Distributed Distributionally Robust Optimization with Non-Convex Objectives

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Abstract

Distributionally Robust Optimization (DRO), which aims to find an optimal decision that minimizes the worst case cost over the ambiguity set of probability distribution, has been widely applied in diverse applications, *e.g.*, network behavior analysis, risk management, *etc.* However, existing DRO techniques face three key challenges: 1) how to deal with the asynchronous updating in a distributed environment; 2) how to leverage the prior distribution effectively; 3) how to properly adjust the degree of robustness according to different scenarios. To this end, we propose an asynchronous distributed algorithm, named **A**synchronous **S**ingle-loo**P** alternat**I**ve g**R**adient proj**E**ction (ASPIRE) algorithm with the it**E**rative **A**ctive **SE**t method (EASE) to tackle the distributed distributionally robust optimization (DDRO) problem. Furthermore, a new uncertainty set, *i.e.*, constrained D-norm uncertainty set, is developed to effectively leverage the prior distribution and flexibly control the degree of robustness. Finally, our theoretical analysis elucidates that the proposed algorithm is guaranteed to converge and the iteration complexity is also analyzed. Extensive empirical studies on real-world datasets demonstrate that the proposed method can not only achieve fast convergence, and remain robust against data heterogeneity as well as malicious attacks, but also tradeoff robustness with performance.

1 Introduction

The past decade has witnessed the proliferation of smartphones and Internet of Things (IoT) devices, which generate a plethora of data everyday. Centralized machine learning requires gathering the data to a particular server to train models which incurs high communication overhead [46] and suffers privacy risks [43]. As a remedy, distributed machine learning methods have been proposed. Considering a distributed system composed of N workers (devices), we denote the dataset of these workers as $\{D_1, \cdots, D_N\}$. For the j^{th} $(1 \le j \le N)$ worker, the labeled dataset is given as $D_j = \{\mathbf{x}_j^i, y_j^i\}$, where $\mathbf{x}_j^i \in \mathbb{R}^d$ and $y_j^i \in \{1, \cdots, c\}$ denote the i^{th} data sample and the corresponding label, respectively. The distributed learning tasks can be formulated as the following optimization problem,

$$\min_{\boldsymbol{w} \in \boldsymbol{\mathcal{W}}} F(\boldsymbol{w}) \quad \text{with} \quad F(\boldsymbol{w}) := \sum\nolimits_j f_j(\boldsymbol{w}), \tag{1}$$

where $\boldsymbol{w} \in \mathbb{R}^p$ is the model parameter to be learned and $\boldsymbol{\mathcal{W}} \subseteq \mathbb{R}^p$ is a nonempty closed convex set, $f_j(\cdot)$ is the empirical risk over the j^{th} worker involving only the local data:

$$f_j(\boldsymbol{w}) = \sum\nolimits_{i: \mathbf{x}_j^i \in D_j} \frac{1}{|D_j|} \mathcal{L}_j(\mathbf{x}_j^i, y_j^i; \boldsymbol{w}), \tag{2}$$

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36th Conference on Neural Information Processing Systems (NeurIPS 2022).

where $\mathcal{L}_j$ is the local objective function over the j^{th} worker. Problem in Eq. (1) arises in numerous areas, such as distributed signal processing [19], multi-agent optimization [36], *etc*. However, such problem does not consider the data heterogeneity [57, 40, 39, 30] among different workers (*i.e.*, data distribution of workers could be substantially different from each other [44]). Indeed, it has been shown that traditional federated approaches, such as FedAvg [33], built for independent and identically distributed (IID) data may perform poorly when applied to Non-IID data [27]. This issue can be mitigated via learning a robust model that aims to achieve uniformly good performance over all workers by solving the following distributionally robust optimization (DRO) problem in a distributed manner:

$$\min_{\boldsymbol{w}\in\boldsymbol{\mathcal{W}}} \max_{\mathbf{p}\in\boldsymbol{\Omega}\subseteq\Delta_N} F(\boldsymbol{w},\mathbf{p}) := \sum\nolimits_j p_j f_j(\boldsymbol{w}), \tag{3}$$

