a} \\ &= (1 + K\eta_t^2) \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*\|_2^2] + \left(\frac{1}{K} + \eta_t^2\right) \mathbb{E}[\|\mathbf{e}^t\|_2^2], \\ &= (1 + K\eta_t^2) \mathbb{E}[\|\mathbf{b}^{L,t} - \mathbf{w}^*\|_2^2] + \left(\frac{1}{K} + \eta_t^2\right) \mathbb{E}[\|\mathbf{e}^t\|_2^2],\end{aligned}\tag{37b}$$

where (37a) is due to the inequality $-2\langle \mathbf{x}, \mathbf{y} \rangle \leq \alpha \|\mathbf{x}\|_2^2 + \frac{1}{\alpha} \|\mathbf{y}\|_2^2$ for $\alpha > 0$ and (37b) follows from the definition of $\{\mathbf{b}^{l,t}\}_{l=0}^L$ in (15).

Next, applying the Cauchy-Schwarz inequality yields

$$\mathbb{E}[\|\mathbf{e}^t\|_2^2] \leq L \sum_{l=0}^{L-1} \mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2] = L\mathbb{E}[\|\mathbf{e}^{0,t}\|_2^2] + L \sum_{l=1}^{L-1} \mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2]. \quad (38)$$

Regarding the first term on the r.h.s. of (38), we have

$$\begin{aligned} \mathbb{E}[\|\mathbf{e}^{0,t}\|_2^2] &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^{0,m,u,t}) - \nabla f(\mathbf{b}^{0,t})] \right\|_2^2 \right], \\ &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^t) - \nabla f(\mathbf{w}^t)] \right\|_2^2 \right], \\ &= \mathbb{E} \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \|\tilde{\nabla} f_{m,u}(\mathbf{w}^t) - \nabla f(\mathbf{w}^t)\|_2^2 \right], \end{aligned} \quad (39a)$$

$$\leq \zeta \mathbb{E}_{\{\mathcal{C}_m\}} \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right], \quad (39b)$$

$$\leq \zeta, \quad (39c)$$

where (39a) is due to the unbiasedness in Assumption 3 and the fact that $\{\tilde{\nabla} f_{m,u}(\mathbf{w}^t)\}$ are independent, (39b) follows from the boundedness Assumption 3, and (39c) is due to the fact that $\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \leq \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} = 1$. Now, the term $\mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2]$ in (38) is rewritten by

$$\begin{aligned} \mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2] &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t})] \right\|_2^2 \right], \\ &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{w}^{l,m,u,t}) + \nabla f(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t})] \right\|_2^2 \right], \\ &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{w}^{l,m,u,t})] \right\|_2^2 \right] \\ &\quad + \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\nabla f(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t})] \right\|_2^2 \right], \end{aligned} \quad (40a)$$

where (40a) follows from Assumption 3 that $\mathbb{E}[\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{w}^{l,m,u,t})] = \mathbf{0}$. Thus, the

following holds

$$\mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2] \leq \zeta \mathbb{E} \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right] + \mathbb{E} \left[\left(\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right) \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \|\nabla f(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t})\|_2^2 \right], \quad (41a)$$

$$\leq \zeta \mathbb{E} \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right] + \mathbb{E} \left[\left(\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right) \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \gamma^2 \|\mathbf{w}^{l,m,u,t} - \mathbf{b}^{l,t}\|_2^2 \right], \quad (41b)$$

$$\leq \zeta + \gamma^2 \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \mathbb{E} \left[\|\mathbf{w}^{l,m,u,t} - \mathbf{b}^{l,t}\|_2^2 \right], \quad (41c)$$

$$= \zeta + K\gamma^2 a^{l,t}, \quad (41d)$$

where (41a) follows from $\mathbb{E}[\|\tilde{\nabla} f_{m,u}(\mathbf{x}) - \nabla f(\mathbf{x})\|_2^2] \leq \zeta$, (41b) follows from Assumption 1, (41c) is due to the fact that $\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} = 1$, and (41d) is due to the definition of $a^{l,t}$ in (16).

From (17b), plugging (39c) and (41d) into (38) leads to

$$\begin{aligned} \mathbb{E}[\|\mathbf{e}^t\|_2^2] &\leq L\zeta + \sum_{l=1}^{L-1} L \left(\zeta + K\gamma^2 a^{l,t} \right), \\ &= L^2\zeta + LK\gamma^2 \sum_{l=1}^{L-1} a^{l,t}, \\ &\leq L^2\zeta + LK\gamma^2 (L-1) \frac{N\eta_t^2 L^2 \zeta}{K} (1 + L\eta_t^2 \gamma^2)^L, \\ &\leq L^2\zeta + NL^4\gamma^2 \zeta \eta_t^2 e^{L^2\eta_t^2 \gamma^2}, \end{aligned} \quad (42a)$$

$$\leq L^2\zeta + NL^4\gamma^2 \zeta \eta_t^2 e, \quad (42b)$$

where (42a) is due to the fact that $(1+x) \leq e^x$ for $x \geq 0$, and (42b) follows from $\eta_t \leq \frac{1}{L\gamma}$.

Plugging (42b) into (37b) and using (17a) give

$$\mathbb{E}[\|\bar{\mathbf{w}}^{t+1} - \mathbf{w}^*\|_2^2] \leq (1 + K\eta_t^2)(1 - \mu\eta_t)^L \mathbb{E}[\|\mathbf{w}^t - \mathbf{w}^*\|_2^2] + \left(\frac{1}{K} + \eta_t^2 \right) (L^2\zeta + NL^4\gamma^2 \zeta \eta_t^2 e),$$

which completes the proof.