

A. Proof of Theorem 1

For the sake of convenience, we first establish some notations:

Let \mathbf{w}_t^i represent the model of the i -th client at the t -th iteration. Let \mathcal{I}_τ denote the global aggregation step, which is defined as $\mathcal{I}_\tau = \{n\tau | n = 1, 2, \dots\}$. Based on Assumption 3, the gradient descent equation can be expressed as:

$$\mathbf{v}_{t+1}^i = \mathbf{w}_t^i - \frac{\eta}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma \mathcal{CN}(0, \mathbf{I}_d) \right) \quad (17)$$

$$\mathbf{w}_{t+1}^i = \begin{cases} \mathbf{v}_{t+1}^i & \text{if } t+1 \notin \mathcal{I}_\tau, \\ \sum_{i=1}^N p_i \mathbf{v}_{t+1}^i & \text{if } t+1 \in \mathcal{I}_\tau. \end{cases} \quad (18)$$

Here, we introduce \mathbf{v}_{t+1}^i to represent the intermediate result of \mathbf{w}_t^i after one iteration of gradient descent.

Inspired by [39], we introduce two virtual sequences in our analysis: $\bar{\mathbf{v}}_t = \sum_{i=1}^N p_i \mathbf{v}_t^i$ and $\bar{\mathbf{w}}_t = \sum_{i=1}^N p_i \mathbf{w}_t^i$. When $t+1 \notin \mathcal{I}_\tau$, $\bar{\mathbf{v}}_t = \bar{\mathbf{w}}_t$, but the server cannot access these two sequences. When $t+1 \in \mathcal{I}_\tau$, the server can access $\bar{\mathbf{w}}_t$.

Therefore, we have:

$$\bar{\mathbf{v}}_{t+1} = \bar{\mathbf{w}}_t - \eta \sum_{i=1}^N \frac{1}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma \mathcal{CN}(0, \mathbf{I}_d) \right) \quad (19)$$

1) Key lemma:

Lemma 4: (Results of one iteration). Assume Assumption 1-3, we have:

$$\mathbb{E} \|\bar{\mathbf{v}}_{t+1} - \mathbf{w}^*\|^2 \leq (1 - \eta\mu) \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 + \eta^2 A$$

since $\Delta_t = \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2$, we have:

$$\Delta_{t+1} \leq (1 - \eta\mu) \Delta_t + \eta^2 A$$

where $A = (\tau - 1)^2 (2 + \eta\mu) \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}} \right) + 3C^2 + \frac{2\Gamma}{\eta} + \frac{\sigma^2 C^2 d}{\hat{B}^2}$, $\Gamma = F^* - \sum_{i=1}^N p_i F_i^*$.

We use mathematical induction to obtain $\Delta_t \leq \frac{v}{t}$ where $v = \max\{\frac{\beta^2 + A}{\beta\mu - 1}, \tau\Delta_1\}$.

STEP 1. When $t = 1$, the equation $\Delta_1 \leq v$ holds obviously.

STEP 2. We assume $\Delta_t \leq \frac{v}{t}$ holds.

STEP 3. on the condition that $\eta = \frac{\beta}{t}$, $\beta > \frac{1}{\mu}$, we know

$$\begin{aligned} \Delta_{t+1} &\leq (1 - \eta\mu) \Delta_t + \eta^2 A \\ &\leq \left(1 - \frac{\beta\mu}{t}\right) \frac{v}{t} + \frac{\beta^2 + A}{t^2} \\ &= \frac{(t-1)v}{t^2} + \left(\frac{\beta^2 + A}{t^2} - \frac{\beta\mu - 1}{t^2} v\right) \\ &\leq \frac{t-1}{t^2} v \leq \frac{v}{t+1} \end{aligned}$$

Therefore, $\Delta_{t+1} \leq \frac{v}{t+1}$ holds, completing the proof by mathematical induction. Hence, $\Delta_t \leq \frac{v}{t}$ holds.

