Convergence Analysis

January 23, 2023

Notation & Definitions

- t : time index, $t \in \mathbb{Z}^+$.
- z_t : position of the target at time t, $z_t \in \mathbb{R}^d$.
- x_t : position of the agent at time t, $x_t \in \mathbb{R}^d$.
- We denote stochastic variables $\tilde{\ell}_t^i(x) := \ell_t^i(x, z)$, $\tilde{\nabla}\ell_{\mu,t}^i(x) := \nabla \ell_{\mu,t}^i(x, z)$, and $\tilde{g}_{\mu,t}^i(x) := g_{\mu,t}^i(x, z)$ for *i.i.d.* $z \sim P_z$, at time t, with the position of i^{th} agent as x for $x \in \mathbb{R}^d$ and $i \in \{1, ..., N\}$.
- $\tilde{\ell}_{\mu,t}^i(x) := \mathbb{E}_u[\tilde{\ell}_t^i(x + \mu u)]$ for $x \in \mathbb{R}^d$, $u \sim \mathcal{N}(0, I_d)$ and $\mu \in \mathbb{R}$.
- $\tilde{\nabla}\ell_{\mu,t}^i(x) := \mathbb{E}_u\left[\tilde{g}_{\mu,t}^i(x)\right]$ where $\tilde{g}_{\mu,t}^i(x) := \dfrac{\tilde{\ell}_t^i(x + \mu u) - \tilde{\ell}_t^i(x)}{\mu} u$ for $x \in \mathbb{R}^d$, $u \sim \mathcal{N}(0, I_d)$ and $\mu \in \mathbb{R}$.

Assumptions

Assumption 1. *(Unbiased Stochastic Zeroth-Order Oracle) For any $t \in \mathbb{Z}^+$, $i \in \{1, \dots, N\}$ and $x \in \mathbb{R}^d$, we have*

$$\mathbb{E}_z\left[\tilde{\ell}_t^i(x)\right] = \ell_t^i(x). \tag{1}$$

Assumption 2. *(Unbiased Stochastic First-Order Oracle) For any $t \in \mathbb{Z}^+$, $i \in \{1, \dots, N\}$ and $x \in \mathbb{R}^d$, we have*

$$\mathbb{E}_z\left[\nabla\tilde{\ell}_t^i(x)\right] = \nabla \ell_t^i(x) \tag{2}$$

Assumption 3. *(L-smoothness) Each $\tilde{\ell}_t^i(x)$ is continuously differentiable and L-smooth over x on $\mathbb{R}^d$, that is, there exists an $L \geq 0$ such that for all $x, y \in \mathbb{R}^d$, $t \in \mathbb{Z}^+$ and $i \in \{1, \dots, N\}$, we have*

$$\|\nabla\tilde{\ell}_t^i(x) - \nabla\tilde{\ell}_t^i(y)\| \leq L\|x - y\|. \tag{3}$$

We denote this by $\tilde{\ell}_t^i(x) \in C_L^{1,1}(\mathbb{R}^d)$. Note that this assumption implies $\ell_t^i(x) \in C_L^{1,1}(\mathbb{R}^d)$.

Assumption 4. *(Contractive Compression) The compression function $\mathcal{C}$ is a contraction mapping, that is,*

$$\mathbb{E}_{\mathcal{C}}\left[\|\mathcal{C}(x) - x\|^2 \mid x\right] \leq (1 - \delta)\|x\|^2 \tag{4}$$

for all $x \in \mathbb{R}^d$ where $0 < \delta \leq 1$, and the expectation is over the randomness generated by compression $\mathcal{C}$.

Assumption 5. *(Bounded Stochastic Gradients) For any $t \in \mathbb{Z}^+$, $i \in \{1, \ldots, N\}$ and $x \in \mathbb{R}^d$, there exist $\sigma, M > 0$ such that*

$$\mathbb{E}_z \left[\|\nabla \tilde{\ell}_t^i(x)\|^2 \right] \leq \sigma^2 + M \|\nabla \ell_t^i(x)\|^2. \tag{5}$$

Assumption 6. *(Bounded Drift in Time) There exist N bounded sequences $\{\omega_t^1\}_{t=1}^T, \ldots, \{\omega_t^N\}_{t=1}^T$ such that for all $t \in \mathbb{Z}^+$ and $i \in \{1, \ldots, N\}$, $|\ell_t^i(x) - \ell_{t+1}^i(x)| \leq \omega_t^i$ for any $x \in \mathbb{R}^d$. Note that in the case where $\ell_{t+1}^i = \ell_t^i$, this assumption holds with $\omega_t^i = 0$.*

Assumption 7. *(Multi-Agent Bounded Loss Assumption) For any $x_t^{1:N} \in \mathbb{R}^{Nd}$, we have*

$$\mathbb{E}_{z_{1:T}} \|\nabla \ell_t^i(x_t^{1:N}) - \nabla \bar{\ell}_t(x_t^{1:N})\|^2 \leq Z^2. \tag{6}$$

Lemmas

Suppose $f(x) \in C_L^{1,1}(\mathbb{R}^d)$. Then, we have the following results:

Lemma 1. *$f_\mu(x) \in C_{L_\mu}^{1,1}(\mathbb{R}^d)$, where $L_\mu \leq L$.*

Lemma 2. *$f_\mu(x)$ has the following gradient with respect to x:*

$$\nabla f_\mu(x) = \frac{1}{(2\pi)^{d/2}} \int \frac{f(x + \mu u) - f(x)}{\mu} u e^{(-\frac{1}{2}\|u\|^2)} \mathrm{d}u, \tag{7}$$

where $u \sim \mathcal{N}(0, I_d)$.

Lemma 3. *For any $x \in \mathbb{R}^d$, we have*

$$|f_\mu(x) - f(x)| \leq \frac{\mu^2 L d}{2}. \tag{8}$$

Lemma 4. *For any $x \in \mathbb{R}^d$, we have*

$$\|\nabla f_\mu(x) - \nabla f(x)\| \leq \frac{\mu}{2} L (d+3)^{\frac{3}{2}}, \tag{9}$$

Lemma 5. *For any $x \in \mathbb{R}^d$, we have*

$$\mathbb{E}_u \left[\left\| \frac{f(x + \mu u) - f(x)}{\mu} u \right\|^2 \right] \leq \frac{\mu^2}{2} L^2 (d+6)^3 + 2(d+4) \|\nabla f(x)\|^2, \tag{10}$$

where $u \sim \mathcal{N}(0, I_d)$.