where $\mathbf{p} = [p_1, \cdots, p_N] \in \mathbb{R}^N$ is the adversarial distribution in N workers, the j^{th} entry in this vector, *i.e.*, p_j represents the adversarial distribution value for the j^{th} worker. $\Delta_N = \{\mathbf{p} \in \mathbb{R}_+^N : \mathbf{1}^\top \mathbf{p} = 1\}$ and $\boldsymbol{\Omega}$ is a subset of Δ_N. Agnostic federated learning (AFL) [35] firstly introduces the distributionally robust (agnostic) loss in federated learning and provides the convergence rate for (strongly) convex functions. However, AFL does not discuss the setting of $\boldsymbol{\Omega}$. DRFA-Prox [16] considers $\boldsymbol{\Omega} = \Delta_N$ and imposes a regularizer on adversarial distribution to leverage the prior distribution. Nevertheless, three key challenges have not yet been addressed by prior works. First, whether it is possible to construct an uncertainty framework that can not only flexibly maintain the trade-off between the model robustness and performance but also effectively leverage the prior distribution? Second, how to design asynchronous algorithms with guaranteed convergence? Compared to synchronous algorithms, the master in asynchronous algorithms can update its parameters after receiving updates from only a small subset of workers [58, 10]. Asynchronous algorithms are particularly desirable in practice since they can relax strict data dependencies and ensure convergence even in the presence of device failures [58]. Finally, whether it is possible to flexibly adjust the degree of robustness? Moreover, it is necessary to provide convergence guarantee when the objectives (*i.e.*, $f_j(\boldsymbol{w}_j), \forall j$) are non-convex.

To this end, we propose ASPIRE-EASE to effectively address the aforementioned challenges. Firstly, different from existing works, the prior distribution is incorporated within the constraint in our formulation, which can not only leverage the prior distribution more effectively but also achieve guaranteed feasibility for any adversarial distribution within the uncertainty set. The prior distribution can be obtained from side information or uniform distribution [41], which is necessary to construct the uncertainty (ambiguity) set and obtain a more robust model [16]. Specifically, we formulate the prior distribution informed distributionally robust optimization (PD-DRO) problem as:

$$\begin{aligned} &\min_{\boldsymbol{z}\in\boldsymbol{\mathcal{Z}},\{\boldsymbol{w}_j\in\boldsymbol{\mathcal{W}}\}} \max_{\mathbf{p}\in\boldsymbol{\mathcal{P}}} \sum\nolimits_j p_j f_j(\boldsymbol{w}_j) \\ &\text{s.t.} \quad \boldsymbol{z} = \boldsymbol{w}_j,\ j = 1,\cdots,N, \\ &\text{var.} \quad \boldsymbol{z}, \boldsymbol{w}_1, \boldsymbol{w}_2, \cdots, \boldsymbol{w}_N, \end{aligned} \tag{4}$$

where $\boldsymbol{z} \in \mathbb{R}^p$ is the global consensus variable, $\boldsymbol{w}_j \in \mathbb{R}^p$ is the local variable (local model parameter) of j^{th} worker and $\boldsymbol{\mathcal{Z}} \subseteq \mathbb{R}^p$ is a nonempty closed convex set. $\boldsymbol{\mathcal{P}} \subseteq \mathbb{R}_+^N$ is the uncertainty (ambiguity) set of adversarial distribution $\mathbf{p}$, which is set based on the prior distribution. To solve the PD-DRO problem in an asynchronous distributed manner, we first propose **A**synchronous **S**ingle-loo**P** alternat**I**ve g**R**adient proj**E**ction (ASPIRE), which employs *simple* gradient projection steps for the update of primal and dual variables at every iteration, thus is computationally *efficient*. Next, the it**E**rative **A**ctive **SE**t method (EASE) is employed to replace the traditional cutting plane method to improve the computational efficiency and speed up the convergence. We further provide the convergence guarantee for the proposed algorithm. Furthermore, a new uncertainty set, *i.e.*, constrained D-norm (CD-norm), is proposed in this paper and its advantages include: 1) it can flexibly control the degree of robustness; 2) the resulting subproblem is computationally simple; 3) it can effectively leverage the prior distribution and flexibly set the bounds for every p_j.