Then by the L -smoothness of $F(\cdot)$, and set $\beta = \frac{2}{\mu}$, $t \leftarrow T$

$$\begin{aligned} \mathbb{E}[F(\bar{\mathbf{w}}_T)] - F^* &\leq \frac{L}{2} \Delta_T \\ &\leq \frac{L}{2T} \left(\frac{4}{\mu^2} + A + \tau\Delta_1 \right) \\ &\leq \frac{L}{2T} \left(\frac{4}{\mu^2} + \tau\Delta_1 + (\tau-1)^2 (2 + \eta\mu) \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right) \right. \\ &\quad \left. + 3C^2 + \frac{2\Gamma}{\eta} + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right) \\ &= \frac{L(2 + \eta\mu) \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right)}{2T} (\tau-1)^2 \\ &\quad + \frac{L}{2T} \left(\frac{4}{\mu^2} + \tau\Delta_1 + 3C^2 + \frac{2\Gamma}{\eta} + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right) \\ &= h(\tau) \end{aligned} \quad (20)$$

where

$$\begin{aligned} h(\tau) &\triangleq \frac{L(2 + \eta\mu) \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right)}{2T} \tau^2 \\ &\quad + \frac{L\Delta_1 - 2L(2 + \eta\mu) \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right)}{2T} \tau + \\ &\quad \frac{L \left((2 + \eta\mu) \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right) + \frac{4}{\mu^2} + 3C^2 + \frac{2\Gamma}{\eta} + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right)}{2T} \end{aligned} \quad (21)$$

2) Proof of Lemma 4:

According to (17),

$$\begin{aligned}
& \|\bar{\mathbf{w}}_{t+1} - \mathbf{w}^*\|^2 \\
&= \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 \\
&\quad - \eta \sum_{i=1}^N p_i \frac{1}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma C \mathcal{N}(0, \mathbf{I}_d) \right) \|^2 \\
&= \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 \\
&\quad + 2\eta \underbrace{\langle \mathbf{w}^* - \bar{\mathbf{w}}_t, \sum_{i=1}^N p_i \frac{1}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma C \mathcal{N}(0, \mathbf{I}_d) \right) \rangle}_{\mathcal{A}_1} \\
&\quad + \eta^2 \underbrace{\left\| \sum_{i=1}^N p_i \frac{1}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma C \mathcal{N}(0, \mathbf{I}_d) \right) \right\|^2}_{\mathcal{A}_2}
\end{aligned} \tag{22}$$

By the convexity of $\|\cdot\|^2$,

$$\begin{aligned}
\mathcal{A}_2 &= \left\| \sum_{i=1}^N p_i \frac{1}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma C \mathcal{N}(0, \mathbf{I}_d) \right) \right\|^2 \\
&\leq \sum_{i=1}^N p_i \left\| \frac{1}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma C \mathcal{N}(0, \mathbf{I}_d) \right) \right\|^2 \\
&\leq \sum_{i=1}^N p_i \left\| \frac{1}{|\mathcal{B}_i|} \sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) \right\|^2 \\
&\quad + \sum_{i=1}^N p_i \left\| \frac{1}{|\mathcal{B}_i|} \sigma C \mathcal{N}(0, \mathbf{I}_d) \right\|^2
\end{aligned}$$

(From the Cauchy Schwartz inequality.)

Take the expectation of \mathcal{A}_2 :

$$\mathbb{E} \mathcal{A}_2 \leq C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2}$$

where $\frac{1}{\hat{B}} = \max_i \mathbb{E} \frac{1}{|\mathcal{B}_i|}$.

$$\begin{aligned}
\mathcal{A}_1 &= -\langle \bar{\mathbf{w}}_t - \mathbf{w}^*, \sum_{i=1}^N p_i \frac{1}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma C \mathcal{N}(0, \mathbf{I}_d) \right) \rangle \\
&= -\underbrace{\langle \bar{\mathbf{w}}_t - \mathbf{w}^*, \sum_{i=1}^N p_i \frac{1}{|\mathcal{B}_i|} \sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) \rangle}_{\mathcal{B}_1} \\
&\quad - \underbrace{\langle \bar{\mathbf{w}}_t - \mathbf{w}^*, \sum_{i=1}^N p_i \frac{1}{|\mathcal{B}_i|} \sigma C \mathcal{N}(0, \mathbf{I}_d) \rangle}_{\mathcal{B}_2}
\end{aligned}$$