Lemma 6. *(Young's inequality) For any $x, y \in \mathbb{R}^d$ and $\lambda > 0$, we have*

$$\langle x, y \rangle \leq \frac{\|x\|^2}{2\lambda} + \frac{\|y\|^2 \lambda}{2}. \tag{11}$$

EF-ZO-SGD Convergence Analysis for Single-Agent

We work with the following algorithm:

Algorithm 1 EF-ZO-SGD

Input: Number of time steps $T \in \mathbb{Z}^+$, smoothing parameter $\mu \in \mathbb{R}$, initial source position $x_0 \in \mathbb{R}^d$, learning rate $\eta \in \mathbb{R}$, sequence of target positions $\{z_t\}_{t=1}^T \subset \mathbb{R}^d$.
Output: Sequence of optimal source positions $\{x_t\}_{t=1}^T \subset \mathbb{R}^d$.

$e_0 = 0$
for $t = 1, \ldots, T$ **do**
  $u_t \sim \mathcal{N}(0, I_d)$
  $\tilde{g}_{\mu,t}(x_t) = \dfrac{\tilde{\ell}_t(x_t + \mu u_t) - \tilde{\ell}_t(x_t)}{\mu} u_t$
  $p_t = \tilde{g}_{\mu,t}(x_t) + e_t$
  $x_{t+1} = x_t - \eta \mathcal{C}(p_t)$
  $e_{t+1} = p_t - \mathcal{C}(p_t)$
end for

In the analysis, we assume that $z_t \in \mathbb{R}^d$ are *i.i.d.* random variables for all $t \in \mathbb{Z}^+$. Furthermore, we drop the superscript notation present in the assumptions, since i is always 1 for the single-agent case.

Let $\tilde{x}_t$ be defined as follows (following the analysis in [1]):

$$\tilde{x}_t := x_t - \eta e_t. \tag{12}$$

From algorithm 1, we know that $e_{t+1} = p_t - \mathcal{C}(p_t)$ and $p_t = \tilde{g}_{\mu,t}(x_t) + e_t$, so we can rewrite $\tilde{x}_{t+1}$ as

$$\begin{aligned}
\tilde{x}_{t+1} &= x_{t+1} - \eta p_t + \eta \mathcal{C}(p_t) \\
&= x_t - \eta \mathcal{C}(p_t) - \eta \tilde{g}_{\mu,t}(x_t) - \eta e_t + \eta \mathcal{C}(p_t) \\
&= x_t - \eta e_t - \eta \tilde{g}_{\mu,t}(x_t) \\
&= \tilde{x}_t - \eta \tilde{g}_{\mu,t}(x_t),
\end{aligned} \tag{13}$$

where $\tilde{g}_{\mu,t}(x_t) = \dfrac{\tilde{\ell}_t(x_t + \mu u_t) - \tilde{\ell}_t(x_t)}{\mu} u_t$ and $u_t \sim \mathcal{N}(0, I_d)$.

By assumption 3, we can write the following:

$$\ell_{\mu,t}(\tilde{x}_{t+1}) \leq \ell_{\mu,t}(\tilde{x}_t) + \langle \nabla \ell_{\mu,t}(\tilde{x}_t), \tilde{x}_{t+1} - \tilde{x}_t \rangle + \frac{L}{2} \|\tilde{x}_{t+1} - \tilde{x}_t\|^2. \tag{14}$$

Now by assumption 6, we get:

$$\ell_{\mu,t+1}(\tilde{x}_{t+1}) \leq \ell_{\mu,t}(\tilde{x}_t) - \eta \langle \tilde{g}_{\mu,t}(x_t), \nabla \ell_{\mu,t}(\tilde{x}_t) \rangle + \frac{L\eta^2}{2} \|\tilde{g}_{\mu,t}(x_t)\|^2 + \omega_t. \tag{15}$$

Since $\nabla \ell_{\mu,t}(x_t) = \mathbb{E}_{u_t,z_t}\left[\tilde{g}_{\mu,t}(x_t)\right]$, taking the expectation of both sides with respect to u_t and z_t, we have the following:

$$\begin{aligned}
\mathbb{E}_{u_t,z_t}\left[\langle \tilde{g}_{\mu,t}(x_t), \nabla \ell_{\mu,t}(\tilde{x}_t) \rangle\right] &= \langle \nabla \ell_{\mu,t}(x_t), \nabla \ell_{\mu,t}(\tilde{x}_t) \rangle \\
&= \frac{1}{2}\|\nabla \ell_{\mu,t}(x_t)\|^2 + \frac{1}{2}\|\nabla \ell_{\mu,t}(\tilde{x}_t)\|^2 - \frac{1}{2}\|\nabla \ell_{\mu,t}(x_t) - \nabla \ell_{\mu,t}(\tilde{x}_t)\|^2.
\end{aligned} \tag{16}$$

In the last step, we use the fact that $2\langle a, b\rangle = \|a\|^2 + \|b\|^2 - \|a-b\|^2$. Plugging this into (15), we get:

$$\begin{aligned}\ell_{\mu,t+1}(\tilde{x}_{t+1}) \leq &\ell_{\mu,t}(\tilde{x}_t) - \frac{\eta}{2}\|\nabla \ell_{\mu,t}(x_t)\|^2 - \frac{\eta}{2}\|\nabla \ell_{\mu,t}(\tilde{x}_t)\|^2 \\ &+ \frac{L^2\eta}{2}\|x_t - \tilde{x}_t\|^2 + \frac{L\eta^2}{2}\mathbb{E}_{u_t,z_t}\left[\|\tilde{g}_{\mu,t}(x_t)\|^2\right] + \omega_t.\end{aligned} \tag{17}$$