Contributions. Our contributions can be summarized as follows:

1. We formulate a PD-DRO problem with CD-norm uncertainty set. PD-DRO incorporates the prior distribution as constraints which can leverage prior distribution more effectively and guarantee robustness. In addition, CD-norm is developed to model the ambiguity set around the prior distribution and it provides a flexible way to control the trade-off between model robustness and performance.

2. We develop a *single-loop asynchronous* algorithm, namely ASPIRE-EASE, to optimize PD-DRO in an asynchronous distributed manner. ASPIRE employs simple gradient projection steps to update the variables at every iteration, which is computationally efficient. And EASE is proposed to replace cutting plane method to enhance the computational efficiency and speed up the convergence. We demonstrate that even if the objectives $f_j(\boldsymbol{w}_j), \forall j$ are non-convex, the proposed algorithm is guaranteed to converge. We also theoretically derive the iteration complexity of ASPIRE-EASE.

3. Extensive empirical studies on four different real world datasets demonstrate the superior performance of the proposed algorithm. It is seen that ASPIRE-EASE can not only ensure the model's robustness against data heterogeneity but also mitigate malicious attacks.

2 Preliminaries

2.1 Distributionally Robust Optimization

Optimization problems often contain uncertain parameters. A small perturbation of the parameters could render the optimal solution of the original optimization problem infeasible or completely meaningless [5]. Distributionally robust optimization (DRO) [28, 17, 7] assumes that the probability distributions of uncertain parameters are unknown but remain in an ambiguity (uncertainty) set and aims to find a decision that minimizes the worst case expected cost over the ambiguity set, whose general form can be expressed as,

$$\min_{\boldsymbol{x}\in\boldsymbol{\mathcal{X}}} \max_{P\in\mathbf{P}} \mathbb{E}_P[r(\boldsymbol{x},\boldsymbol{\xi})], \tag{5}$$

where $\boldsymbol{x} \in \boldsymbol{\mathcal{X}}$ represents the decision variable, $\mathbf{P}$ is the ambiguity set of probability distributions P of uncertain parameters $\boldsymbol{\xi}$. Existing methods for solving DRO can be broadly grouped into two widely-used categories [42]: 1) Dual methods [15, 50, 18] reformulate the primal DRO problems as deterministic optimization problems through duality theory. Ben-Tal et al. [2] reformulate the robust linear optimization (RLO) problem with an ellipsoidal uncertainty set as a second-order cone optimization problem (SOCP). 2) Cutting plane methods [34, 6] (also called adversarial approaches [21]) continuously solve an approximate problem with a finite number of constraints of the primal DRO problem, and subsequently check whether new constraints are needed to refine the feasible set. Recently, several new methods [41, 29, 23] have been developed to solve DRO, which need to solve the inner maximization problem at every iteration.

2.2 Cutting Plane Method for PD-DRO

In this section, we introduce the cutting plane method for PD-DRO in Eq. (4). We first reformulate PD-DRO by introducing an additional variable $h \in \boldsymbol{\mathcal{H}}$ ($\boldsymbol{\mathcal{H}} \subseteq \mathbb{R}^1$ is a nonempty closed convex set) and protection function $g(\{\boldsymbol{w}_j\})$ [55]. Introducing additional variable h is an epigraph reformulation [3, 56]. In this case, Eq. (4) can be reformulated as the form with uncertainty in the constraints:

$$\begin{aligned} &\min_{\boldsymbol{z}\in\boldsymbol{\mathcal{Z}},\{\boldsymbol{w}_j\in\boldsymbol{\mathcal{W}}\},h\in\boldsymbol{\mathcal{H}}} \quad h \\ &\text{s.t.} \ \sum\nolimits_j \overline{p} f_j(\boldsymbol{w}_j) + g(\{\boldsymbol{w}_j\}) - h \leq 0, \\ &\qquad \boldsymbol{z} = \boldsymbol{w}_j, \ j = 1,\cdots,N, \\ &\text{var.} \quad \boldsymbol{z}, \boldsymbol{w}_1, \boldsymbol{w}_2, \cdots, \boldsymbol{w}_N, h, \end{aligned} \tag{6}$$

where $\overline{p}$ is the nominal value of the adversarial distribution for every worker and $g(\{\boldsymbol{w}_j\}) = \max\limits_{\mathbf{p}\in\boldsymbol{\mathcal{P}}} \sum_j (p_j - \overline{p}) f_j(\boldsymbol{w}_j)$ is the protection function. Eq. (6) is a semi-infinite program (SIP) which contains infinite constraints and cannot be solved directly [42]. Denoting the set of cutting plane parameters in $(t+1)^{\text{th}}$ iteration as $\mathbf{A}^t \subseteq \mathbb{R}^N$, the following function is used to approximate $g(\{\boldsymbol{w}_j\})$:

$$\overline{g}(\{\boldsymbol{w}_j\}) = \max_{\boldsymbol{a}_l\in\mathbf{A}^t} \boldsymbol{a}_l^\top \mathbf{f}(\boldsymbol{w}) = \max_{\boldsymbol{a}_l\in\mathbf{A}^t} \sum\nolimits_j a_{l,j} f_j(\boldsymbol{w}_j), \tag{7}$$

where $\boldsymbol{a}_l = [a_{l,1},\cdots,a_{l,N}] \in \mathbb{R}^N$ denotes the parameters of l^{th} cutting plane in $\mathbf{A}^t$ and $\mathbf{f}(\boldsymbol{w}) = [f_1(\boldsymbol{w}_1),\cdots,f_N(\boldsymbol{w}_N)] \in \mathbb{R}^N$. Substituting the protection function $g(\{\boldsymbol{w}_j\})$ with $\overline{g}(\{\boldsymbol{w}_j\})$, we can obtain the following approximate problem:

$$\begin{aligned} &\min_{\boldsymbol{z}\in\boldsymbol{\mathcal{Z}},\{\boldsymbol{w}_j\in\boldsymbol{\mathcal{W}}\},h\in\boldsymbol{\mathcal{H}}} \quad h \\ &\text{s.t.} \ \sum\nolimits_j (\overline{p} + a_{l,j}) f_j(\boldsymbol{w}_j) - h \leq 0, \forall \boldsymbol{a}_l \in \mathbf{A}^t, \\ &\qquad \boldsymbol{z} = \boldsymbol{w}_j, \ j = 1,\cdots,N, \\ &\text{var.} \quad \boldsymbol{z}, \boldsymbol{w}_1, \boldsymbol{w}_2, \cdots, \boldsymbol{w}_N, h. \end{aligned} \tag{8}$$

3 ASPIRE

Distributed optimization is an attractive approach for large-scale learning tasks [54, 8] since it does not require data aggregation, which protects data privacy while also reducing bandwidth requirements [45]. When the neural network models (*i.e.*, $f_j(\boldsymbol{w}_j), \forall j$ are non-convex functions) are used, solving problem in Eq. (8) in a distributed manner facing two challenges: 1) Computing the optimal solution to a non-convex subproblem requires a large number of iterations and therefore is highly computationally intensive if not impossible. Thus, the traditional Alternating Direction Method of Multipliers (ADMM) is ineffective. 2) The communication delays of workers may differ significantly [11], thus, asynchronous algorithms are strongly preferred.