Because the noise has a mean of 0:

$$\mathbb{E} \mathcal{B}_2 = 0 \tag{23}$$

Add a zero term to \mathcal{B}_1 :

$$\begin{aligned}
\mathcal{B}_1 &= -\sum_{i=1}^N p_i \langle \bar{\mathbf{w}}_t - \mathbf{w}_t^i + \mathbf{w}_t^i - \mathbf{w}^*, \frac{1}{|\mathcal{B}_i|} \sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) \rangle \\
&= -\underbrace{\sum_{i=1}^N p_i \langle \bar{\mathbf{w}}_t - \mathbf{w}_t^i, \frac{1}{|\mathcal{B}_i|} \sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) \rangle}_{\mathcal{C}_1} \\
&\quad - \underbrace{\sum_{i=1}^N p_i \langle \mathbf{w}_t^i - \mathbf{w}^*, \frac{1}{|\mathcal{B}_i|} \sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) \rangle}_{\mathcal{C}_2}
\end{aligned}$$

By Cauchy-Schwarz inequality and AM-GM inequality, we have

$$\begin{aligned}
\mathcal{C}_1 &\leq \frac{1}{\eta} \sum_{i=1}^N p_i \|\bar{\mathbf{w}}_t - \mathbf{w}_t^i\|^2 + \eta \sum_{i=1}^N p_i \left\| \frac{1}{|\mathcal{B}_i|} \sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) \right\|^2 \\
&\leq \frac{1}{\eta} \sum_{i=1}^N p_i \|\bar{\mathbf{w}}_t - \mathbf{w}_t^i\|^2 + \eta C^2
\end{aligned}$$

According to Assumption 2, we get

$$\begin{aligned}
\mathcal{C}_2 &\leq -\sum_{i=1}^N p_i \langle \mathbf{w}_t^i - \mathbf{w}^*, \frac{1}{|\mathcal{B}_i|} \sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) \rangle \\
&\leq -\sum_{i=1}^N p_i (F_i(\mathbf{w}_t^i) - F_i(\mathbf{w}^*)) - \sum_{i=1}^N p_i \frac{\mu}{2} \|\mathbf{w}_t^i - \mathbf{w}^*\|^2 \\
&= -\sum_{i=1}^N p_i (F_i(\mathbf{w}_t^i) - F(\mathbf{w}^*) + F(\mathbf{w}^*) - F_i(\mathbf{w}^*)) \\
&\quad - \frac{\mu}{2} \sum_{i=1}^N p_i \|\mathbf{w}_t^i - \mathbf{w}^*\|^2 \\
&= -\sum_{i=1}^N p_i (F_i(\mathbf{w}_t^i) - F(\mathbf{w}^*)) + \sum_{i=1}^N p_i (F_i(\mathbf{w}^*) - F(\mathbf{w}^*)) \\
&\quad - \frac{\mu}{2} \sum_{i=1}^N p_i \|\mathbf{w}_t^i - \mathbf{w}^*\|^2 \\
&\leq -\underbrace{\sum_{i=1}^N p_i (F_i(\mathbf{w}_t^i) - F(\mathbf{w}^*))}_{\mathcal{D}_1} - \frac{\mu}{2} \sum_{i=1}^N p_i \|\mathbf{w}_t^i - \mathbf{w}^*\|^2 + \Gamma
\end{aligned}$$

where $\Gamma \triangleq \sum_{i=1}^N p_i (F(\mathbf{w}^*) - F_i(\mathbf{w}^*))$.

Process the \mathcal{D}_1

$$\begin{aligned}
\mathcal{D}_1 &= \sum_{i=1}^N p_i (F_i(\mathbf{w}_t^i) - F(\mathbf{w}^*)) \\
&= \sum_{i=1}^N p_i (F_i(\mathbf{w}_t^i) - F_i(\bar{\mathbf{w}}_t)) + \sum_{i=1}^N p_i (F_i(\bar{\mathbf{w}}_t) - F(\mathbf{w}^*)) \\
&\geq \sum_{i=1}^N p_i \langle \nabla F_i(\bar{\mathbf{w}}_t), \mathbf{w}_t^i - \bar{\mathbf{w}}_t \rangle + (F(\bar{\mathbf{w}}_t) - F(\mathbf{w}^*)) \\
&\quad \text{(from the Assumption 2)} \\
&\geq -\frac{1}{2} \sum_{i=1}^N p_i \left[\eta \|F_i(\bar{\mathbf{w}}_t)\|^2 + \frac{1}{\eta} \|\mathbf{w}_t^i - \bar{\mathbf{w}}_t\|^2 \right] \\
&\quad + (F(\bar{\mathbf{w}}_t) - F(\mathbf{w}^*)) \\
&\quad \text{(from the AM-GM inequality)} \\
&\geq -\sum_{i=1}^N p_i \left[\eta L (F_i(\bar{\mathbf{w}}_t) - F(\mathbf{w}^*)) + \frac{1}{2\eta} \|\mathbf{w}_t^i - \bar{\mathbf{w}}_t\|^2 \right] \\
&\quad + (F(\bar{\mathbf{w}}_t) - F(\mathbf{w}^*)) \\
&\quad \text{(from the Assumption 1)} \\
&= (1 - \eta L) (F(\bar{\mathbf{w}}_t) - F(\mathbf{w}^*)) + \frac{1}{2\eta} \sum_{i=1}^N p_i \|\mathbf{w}_t^i - \bar{\mathbf{w}}_t\|^2
\end{aligned}$$