Note that $\|\nabla \ell_{\mu,t}(x_t) - \nabla \ell_{\mu,t}(\tilde{x}_t)\|^2 \leq L^2\|x_t - \tilde{x}_t\|^2$ by assumption 3, with subsequent application of lemma 1. Also, we can drop -$\frac{\eta}{2}\|\nabla \ell_{\mu,t}(\tilde{x}_t)\|^2$ because it is nonpositive. Using the fact that $\tilde{x}_t - x_t = \eta e_t$, we get:

$$\underbrace{\frac{\eta}{2}\|\nabla \ell_{\mu,t}(x_t)\|^2}_{\text{Term III}} \leq \underbrace{\left[\ell_{\mu,t}(\tilde{x}_t) - \ell_{\mu,t+1}(\tilde{x}_{t+1})\right]}_{\text{Term II}} + \underbrace{\frac{L\eta^2}{2}\mathbb{E}_{u_t,z_t}\left[\|\tilde{g}_{\mu,t}(x_t)\|^2\right]}_{\text{Term I}} + \underbrace{\frac{L^2\eta^3}{2}\|e_t\|^2}_{\text{Term IV}} + \omega_t. \tag{18}$$

We will put an upper bound to the terms I, II, and IV and a lower bound to term III. Starting with **term I**, by lemma 5, we know that

$$\mathbb{E}_{u_t,z_{1:T}}\left[\|\tilde{g}_{\mu,t}(x_t)\|^2\right] \leq 2(d+4)\mathbb{E}_{z_{1:T}}\left[\|\tilde{\nabla}\ell_t(x_t)\|^2\right] + \frac{\mu^2L^2}{2}(d+6)^3, \tag{19}$$

where $\mathbb{E}_{z_{1:T}}[\|\tilde{\nabla}\ell_t(x_t)\|^2] \leq M\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_t(x_t)\|^2\right] + \sigma^2$ by assumption 5. Note that, in this step, we use the the principle of causality and the fact that z_t are *i.i.d.*.

We can put the following upper bound to **term II** by means of a telescoping sum and subsequently applying lemma 3:

$$\begin{aligned}\sum_{t=1}^{T}\left[\ell_{\mu,t}(\tilde{x}_t) - \ell_{\mu,t+1}(\tilde{x}_{t+1})\right] &= \ell_{\mu,1}(\tilde{x}_1) - \ell_{\mu,T+1}(\tilde{x}_{T+1}) \\ &\leq \mu^2Ld + \ell_1(\tilde{x}_1) - \ell_{T+1}(\tilde{x}_{T+1}) \\ &= \mu^2Ld + \ell_1(x_1) - \ell_{T+1}(\tilde{x}_{T+1}),\end{aligned} \tag{20}$$

where we use the fact that $\ell(x_1) = \ell_1(\tilde{x}_1)$ because $\tilde{x}_1 = x_1$ by definition. Then, we can do the following

$$\begin{aligned}\sum_{t=1}^{T}\left[\ell_{\mu,t}(\tilde{x}_t) - \ell_{\mu,t+1}(\tilde{x}_{t+1})\right] &\leq \mu^2Ld + \ell_1(x_1) - \ell_{T+1}(\tilde{x}_{T+1}) \\ &\leq \mu^2Ld + \ell_1(x_1) - \ell_{T+1}(x^*_{T+1}),\end{aligned} \tag{21}$$

where $x^*_{T+1} = \arg\min_x \ell_{T+1}(x)$.

We can put the following lower bound to **term III** by using lemma 4 and lemma 6:

$$\frac{1}{2}\|\nabla \ell_t(x_t)\|^2 - \frac{\mu^2L^2}{4}(d+3)^3 \leq \|\nabla \ell_{\mu,t}(x_t)\|^2. \tag{22}$$

Lastly, we can put the following upper bound to **term IV** by assumption 4 and lemma 6:

$$\begin{aligned}
\mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}[\|e_{t+1}\|^2] &= \mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}\left[\|p_t - \mathcal{C}_t(p_t)\|^2\right] \leq (1-\delta)\mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}\left[\|p_t\|^2\right] \\
&= (1-\delta)\mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}\left[\|e_t + \tilde{g}_{\mu,t}(x_t)\|^2\right] \\
&\leq (1-\delta)(1+\varphi)\mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}\left[\|e_t\|^2\right] + (1-\delta)(1+\frac{1}{\varphi})\mathbb{E}_{u_{1:T},z_{1:T}}\left[\|\tilde{g}_{\mu,t}(x_t)\|^2\right] \\
&= \sum_{i=1}^{t}\left[(1-\delta)(1+\varphi)\right]^{t-i}(1-\delta)(1+\frac{1}{\varphi})\mathbb{E}_{u_i,z_{1:T}}\left[\|\tilde{g}_{\mu,i}(x_i)\|^2\right],
\end{aligned} \tag{23}$$

for some $\varphi > 0$, $z_t, u_t, \mathcal{C}_t$ are *i.i.d.*, and $\mathbb{E}_{\mathcal{C}_t}[\,\cdot\,]$ denotes the expectation over the randomness at time t due to the compression used. Note that by using lemma 5 and assumption 5,

$$\mathbb{E}_{u_t,z_{1:T}}[\|\tilde{g}_{\mu,t}(x_t)\|^2] \leq A\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_t(x_t)\|^2\right] + B, \tag{24}$$

where

$$\begin{aligned}
B &= 2\sigma^2(d+4) + \frac{\mu^2 L^2}{2}(d+6)^3 \text{ and} \\
A &= 2M(d+4).
\end{aligned} \tag{25}$$

So we can rewrite (23) as follows:

$$\mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}\left[\|e_{t+1}\|^2\right] \leq \sum_{i=1}^{t}\left[(1-\delta)(1+\varphi)\right]^{t-i}(1-\delta)(1+\frac{1}{\varphi})\left[A\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_i(x_i)\|^2\right] + B\right]. \tag{26}$$