To this end, we propose the **A**synchronous **S**ingle-loo**P** alternat**I**ve g**R**adient proj**E**ction (ASPIRE). The advantages of the proposed algorithm include: 1) ASPIRE uses simple gradient projection steps to update variables in each iteration and therefore it is computationally more efficient than the traditional ADMM method, which seeks to find the optimal solution in non-convex (for $\boldsymbol{w}_j, \forall j$) and convex (for $\boldsymbol{z}$ and h) optimization subproblems every iteration, 2) the proposed asynchronous algorithm does not need strict synchronization among different workers. Therefore, ASPIRE remains resilient against communication delays and potential hardware failures from workers. Details of the algorithm are given below. Firstly, we define the node as master which is responsible for updating the global variable $\boldsymbol{z}$, and we define the node which is responsible for updating the local variable $\boldsymbol{w}_j$ as worker j. In each iteration, the master updates its variables once it receives updates from at least S workers, *i.e.*, active workers, satisfying $1 \leq S \leq N$. $\mathbf{Q}^{t+1}$ denotes the index subset of workers from which the master receives updates during $(t+1)^{\text{th}}$ iteration. We also assume the master will receive updated variables from every worker at least once for each τ iterations. The augmented Lagrangian function of Eq. (8) can be written as:

$$L_p = h + \sum\nolimits_l \lambda_l \Big(\sum\nolimits_j (\overline{p} + a_{l,j}) f_j(\boldsymbol{w}_j) - h\Big) + \sum\nolimits_j \boldsymbol{\phi}_j^\top (\boldsymbol{z} - \boldsymbol{w}_j) + \sum\nolimits_j \frac{\kappa_1}{2} ||\boldsymbol{z} - \boldsymbol{w}_j||^2, \tag{9}$$

where $L_p = L_p(\{\boldsymbol{w}_j\}, \boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\})$, $\lambda_l \in \boldsymbol{\Lambda}, \forall l$ and $\boldsymbol{\phi}_j \in \boldsymbol{\Phi}, \forall j$ represent the dual variables of inequality and equality constraints in Eq. (8), respectively. $\boldsymbol{\Lambda} \subseteq \mathbb{R}^1$ and $\boldsymbol{\Phi} \subseteq \mathbb{R}^p$ are nonempty closed convex sets, constant $\kappa_1 > 0$ is a penalty parameter. Note that Eq. (9) does not consider the second-order penalty term for inequality constraint since it will invalidate the distributed optimization. Following [52], the regularized version of Eq. (9) is employed to update all variables as follows,

$$\widetilde{L}_p(\{\boldsymbol{w}_j\}, \boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\}) = L_p - \sum\nolimits_l \frac{c_1^t}{2} ||\lambda_l||^2 - \sum\nolimits_j \frac{c_2^t}{2} ||\boldsymbol{\phi}_j||^2, \tag{10}$$

where c_1^t and c_2^t denote the regularization terms in $(t+1)^{\text{th}}$ iteration. To avoid enumerating the whole dataset, the mini-batch loss could be used. A batch of instances with size m can be randomly sampled from each worker during each iteration. The loss function of these instances from j^{th} worker is given by $\hat{f}_j(\boldsymbol{w}_j) = \sum\limits_{i=1}^{m} \frac{1}{m} \mathcal{L}_j(\mathbf{x}_j^i, y_j^i; \boldsymbol{w}_j)$. It is evident that $\mathbb{E}[\hat{f}_j(\boldsymbol{w}_j)] = f_j(\boldsymbol{w}_j)$ and $\mathbb{E}[\nabla \hat{f}_j(\boldsymbol{w}_j)] = \nabla f_j(\boldsymbol{w}_j)$. In $(t+1)^{\text{th}}$ master iteration, the proposed algorithm proceeds as follows.