Hence, we get

$$\begin{aligned}
\mathcal{B}_1 &\leq \frac{1}{\eta} \sum_{i=1}^N p_i \|\bar{\mathbf{w}}_t - \mathbf{w}_t^i\|^2 + \eta C^2 \\
&\quad + (\eta L - 1) (F(\bar{\mathbf{w}}_t) - F(\mathbf{w}^*)) - \frac{1}{2\eta} \|\mathbf{w}_t^i - \bar{\mathbf{w}}_t\|^2 \\
&\quad - \frac{\mu}{2} \sum_{i=1}^N p_i \|\mathbf{w}_t^i - \mathbf{w}^*\|^2 + \Gamma \\
&\leq -\frac{\mu}{2} \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 + \left(\frac{1}{\eta} + \frac{\mu}{2}\right) \sum_{i=1}^N p_i \|\bar{\mathbf{w}}_t - \mathbf{w}_t^i\|^2 + \eta C^2 + \Gamma
\end{aligned}$$

Comprehensive equation $\mathcal{A} - \mathcal{D}$, take exception to (22):

$$\begin{aligned}
\mathbb{E} \|\bar{\mathbf{v}}_{t+1} - \mathbf{w}^*\|^2 &= \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 + 2\eta \mathbb{E} \mathcal{A}_1 + \eta^2 \mathbb{E} \mathcal{A}_2 \\
&\leq \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 + \eta^2 \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right) \\
&\quad + 2\eta \left(-\frac{\mu}{2} \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 \right) \\
&\quad + \left(\frac{1}{\eta} + \frac{\mu}{2} \right) \sum_{i=1}^N p_i \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}_t^i\|^2 + \eta C^2 + \Gamma \\
&= (1 - \eta\mu) \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 + (2 + \eta\mu) \sum_{i=1}^N p_i \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}_t^i\|^2 \\
&\quad + 3\eta^2 C^2 + 2\eta\Gamma + \frac{\eta^2 \sigma^2 C^2 d}{\hat{B}^2} \tag{24}
\end{aligned}$$

Then we do such process:

$$\begin{aligned}
&\sum_{i=1}^N p_i \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}_t^i\|^2 \\
&= \sum_{i=1}^N p_i \mathbb{E} \|(\mathbf{w}_t^i - \bar{\mathbf{w}}_{t_0}) - (\bar{\mathbf{w}}_t - \bar{\mathbf{w}}_{t_0})\|^2 \\
&\leq \sum_{i=1}^N p_i \mathbb{E} \sum_{t=t_0}^{t-1} (\tau - 1) \eta^2 \left\| \frac{1}{|\mathcal{B}_i|} \left(\sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) + \sigma \mathcal{CN}(0, \mathbf{I}_d) \right) \right\|^2 \\
&\leq \sum_{i=1}^N p_i \eta^2 (\tau - 1)^2 \left(\mathbb{E} \left\| \frac{1}{|\mathcal{B}_i|} \sum_{s \in \mathcal{B}_i(t)} \nabla F_i(\mathbf{w}_t^i, s) \right\|^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right) \\
&\leq \eta^2 (\tau - 1)^2 \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right) \tag{25}
\end{aligned}$$

Combine equation (22) and equation (25):

$$\mathbb{E} \|\bar{\mathbf{v}}_{t+1} - \mathbf{w}^*\|^2 \leq (1 - \eta\mu) \mathbb{E} \|\bar{\mathbf{w}}_t - \mathbf{w}^*\|^2 + \eta A \tag{26}$$

where

$$A = (\tau - 1)^2 (2 + \eta\mu) \left(C^2 + \frac{\sigma^2 C^2 d}{\hat{B}^2} + 3C^2 + \frac{2\Gamma}{\eta} + \frac{\sigma^2 C^2 d}{\hat{B}^2} \right) \tag{27}$$