If we set $\varphi := \frac{\delta}{2(1-\delta)}$, then $1 + \frac{1}{\varphi} \leq \frac{2}{\delta}$ and $(1-\delta)(1+\varphi) = (1-\frac{\delta}{2})$, so we get:

$$\mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}\left[\|e_{t+1}\|^2\right] \leq \sum_{i=1}^{t}\left(1-\frac{\delta}{2}\right)^{t-i}\left[A\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_i(x_i)\|^2\right] + B\right]\frac{2(1-\delta)}{\delta}. \tag{27}$$

If we sum through all $\mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}[\|e_t\|^2]$, we get:

$$\begin{aligned}
\sum_{t=1}^{T}\mathbb{E}_{u_{1:T},z_{1:T},\mathcal{C}_{1:T}}\left[\|e_t\|^2\right] &\leq \sum_{t=1}^{T}\sum_{i=1}^{t-1}\left(1-\frac{\delta}{2}\right)^{t-i}\left[A\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_i(x_i)\|^2\right] + B\right]\frac{2(1-\delta)}{\delta} \\
&\leq \sum_{t=1}^{T}\left[A\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_t(x_t)\|^2\right] + B\right]\sum_{i=0}^{\infty}\left(1-\frac{\delta}{2}\right)^{i}\frac{2(1-\delta)}{\delta} \\
&\leq \sum_{t=1}^{T}\left[A\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_t(x_t)\|^2\right] + B\right]C,
\end{aligned} \tag{28}$$

where $C = \frac{2(1-\delta)}{\delta}\frac{2}{\delta} \leq \frac{4}{\delta^2}$. If we define $\Delta := \ell_1(x_1) - \ell_{T+1}(x^*_{T+1})$ and combine the upper bounds derived in (19), (20), (23), and the lower bound derived in (22) and plug them into (18), we get the following:

$$
\begin{aligned}
&\sum_{t=1}^{T}\frac{\eta}{4}\mathbb{E}_{z_{1:T}}\left[\|\nabla\ell_t(x_t)\|^2\right]-\frac{\eta\mu^2L^2}{8}(d+3)^3T\\
&\quad\le \mu^2Ld+\Delta+\frac{T\mu^2L^3\eta^2}{4}(d+6)^3+\frac{L\eta^2}{2}\sigma^2T\times 2(d+4)\\
&\quad+\frac{L\eta^2}{2}\times 2M(d+4)\sum_{t=1}^{T}\mathbb{E}_{z_{1:T}}\left[\|\nabla\ell_t(x_t)\|^2\right]+\frac{\eta^3L^2}{2}\times\frac{4}{\delta^2}T\left[2\sigma^2(d+4)+\frac{\mu^2L^2}{2}(d+6)^3\right]\\
&\quad+\frac{\eta^3L^2}{2}\times\frac{4}{\delta^2}\sum_{t=1}^{T}2M(d+4)\mathbb{E}_{z_{1:T}}\left[\|\nabla\ell_t(x_t)\|^2\right]+\sum_{t=1}^{T}\omega_t.
\end{aligned}
\tag{29}
$$

Now, since z_t's are *i.i.d.* for all $t\in\mathbb{Z}^+$, we have:

$$
\begin{aligned}
\frac{E}{T}\sum_{t=1}^{T}\mathbb{E}_{z_{1:T}}\left[\|\nabla\ell_t(x_t)\|^2\right]\le{}&\frac{\mu^2Ld+\Delta}{T}+\frac{\eta^2L^3\mu^2(d+6)^3}{4}+L\eta^2\sigma^2(d+4)+\frac{\eta\mu^2L^2(d+3)^3}{8}\\
&+\frac{\eta^3L^2}{\delta^2}4\sigma^2(d+4)+\frac{\eta^3L^2}{\delta^2}\mu^2L^2(d+6)^3+\frac{1}{T}\sum_{t=1}^{T}\omega_t,
\end{aligned}
\tag{30}
$$

where

$$
\begin{aligned}
E&=\frac{\eta}{4}-LM\eta^2(d+4)-\frac{L^2\eta^3}{\delta^2}4M(d+4)\\
&=\eta\left[\frac{1}{4}-LM\eta(d+4)\left(1+\frac{4L\eta}{\delta^2}\right)\right].
\end{aligned}
\tag{31}
$$

If $\eta\le\frac{1}{4L}$, instead first upper bound will be:

$$
1+\frac{4L\eta}{\delta^2}\le 1+\frac{1}{\delta^2}=\frac{\delta^2+1}{\delta^2}\le\frac{2}{\delta^2}.
\tag{32}
$$

We proceed to find an η such that

$$
\frac{2}{\delta^2}LM\eta(d+4)\le\frac{1}{8}.
\tag{33}
$$

Then, we get

$$
\eta\le\frac{\delta^2}{16LM(d+4)},
\tag{34}
$$

which implies $E\ge\frac{\eta}{8}$. Multiplying all terms in the bound by $\frac{8}{\eta}$,

$$
\begin{aligned}
\frac{1}{T}\sum_{t=1}^{T}\mathbb{E}_{z_{1:T}}\left[\|\nabla\ell_t(x_t)\|^2\right]\le{}&\frac{8\Delta}{(\eta T)}+\frac{8\mu^2Ld}{\eta T}+2\eta L^3\mu^2(d+6)^3\\
&+8L\eta\sigma^2(d+4)+\mu^2L^2(d+3)^3\\
&+\frac{32\eta^2L^2}{\delta^2}\sigma^2(d+4)+\frac{8\eta^2L^4\mu^2(d+6)^3}{\delta^2}+\frac{8}{\eta T}\sum_{t=1}^{T}\omega_t.
\end{aligned}
\tag{35}
$$

Let

$$
\eta=\frac{1}{\sigma\sqrt{(d+4)MTL}}\quad\text{and}\quad\mu=\frac{1}{(d+4)\sqrt{T}}.
\tag{36}
$$

Then, for a numerical constant $C > 0$, we have

$$\frac{1}{CT}\sum_{t=1}^{T}\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_t(x_t)\|^2\right] \leq \frac{1}{\delta^2}\frac{dL\Delta}{T} + \sigma\sqrt{\frac{d}{T}L\Delta M} + \frac{1}{\eta T}\sum_{t=1}^{T}\omega_t. \tag{37}$$

Defining $\bar{\omega} := \sum_{t=1}^{T}\omega_t$, the number of times steps T to obtain a ξ-first order solution is

$$T = \mathcal{O}\left(\frac{d\sigma^2 L\Delta M}{\xi^2} + \frac{dL\Delta}{\delta^2\xi} + \frac{\bar{\omega}\sigma^2 dML}{\xi^2}\right). \tag{38}$$

Remark: In choosing $\eta = \frac{1}{\sigma\sqrt{(d+4)MTL}}$, we assumed that it satisfies (69). For this to hold, T can be made arbitrarily large as long as it does not exceed the bound we found in (72). (71) and (69) imply that

$$T = \Omega\left(\frac{dLM}{\delta^4\sigma^2}\right). \tag{39}$$

In practice, since $\xi \ll \delta$, this term is smaller than (37). This fact is also demonstrated by our experiments.