1) *Active workers* update the local variables $\boldsymbol{w}_j$ as follows,

$$\boldsymbol{w}_j^{t+1} = \begin{cases} \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}_j^t - \alpha_{\boldsymbol{w}}^{\widetilde{t}_j} \nabla_{\boldsymbol{w}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^{\widetilde{t}_j}\}, \boldsymbol{z}^{\widetilde{t}_j}, h^{\widetilde{t}_j}, \{\lambda_l^{\widetilde{t}_j}\}, \{\boldsymbol{\phi}_j^{\widetilde{t}_j}\})), \forall j \in \mathbf{Q}^{t+1}, \\ \boldsymbol{w}_j^t, \forall j \notin \mathbf{Q}^{t+1}, \end{cases} \tag{11}$$

where $\widetilde{t}_j$ is the last iteration during which worker j was active. It is seen that $\forall j \in \mathbf{Q}^{t+1}, \boldsymbol{w}_j^t = \boldsymbol{w}_j^{\widetilde{t}_j}$ and $\boldsymbol{\phi}_j^t = \boldsymbol{\phi}_j^{\widetilde{t}_j}$. $\alpha_{\boldsymbol{w}}^{\widetilde{t}_j}$ represents the step-size and let $\alpha_{\boldsymbol{w}}^t = \eta_{\boldsymbol{w}}^t$ when $t < T_1$ and $\alpha_{\boldsymbol{w}}^t = \underline{\eta_{\boldsymbol{w}}}$ when $t \geq T_1$, where $\eta_{\boldsymbol{w}}^t$ and constant $\underline{\eta_{\boldsymbol{w}}}$ will be introduced below. $\mathcal{P}_{\boldsymbol{\mathcal{W}}}$ represents the projection onto the closed convex set $\boldsymbol{\mathcal{W}}$ and we set $\boldsymbol{\mathcal{W}} = \{\boldsymbol{w}_j | \, ||\boldsymbol{w}_j||_\infty \leq \alpha_1\}$, α_1 is a positive constant. And then, the active workers ($j \in \mathbf{Q}^{t+1}$) transmit their local model parameters $\boldsymbol{w}_j^{t+1}$ and loss $f_j(\boldsymbol{w}_j)$ to the master.

2) After receiving the updates from active workers, the *master* updates the global consensus variable $\boldsymbol{z}$, additional variable h and dual variables λ_l as follows,

$$\boldsymbol{z}^{t+1} = \mathcal{P}_{\boldsymbol{\mathcal{Z}}}(\boldsymbol{z}^t - \eta_{\boldsymbol{z}}^t \nabla_{\boldsymbol{z}} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\}, \boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})), \tag{12}$$

$$h^{t+1} = \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\}, \boldsymbol{z}^{t+1}, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})), \tag{13}$$

$$\lambda_l^{t+1} = \mathcal{P}_{\mathbf{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\}, \boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})), \ l = 1, \cdots, |\mathbf{A}^t|, \tag{14}$$

where $\eta_{\boldsymbol{z}}^t$, η_h^t and ρ_1 represent the step-sizes. $\mathcal{P}_{\boldsymbol{\mathcal{Z}}}$, $\mathcal{P}_{\boldsymbol{\mathcal{H}}}$ and $\mathcal{P}_{\mathbf{\Lambda}}$ respectively represent the projection onto the closed convex sets $\boldsymbol{\mathcal{Z}}$, $\boldsymbol{\mathcal{H}}$ and $\mathbf{\Lambda}$. We set $\boldsymbol{\mathcal{Z}} = \{\boldsymbol{z} | \ ||\boldsymbol{z}||_\infty \leq \alpha_1\}$, $\boldsymbol{\mathcal{H}} = \{h | \ 0 \leq h \leq \alpha_2\}$ and $\mathbf{\Lambda} = \{\lambda_l | \ 0 \leq \lambda_l \leq \alpha_3\}$, where α_2 and α_3 are positive constants. $|\mathbf{A}^t|$ denotes the number of cutting planes. Then, master broadcasts $\boldsymbol{z}^{t+1}$, h^{t+1}, $\{\lambda_l^{t+1}\}$ to the active workers.

