

APPENDIX E
PROOF OF LEMMA 8

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

$$\begin{aligned}\bar{\mathbf{w}}^{t+1} &= \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} \mathbf{w}^{L,m,u,t}, \\ &= \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} (\mathbf{w}^{L-1,m,u,t} - \eta_t \tilde{\nabla} f_{m,u}(\mathbf{w}^{L-1,m,u,t})),\end{aligned}\tag{38a}$$

$$= \mathbf{w}^t - \eta_t \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} \sum_{l=0}^{L-1} \tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) \right],\tag{38b}$$

$$\begin{aligned}&= \mathbf{w}^t - \eta_t \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} \sum_{l=0}^{L-1} (\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t}) + \nabla f(\mathbf{b}^{l,t})) \right], \\ &= \mathbf{w}^t - \eta_t \left[\mathbf{e}^{0,t} + \nabla f(\mathbf{b}^{0,t}) + \dots + \mathbf{e}^{L-1,t} + \nabla f(\mathbf{b}^{L-1,t}) \right], \\ &= \mathbf{w}^t - \eta_t (\mathbf{g}^t + \mathbf{e}^t),\end{aligned}\tag{38c}$$

where (38a) comes from Step 8 of Algorithm 1 and (38b) is due to the fact that $\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} = 1$.

From (38c), the following holds

$$\begin{aligned}\mathbb{E}[\|\bar{\mathbf{w}}^{t+1} - \mathbf{w}^*\|_2^2] &= \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^* - \eta_t \mathbf{e}^t\|_2^2], \\ &= \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*\|_2^2] - 2\eta_t \langle \mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*, \mathbf{e}^t \rangle + \eta_t^2 \mathbb{E}[\|\mathbf{e}^t\|_2^2], \\ &\leq \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*\|_2^2] + K\eta_t^2 \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*\|_2^2] \\ &\quad + \frac{1}{K} \mathbb{E}[\|\mathbf{e}^t\|_2^2] + \eta_t^2 \mathbb{E}[\|\mathbf{e}^t\|_2^2],\end{aligned}\tag{39a}$$

$$\begin{aligned}&= (1 + K\eta_t^2) \mathbb{E}[\|\mathbf{w}^t - \eta_t \mathbf{g}^t - \mathbf{w}^*\|_2^2] + \left(\frac{1}{K} + \eta_t^2 \right) \mathbb{E}[\|\mathbf{e}^t\|_2^2], \\ &= (1 + K\eta_t^2) \mathbb{E}[\|\mathbf{b}^{L,t} - \mathbf{w}^*\|_2^2] + \left(\frac{1}{K} + \eta_t^2 \right) \mathbb{E}[\|\mathbf{e}^t\|_2^2],\end{aligned}\tag{39b}$$

where (39a) 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 (39b) follows from the definition of $\{\mathbf{b}^{l,t}\}$ in (18).

Next, applying the Cauchy-Schwarz inequality yields

$$\mathbb{E}[\|\mathbf{e}^t\|_2^2] \leq L \sum_{l=0}^{L-1} \mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2] = L\mathbb{E}[\|\mathbf{e}^{0,t}\|_2^2] + L \sum_{l=1}^{L-1} \mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2]. \quad (40)$$

We have

$$\begin{aligned} \mathbb{E}[\|\mathbf{e}^{0,t}\|_2^2] &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^{0,m,u,t}) - \nabla f(\mathbf{b}^{0,t})] \right\|_2^2 \right], \\ &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^t) - \nabla f(\mathbf{w}^t)] \right\|_2^2 \right], \\ &= \mathbb{E} \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \|\tilde{\nabla} f_{m,u}(\mathbf{w}^t) - \nabla f(\mathbf{w}^t)\|_2^2 \right], \end{aligned} \quad (41a)$$

$$\leq \zeta \mathbb{E}_{\{\mathcal{C}_m\}} \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right], \quad (41b)$$