Lastly, if $\omega_t = 0$ for all $t \in \mathbb{Z}^+$, i.e., in the case where the loss function is time-invariant, the number of time steps T to obtain a ξ-first order solution is:

$$T = \mathcal{O}\left(\frac{d\sigma^2 L\Delta M}{\xi^2} + \frac{dL\Delta}{\delta^2\xi}\right). \tag{40}$$

FED-EF-ZO-SGD Convergence Analysis for Multi-Agent

We work with the following algorithm in the experiments section of the paper:

Algorithm 2 FED-EF-ZO-SGD

Input: Number of time steps $T \in \mathbb{Z}^+$, number of agents $N \in \mathbb{Z}^+$, smoothing parameter $\mu \in \mathbb{R}$, initial agent positions $x_0^{1:N} \in \mathbb{R}^{Nd}$, learning rate $\eta \in \mathbb{R}$, sequence of target positions $\left\{z^{1:N}\right\}_{t=1}^{T} \subset \mathbb{R}^{Nd}$.

Output: Sequence of optimal target positions $\left\{x^{1:N}\right\}_{t=1}^{T} \subset \mathbb{R}^{Nd}$.

for $i = 1, \ldots, N$ **do**
  $e_0^i = 0$
end for
for $t = 1, \ldots, T$ **do**
  Runs on each agent:
  for $i = 1, \ldots, N$ **do**
    $u_t^i \sim \mathcal{N}(0, I_{Nd})$
    $\tilde{g}_{\mu,t}^i(x_t^{1:N}) = \dfrac{\tilde{\ell}_t^i(x_t^{1:N} + \mu u_t^i) - \tilde{\ell}_t^i(x_t^{1:N})}{\mu} u_t^i$
    $p_t^i = \tilde{g}_{\mu,t}^i(x_t^{1:N}) + e_t^i$
    $e_{t+1}^i = p_t^i - \mathcal{C}(p_t^i)$
    transmit_to_server $\left(\mathcal{C}(p_t^i)\right)$
  end for
  Runs on the server:
  $\mathcal{G}_t = \frac{1}{N}\sum_{i=1}^{N} \mathcal{C}(p_t^i)$
  $x_{t+1}^{1:N} = x_t^{1:N} - \eta \mathcal{G}_t$
  transmit_to_clients $\left(x_{t+1}^{1:N}\right)$
end for

We assume in the following that $z_t^{1:N} \in \mathbb{R}^{Nd}$ are *i.i.d.* random variables for all $t \in \mathbb{Z}^+$. Similar to the analysis in the single-agent case, we begin by defining:

$$\bar{e}_t := \frac{1}{N}\sum_{i=1}^{N} e_t^i, \tag{41}$$

and

$$\tilde{x}_t^{1:N} := x_t^{1:N} - \eta \bar{e}_t. \tag{42}$$

Additionally, our global loss function in this scenario is:

$$\bar{\tilde{\ell}}_t \left(x_t^{1:N}\right) = \frac{1}{N}\sum_{i=1}^{N} \tilde{\ell}_t^i \left(x_t^{1:N}\right) \tag{43}$$

Now, we have:

$$
\begin{aligned}
\tilde{x}_{t+1}^{1:N} &= x_{t+1}^{1:N} - \eta \bar{e}_{t+1} \\
&= x_{t+1}^{1:N} - \eta \frac{1}{N} \sum_{i=1}^{N} \left[p_t^i - \mathcal{C}\left(p_t^i\right) \right] \\
&= x_t^{1:N} - \eta \mathcal{G}_t - \eta \frac{1}{N} \sum_{i=1}^{N} \left[p_t^i - \mathcal{C}\left(p_t^i\right) \right] \\
&= x_t^{1:N} - \eta \frac{1}{N} \sum_{i=1}^{N} p_t^i \\
&= x_t^{1:N} - \eta \frac{1}{N} \sum_{i=1}^{N} \left[\tilde{g}_{\mu,t}^i \left(x_t^{1:N}\right) + e_t^i \right] \\
&= \tilde{x}_t^{1:N} - \eta \bar{\tilde{g}}_{\mu,t}\left(x_t^{1:N}\right),
\end{aligned} \tag{44}
$$

where we define $\bar{\tilde{g}}_{\mu,t}(x_t^{1:N}) := \frac{1}{N}\sum_{i=1}^{N} \tilde{g}_{\mu,t}^i\left(x_t^{1:N}\right)$. Now, we have by Assumption 3 that each ℓ_t^i is $L-$smooth, therefore, our global loss function $\bar{\ell}_t$ is also $L-$smooth. Using Lemma 1, we write

$$
\bar{\ell}_{\mu,t}\left(\tilde{x}_{t+1}^{1:N}\right) \leq \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right) + \left\langle \nabla \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right), \tilde{x}_{t+1}^{1:N} - \tilde{x}_t^{1:N} \right\rangle + \frac{L}{2}\left\| \tilde{x}_{t+1}^{1:N} - \tilde{x}_t^{1:N} \right\|^2. \tag{45}
$$