3) *Active workers* update the local dual variables $\boldsymbol{\phi}_j$ as follows,

$$\boldsymbol{\phi}_j^{t+1} = \begin{cases} \mathcal{P}_{\mathbf{\Phi}}(\boldsymbol{\phi}_j^t + \rho_2 \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\}, \boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^t\})), \forall j \in \mathbf{Q}^{t+1}, \\ \boldsymbol{\phi}_j^t, \forall j \notin \mathbf{Q}^{t+1}, \end{cases} \tag{15}$$

where ρ_2 represents the step-size and $\mathcal{P}_{\mathbf{\Phi}}$ represents the projection onto the closed convex set $\mathbf{\Phi}$ and we set $\mathbf{\Phi} = \{\boldsymbol{\phi}_j | \ ||\boldsymbol{\phi}_j||_\infty \leq \alpha_4\}$, α_4 is a positive constant. And master can also obtain $\{\boldsymbol{\phi}_j^{t+1}\}$ according to Eq. (15). It is seen that the projection operation in each step is computationally simple since the closed convex sets have simple structures [4].

4 Iterative Active Set Method

Cutting plane methods may give rise to numerous linear constraints and lots of extra message passing [55]. Moreover, more iterations are required to obtain the ε-stationary point when the size of a set containing cutting planes increases (which corresponds to a larger M), which can be seen in Theorem 1. To improve the computational efficiency and speed up the convergence, we consider removing the inactive cutting planes. The proposed it**E**rative **A**ctive **SE**t method (EASE) can be divided into the two steps: during T_1 iterations, 1) solving the cutting plane generation subproblem to generate cutting plane, and 2) removing the inactive cutting plane every k iterations, where $k > 0$ is a pre-set constant and can be controlled flexibly.

The cutting planes are generated according to the uncertainty set. For example, if we employ ellipsoid uncertainty set, the cutting plane is generated via solving a SOCP. In this paper, we propose CD-norm uncertainty set, which can be expressed as follows,

$$\boldsymbol{\mathcal{P}} = \{\mathbf{p} : -\widetilde{p}_j \leq p_j - q_j \leq \widetilde{p}_j, \sum\nolimits_j |\frac{p_j - q_j}{\widetilde{p}_j}| \leq \Gamma, \mathbf{1}^\top \mathbf{p} = 1\}, \tag{16}$$

where $\Gamma \in \mathbb{R}^1$ can flexibly control the level of robustness, $\mathbf{q} = [q_1, \cdots, q_N] \in \mathbb{R}^N$ represents the prior distribution, $-\widetilde{p}_j$ and $\widetilde{p}_j$ ($\widetilde{p}_j \geq 0$) represent the lower and upper bounds for $p_j - q_j$, respectively. The setting of $\mathbf{q}$ and $\widetilde{p}_j, \forall j$ are based on the prior knowledge. D-norm is a classical uncertainty set (which is also called as budget uncertainty set) [5]. We call Eq. (16) CD-norm uncertainty set since $\mathbf{p}$ is a probability vector so all the entries of this vector are non-negative and add up to exactly one, *i.e.*, $\mathbf{1}^\top \mathbf{p} = 1$. Due to the special structure of CD-norm, the cutting plane generation subproblem is easy to solve and the level of robustness in terms of the outage probability, *i.e.*, probabilistic bounds of the violations of constraints can be flexibly adjusted via a single parameter Γ. We claim that l_1-norm (or twice total variation distance) uncertainty set is closely related to CD-norm uncertainty set. Nevertheless, there are two differences: 1) CD-norm uncertainty set could be regarded as a weighted l_1-norm with additional constraints. 2) CD-norm uncertainty set can flexibly set the lower and upper bounds for every p_j (*i.e.*, $q_j - \widetilde{p}_j \leq p_j \leq p_j + \widetilde{p}_j$), while $0 \leq p_j \leq 1, \forall j$ in l_1-norm uncertainty set. Based on the CD-norm uncertainty set, the cutting plane can be derived as follows,