$$\leq \zeta, \quad (41c)$$

where (41a) is due to the unbiasedness in Assumption 3 and the fact that $\{\tilde{\nabla} f_{m,u}(\mathbf{w}^t)\}$ are independent, $\forall d_{m,u} \in \mathcal{C}_m$, (41b) follows from the boundedness Assumption 3, and (41c) 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 (40) is rewritten by

$$\begin{aligned} \mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2] &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t})] \right\|_2^2 \right], \\ &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{w}^{l,m,u,t}) + \nabla f(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t})] \right\|_2^2 \right], \\ &= \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\tilde{\nabla} f_{m,u}(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{w}^{l,m,u,t})] \right\|_2^2 \right] \\ &\quad + \mathbb{E} \left[\left\| \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} [\nabla f(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t})] \right\|_2^2 \right], \end{aligned} \quad (42a)$$

where (42a) and (43a) follow from Assumption 3 that $\mathbb{E}[\tilde{\nabla} f_{m,u}(\mathbf{x}) - \nabla f(\mathbf{x})] = \mathbf{0}$. Thus, the

following holds

$$\mathbb{E}[\|\mathbf{e}^{l,t}\|_2^2] \leq \zeta \mathbb{E} \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right] + \mathbb{E} \left[\left(\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right) \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \|\nabla f(\mathbf{w}^{l,m,u,t}) - \nabla f(\mathbf{b}^{l,t})\|_2^2 \right], \quad (43a)$$

$$\leq \zeta \mathbb{E} \left[\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right] + \mathbb{E} \left[\left(\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u}^2 \right) \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \gamma^2 \|\mathbf{w}^{l,m,u,t} - \mathbf{b}^{l,t}\|_2^2 \right], \quad (43b)$$

$$\leq \zeta + \gamma^2 \sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \mathbb{E}[\|\mathbf{w}^{l,m,u,t} - \mathbf{b}^{l,t}\|_2^2], \quad (43c)$$

$$= \zeta + K\gamma^2 a^{l,t}, \quad (43d)$$

where (43a) follows $\mathbb{E}[\|\tilde{\nabla} f_{m,u}(\mathbf{x}) - \nabla f(\mathbf{x})\|_2^2] \leq \zeta$. (43b) follows from Assumption 1, (43c) is due to the fact that $\sum_{m=1}^M \sum_{d_{m,u} \in \mathcal{C}_m} \omega_{m,u} = 1$, and (43d) is due to the definition of $a^{l,t}$ in (19).

From (20b), plugging (41c) and (43d) into (40) leads to

$$\begin{aligned} \mathbb{E}[\|\mathbf{e}^t\|_2^2] &\leq L\zeta + \sum_{l=1}^{L-1} L \left(\zeta + K\gamma^2 a^{l,t} \right), \\ &= \frac{L^3 - L^2 + L}{2} \zeta + LK\gamma^2 \sum_{l=1}^{L-1} a^{l,t}, \\ &\leq \frac{L^3 \zeta}{2} + LK\gamma^2 (L-1) \frac{N\eta_t^2 L^2 \zeta}{K} (1 + L\eta_t^2 \gamma^2)^L, \\ &\leq \frac{L^3 \zeta}{2} + NL^4 \gamma^2 \zeta \eta_t^2 e^{L^2 \eta_t^2 \gamma^2}, \end{aligned} \quad (44a)$$

$$\leq \frac{L^3 \zeta}{2} + NL^4 \gamma^2 \zeta \eta_t^2 e, \quad (44b)$$

where (44a) is due to the fact that $(1+x) \leq e^x$, for $0 \leq x$, and (44b) follows from $\eta_t \leq \frac{1}{L\gamma}$.

Plugging (44b) into (39b) and using (20a) gives

$$\mathbb{E}[\|\bar{\mathbf{w}}^{t+1} - \mathbf{w}^*\|_2^2] \leq (1 + K\eta_t^2)(1 - \mu\eta_t)^L \mathbb{E}[\|\mathbf{w}^t - \mathbf{w}^*\|_2^2] + \left(\frac{1}{K} + \eta_t^2 \right) \left(\frac{L^3 \zeta}{2} + NL^4 \gamma^2 \zeta \eta_t^2 e \right),$$

which completes the proof.