By Assumption 6, this implies

$$
\bar{\ell}_{\mu,t+1}\left(\tilde{x}_{t+1}^{1:N}\right) \leq \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right) - \eta \left\langle \bar{\tilde{g}}_{\mu,t}\left(x_t^{1:N}\right), \nabla \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right) \right\rangle + \frac{L\eta^2}{2}\left\| \bar{\tilde{g}}_{\mu,t}\left(x_t^{1:N}\right) \right\|^2 + \omega_t, \tag{46}
$$

where $\omega_t = \max\{w_t^1, ..., w_t^N\}$. Now, since we have

$$
\mathbb{E}_{u_t^{1:N}}\left[\bar{\tilde{g}}_{\mu,t}\left(x_t^{1:N}\right)\right] = \mathbb{E}_{u_t^{1:N}}\left[\frac{1}{N}\sum_{i=1}^{N} \tilde{g}_{\mu,t}^i\left(x_t^{1:N}\right)\right] = \frac{1}{N}\sum_{i=1}^{N} \nabla \tilde{\ell}_{\mu,t}^i\left(x_t^{1:N}\right) = \nabla \bar{\tilde{\ell}}_{\mu,t}\left(x_t^{1:N}\right), \tag{47}
$$

the following holds:

$$
\begin{aligned}
\mathbb{E}_{u_t^{1:N}, z_t^{1:N}}\left[\left\langle \bar{\tilde{g}}_{\mu,t}\left(x_t^{1:N}\right), \nabla \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right)\right\rangle\right] &= \left\langle \nabla \bar{\ell}_{\mu,t}\left(x_t^{1:N}\right), \nabla \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right)\right\rangle \\
&= \frac{1}{2}\left\|\nabla \bar{\ell}_{\mu,t}\left(x_t^{1:N}\right)\right\|^2 + \frac{1}{2}\left\|\nabla \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right)\right\|^2 \\
&\quad - \frac{1}{2}\left\|\nabla \bar{\ell}_{\mu,t}\left(x_t^{1:N}\right) - \nabla \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right)\right\|^2,
\end{aligned} \tag{48}
$$

since $\mathbb{E}_{z_t^{1:N}}[\nabla \bar{\tilde{\ell}}(x_t^{1:N})] = \nabla \bar{\ell}(x_t^{1:N})$. Now, combining this with (46) and using $L-$smoothness, we obtain:

$$
\begin{aligned}
\bar{\ell}_{\mu,t+1}\left(\tilde{x}_{t+1}^{1:N}\right) &\leq \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right) - \frac{\eta}{2}\left\|\nabla \bar{\ell}_{\mu,t}\left(x_t^{1:N}\right)\right\|^2 - \frac{\eta}{2}\left\|\nabla \bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right)\right\|^2 \\
&\quad + \frac{L^2\eta}{2}\left\|x_t^{1:N} - \tilde{x}_t^{1:N}\right\|^2 + \frac{L\eta^2}{2}\mathbb{E}_{u_t^{1:N}, z_t^{1:N}}\left[\left\|\bar{\tilde{g}}_{\mu,t}\left(x_t^{1:N}\right)\right\|^2\right] + \omega_t
\end{aligned} \tag{49}
$$

Note that third term at the right side of the inequality can be dropped because it is negative or zero. Using the definition of $\tilde{x}_t^{1:N}$, and taking the expectation of both sides with respect to $u_t^{1:N}$

and $z_t^{1:N}$, we have the following main inequality:

$$\underbrace{\frac{\eta}{2}\left\|\nabla\bar{\ell}_{\mu,t}\left(x_t^{1:N}\right)\right\|^2}_{\text{Term I}} \leq \underbrace{\left[\bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right)-\bar{\ell}_{\mu,t+1}\left(\tilde{x}_{t+1}^{1:N}\right)\right]}_{\text{Term II}} + \underbrace{\frac{L\eta^2}{2}\mathbb{E}_{u_t^{1:N},z_t^{1:N}}\left[\left\|\bar{\tilde{g}}_{\mu,t}\left(x_t^{1:N}\right)\right\|^2\right]}_{\text{Term III}} + \underbrace{\frac{L^2\eta^3}{2}\|\bar{e}_t\|^2}_{\text{Term IV}} + \omega_t. \tag{50}$$

We will continue the proof by putting an upper bound to terms I, II, and IV and a lower bound to term III. Starting with **term III**, using Jensen's inequality we get

$$\mathbb{E}_{u_t^{1:N},z_t^{1:N}}\left[\left\|\bar{\tilde{g}}_{\mu,t}(x_t^{1:N})\right\|^2\right] = \mathbb{E}_{u_t^{1:N},z_t^{1:N}}\left[\left\|\frac{1}{N}\sum_{i=1}^N \tilde{g}_{\mu,t}^i(x_t^{1:N})\right\|^2\right] \leq \frac{1}{N}\sum_{i=1}^N \mathbb{E}_{u_t^{1:N},z_t^{1:N}}\left[\left\|\tilde{g}_{\mu,t}^i(x_t^{1:N})\right\|^2\right] \tag{51}$$

Then, by Lemma 5 we know

$$\mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N}}\left[\|\tilde{g}_{\mu,t}^i(x_t^{1:N})\|^2\right] \leq 2(d+4)\mathbb{E}_{z_{1:T}}\left[\|\nabla\tilde{\ell}_t^i(x_t^{1:N})\|^2\right] + \frac{\mu^2L^2}{2}(d+6)^3. \tag{52}$$

Using Assumption 5, we have $\mathbb{E}_{z_{1:T}}[\|\nabla\tilde{\ell}_t^i(x_t^{1:N})\|^2] \leq M\mathbb{E}_{z_{1:T}}\left[\|\nabla\ell_t^i(x_t^{1:N})\|^2\right] + \sigma^2$. Lastly, using Young's inequality and Assumption 7, we have

$$\begin{aligned}\mathbb{E}_{z_{1:T}}[\|\nabla\ell_t^i(x_t^{1:N})\|^2] &\leq \mathbb{E}_{z_{1:T}}[\|\nabla\ell_t^i(x_t^{1:N})-\nabla\bar{\ell}_t(x_t^{1:N})\|^2] + \mathbb{E}_{z_{1:T}}[\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2] \\ &\leq Z^2 + \mathbb{E}_{z_{1:T}}[\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2]\end{aligned} \tag{53}$$

For **term II**, if we do a summation on both sides of (50) from $t=1$ to T, we get a telescoping sum:

$$\sum_{t=1}^T\left[\bar{\ell}_{\mu,t}\left(\tilde{x}_t^{1:N}\right)-\bar{\ell}_{\mu,t+1}\left(\tilde{x}_{t+1}^{1:N}\right)\right] = \bar{\ell}_{\mu,1}\left(\tilde{x}_1^{1:N}\right)-\bar{\ell}_{\mu,T+1}\left(\tilde{x}_{T+1}^{1:N}\right). \tag{54}$$

By adding and subtracting $\bar{\ell}_1(\tilde{x}_1^{1:N})$ and $\bar{\ell}_{T+1}(\tilde{x}_{T+1}^{1:N})$ to both sides and using Lemma 3, we have:

$$\begin{aligned}\bar{\ell}_{\mu,1}\left(\tilde{x}_1^{1:N}\right)-\bar{\ell}_{\mu,T+1}\left(\tilde{x}_{T+1}^{1:N}\right) &\leq \mu^2Ld + \bar{\ell}_1(x_1^{1:N}) - \bar{\ell}_{T+1}(\tilde{x}_{T+1}^{1:N}). \\ &\leq \mu^2Ld + \bar{\ell}_1(x_1^{1:N}) - \bar{\ell}_{T+1}(x_{T+1}^*) \\ &= \mu^2Ld + \Delta,\end{aligned} \tag{55}$$

where $x_{T+1}^* = \arg\min_x \min_{i=\{1,\dots,N\}} \ell_{T+1}^i(x)$ and $\Delta = \bar{\ell}_1(x_1^{1:N}) - \bar{\ell}_{T+1}(x_{T+1}^*)$. Note that we use $\tilde{x}_1^{1:N} = x_1^{1:N}$. For **term I**, one should note that if $\ell_t^i(x)\in C_L^{1,1}$, then $\ell_{\mu,t}^i(x)\in C_L^{1,1}$ by Lemma 1. This implies that $\bar{\ell}_{\mu,t}(x)\in C_L^{1,1}$ because $\bar{\ell}_{\mu,t}(x) = \frac{1}{N}\sum_{i=1}^N \ell_{\mu,t}^i(x)$. Thus, using Lemma 4 and 6, we get

$$\frac{1}{2}\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2 - \frac{\mu^2L^2(d+3)^2}{4} \leq \|\nabla\bar{\ell}_{\mu,t}(x_t^{1:N})\|^2. \tag{56}$$

Finally, for **term IV**, we use the similar recursive summation. We want to put an upper bound to $\|\bar{e}_t\|^2$. We can do so by taking the expectation of both sides in (50) with respect to $u_{1:T}^{1:N}, z_{1:T}^{1:N}, C_{1:T}$ and put an upper bound to $\mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\|\bar{e}_t\|^2\right]$ instead. By Jensen's inequality, we can do the following:

$$\begin{aligned}\mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\|\bar{e}_t\|^2\right] = \mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\left\|\frac{1}{N}\sum_{i=1}^N e_t^i\right\|^2\right] &\leq \mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\frac{1}{N}\sum_{i=1}^N \left\|e_t^i\right\|^2\right] \\ &= \frac{1}{N}\sum_{i=1}^N \mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\|e_t^i\|^2\right]\end{aligned} \tag{57}$$

Note that putting an upper bound to the terms inside summation is nothing but putting an upper bound to the single-agent case, which we have done in EF-ZO-SGD Convergence Analysis for Single-Agent. Hence, we know

$$\mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\|e_{t-1}^i\|^2\right] \leq \sum_{j=1}^{t-1}[(1-\delta)(1+\varphi)]^{t-1-j}(1-\delta)\left(1+\frac{1}{\varphi}\right)\left[A\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_j^i(x_j^{1:N})\|^2\right]+B\right]. \tag{58}$$

Using this fact in (57), we obtain

$$\mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\|e_t^{1:N}\|^2\right] \leq \frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{t-1}[(1-\delta)(1+\varphi)]^{t-1-j}(1-\delta)\left(1+\frac{1}{\varphi}\right)\left[A\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_j^i(x_j^{1:N})\|^2\right]+B\right]. \tag{59}$$

Using the same procedure in (28), if we sum both sides through $t=1$ to $t=T$, we get the following inequality:

$$\sum_{t=1}^{T}\mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\|e_t^{1:N}\|^2\right] \leq \frac{1}{N}\sum_{i=1}^{N}\sum_{t=1}^{T}\left[A\mathbb{E}_{z_{1:T}}\|\nabla \ell_t^i(x_t^{1:N})\|^2+B\right]C, \tag{60}$$

where $A=2M(d+4), B=2\sigma^2(d+4)+\frac{\mu^2L^2(d+6)^3}{2}$ and $C=\frac{4(1-\delta)}{\delta^2}\leq\frac{4}{\delta^2}$. Another way of expressing 60 is:

$$\sum_{t=1}^{T}\mathbb{E}_{u_{1:T}^{1:N},z_{1:T}^{1:N},C_{1:T}}\left[\|e_t^{1:N}\|^2\right] \leq \sum_{t=1}^{T}\left[A\left(\frac{1}{N}\sum_{i=1}^{N}\mathbb{E}_{z_{1:T}}\|\nabla \ell_t^i(x_t^{1:N})\|^2\right)+B\right]C. \tag{61}$$

We need to put an upper bound to $\frac{1}{N}\sum_{i=1}^{N}\mathbb{E}_{z_{1:T}}\|\nabla \ell_t^i(x_t^{1:N})\|^2$ such that we will have $\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2$. Then, we can do the following:

$$\begin{aligned}\frac{1}{N}\sum_{i=1}^{N}\mathbb{E}_{z_{1:T}}\|\nabla \ell_t^i(x_t^{1:N})\|^2 &\leq \frac{1}{N}\sum_{i=1}^{N}\mathbb{E}_{z_{1:T}}\|\nabla \ell_t^i(x_t^{1:N})-\nabla\bar{\ell}_t(x_t^{1:N})+\nabla\bar{\ell}_t(x_t^{1:N})\|^2\\ &\leq \frac{2}{N}\sum_{i=1}^{N}\mathbb{E}_{z_{1:T}}\left[\|\nabla \ell_t^i(x_t^{1:N})-\nabla\bar{\ell}_t(x_t^{1:N})\|^2\right]+\frac{2}{N}\sum_{i=1}^{N}\mathbb{E}_{z_{1:T}}\left[\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2\right]\end{aligned} \tag{62}$$

and in the last step we used Young's inequality. Lastly, using Assumption 7, we get

$$\frac{1}{N}\sum_{i=1}^{N}\mathbb{E}_{z_{1:T}}\|\nabla \ell_t^i(x_t^{1:N})\|^2 \leq 2Z^2+2\mathbb{E}_{z_{1:T}}\left[\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2\right]. \tag{63}$$

where $C=\frac{2(1-\delta)}{\delta}\frac{2}{\delta}\leq\frac{4}{\delta^2}$. If we define $\Delta := \ell_1(x_1)-\ell_{T+1}(x_{T+1}^*)$ and combine the upper bounds derived for Term II, III and IV, and the lower bound derived for Term I and plug them into (50) we get the following:

$$\begin{aligned}
&\sum_{t=1}^{T}\frac{\eta}{4}\mathbb{E}_{z_{1:T}}\left[\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2\right]-\frac{\eta\mu^2L^2}{8}(d+3)^3T\\
&\quad\leq \mu^2Ld+\Delta+\frac{T\mu^2L^3\eta^2}{4}(d+6)^3+\frac{L\eta^2}{2}\sigma^2T\times 2(d+4)\\
&\quad+\frac{L\eta^2}{2}\times 2M(d+4)\left(ZT+\sum_{t=1}^{T}\mathbb{E}_{z_{1:T}}\left[\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2\right]\right)+\frac{\eta^3L^2}{2}\times\frac{4}{\delta^2}T\left[2\sigma^2(d+4)+\frac{\mu^2L^2}{2}(d+6)^3\right]\\
&\quad+\frac{\eta^3L^2}{2}\times\frac{4}{\delta^2}\sum_{t=1}^{T}2M(d+4)\left(2Z+2\mathbb{E}_{z_{1:T}}\left[\|\nabla\bar{\ell}_t(x_t^{1:N})\|^2\right]\right)+\sum_{t=1}^{T}\omega_t.
\end{aligned}\tag{64}$$

Now, since z_t's are *i.i.d.* for all $t\in\mathbb{Z}^+$, we have:

$$\begin{aligned}
\frac{E}{T}\sum_{t=1}^{T}\mathbb{E}_{z_{1:T}}\left[\|\nabla\bar{\ell}_t(x_t)\|^2\right]\leq\ &\frac{\mu^2Ld+\Delta}{T}+\frac{\eta^2L^3\mu^2(d+6)^3}{4}+L\eta^2\sigma^2(d+4)+\frac{\eta\mu^2L^2(d+3)^3}{8}\\
&+\frac{\eta^3L^2}{\delta^2}4\sigma^2(d+4)+\frac{\eta^3L^2}{\delta^2}\mu^2L^2(d+6)^3+\frac{1}{T}\sum_{t=1}^{T}\omega_t+L\eta^2M(d+4)Z\\
&+\frac{2\eta^3L^2}{\delta^2}4MZ(d+4)
\end{aligned}\tag{65}$$

where

$$\begin{aligned}
E&=\frac{\eta}{4}-LM\eta^2(d+4)-\frac{L^2\eta^3}{\delta^2}8M(d+4)\\
&=\eta\left[\frac{1}{4}-LM\eta(d+4)\left(1+\frac{8L\eta}{\delta^2}\right)\right].
\end{aligned}\tag{66}$$

If $\eta\leq\frac{1}{8L}$, instead first upper bound will be:

$$1+\frac{8L\eta}{\delta^2}\leq 1+\frac{1}{\delta^2}=\frac{\delta^2+1}{\delta^2}\leq\frac{2}{\delta^2}.\tag{67}$$

We proceed to find an η such that

$$\frac{2}{\delta^2}LM\eta(d+4)\leq\frac{1}{8}.\tag{68}$$

Then, we get

$$\eta\leq\frac{\delta^2}{16LM(d+4)},\tag{69}$$

which implies $E \geq \frac{\eta}{8}$. Multiplying all terms in the bound by $\frac{8}{\eta}$,

$$\begin{aligned}\frac{1}{T}\sum_{t=1}^{T}\mathbb{E}_{z_{1:T}}\left[\|\nabla\bar{\ell}_t(x_t)\|^2\right] \leq& \frac{8\Delta}{(\eta T)} + \frac{8\mu^2 Ld}{\eta T} + 2\eta L^3\mu^2(d+6)^3 \\ &+ 8L\eta\sigma^2(d+4) + \mu^2L^2(d+3)^3 \\ &+ \frac{32\eta^2L^2}{\delta^2}\sigma^2(d+4) + \frac{8\eta^2L^4\mu^2(d+6)^3}{\delta^2} + \frac{8}{\eta T}\sum_{t=1}^{T}\omega_t \\ &+ 8L\eta M(d+4)Z + \frac{16\eta^2L^2}{\delta^2}4MZ(d+4).\end{aligned} \tag{70}$$

Let

$$\eta = \frac{1}{\sigma\sqrt{(d+4)MTL}} \quad \text{and} \quad \mu = \frac{1}{(d+4)\sqrt{T}}. \tag{71}$$

Defining $\bar{\omega} := \sum_{t=1}^{T}\omega_t$, the number of times steps T to obtain a ξ-first order solution is

$$T = \mathcal{O}\left(\frac{dML(\sigma^2\Delta + \sigma^2\bar{\omega} + Z^4)}{\xi^2} + \frac{L(d\Delta + Z^2)}{\delta^2\xi}\right). \tag{72}$$

References

[1] S. P. Karimireddy, Q. Rebjock, S. U. Stich, and M. Jaggi, "Error feedback fixes signsgd and other gradient compression schemes," 2019.