1) Solve the following problem,

$$\begin{aligned} \mathbf{p}^{t+1} = \underset{p_1, \cdots, p_N}{\arg\max} & \sum\nolimits_j (p_j - \overline{p}) f_j(\boldsymbol{w}_j) \\ \text{s.t.} \ \sum\nolimits_j |\frac{p_j - q_j}{\widetilde{p}_j}| \leq \Gamma, & \ -\widetilde{p}_j \leq p_j - q_j \leq \widetilde{p}_j, \forall j, \ \sum\nolimits_j p_j = 1 \\ \text{var.} & \quad p_1, \cdots, p_N, \end{aligned} \tag{17}$$

where $\mathbf{p}^{t+1} = [p_1^{t+1}, \cdots, p_N^{t+1}] \in \mathbb{R}^N$. Let $\widetilde{\mathbf{a}}^{t+1} = \mathbf{p}^{t+1} - \overline{\mathbf{p}}$, where $\overline{\mathbf{p}} = [\overline{p}, \cdots, \overline{p}] \in \mathbb{R}^N$. This first step aims to obtain the distribution $\widetilde{\mathbf{a}}^{t+1}$ by solving problem in Eq. (17). This problem can be effectively solved through combining merge sort [13] (for sorting $\widetilde{p}_j f_j(\boldsymbol{w}_j), j = 1, \cdots, N$) with few basic arithmetic operations (for obtaining $p_j^{t+1}, j = 1, \cdots, N$). Since N is relatively large in

Algorithm 1 ASPIRE-EASE

Initialization: iteration $t=0$, variables $\{\boldsymbol{w}_j^0\}$, $\boldsymbol{z}^0$, h^0, $\{\lambda_l^0\}$, $\{\boldsymbol{\phi}_j^0\}$ and set $\mathbf{A}^0$.
repeat
  for *active worker* **do**
    updates local $\boldsymbol{w}_j^{t+1}$ according to Eq. (11);
  end for
  active workers transmit local model parameters and loss to *master*;
  master receives updates from *active workers* **do**
    updates $\boldsymbol{z}^{t+1}$, h^{t+1}, $\{\lambda_l^{t+1}\}$, $\{\boldsymbol{\phi}_j^{t+1}\}$ in master according to Eq. (12), (13), (14), (15);
  master broadcasts $\boldsymbol{z}^{t+1}$, h^{t+1}, $\{\lambda_l^{t+1}\}$ to *active workers*;
  for *active worker* **do**
    updates local $\boldsymbol{\phi}_j^{t+1}$ according to Eq. (15);
  end for
  if $(t+1)$ mod $k==0$ and $t<T_1$ **then**
    master updates $\mathbf{A}^{t+1}$ according to Eq. (19) and (20), and broadcast parameters to all workers;
  end if
  $t=t+1$;
until convergence

distributed system, the arithmetic complexity of solving problem in Eq. (17) is dominated by merge sort, which can be regarded as $\mathcal{O}(N\log(N))$.

2) Let $\mathbf{f}(\boldsymbol{w})=[f_1(\boldsymbol{w}_1),\cdots,f_N(\boldsymbol{w}_N)]\in\mathbb{R}^N$, check the feasibility of the following constraints:

$$\widetilde{\mathbf{a}}^{t+1\top}\mathbf{f}(\boldsymbol{w})\leq\max_{\boldsymbol{a}_l\in\mathbf{A}^t}\boldsymbol{a}_l{}^\top\mathbf{f}(\boldsymbol{w}). \tag{18}$$

3) If Eq. (18) is violated, $\widetilde{\mathbf{a}}^{t+1}$ will be added into $\mathbf{A}^t$:

$$\mathbf{A}^{t+1}=\begin{cases}\mathbf{A}^t\cup\{\widetilde{\mathbf{a}}^{t+1}\},\text{if Eq.(18) is violated,}\\ \mathbf{A}^t,\text{otherwise,}\end{cases} \tag{19}$$

when a new cutting plane is added, its corresponding dual variable $\lambda_{|\mathbf{A}^t|+1}^{t+1}=0$ will be generated. After the cutting plane subproblem is solved, the inactive cutting plane will be removed, that is:

$$\mathbf{A}^{t+1}=\begin{cases}\complement_{\mathbf{A}^{t+1}}\{\boldsymbol{a}_l\},\text{if }\lambda_l^{t+1}=0\text{ and }\lambda_l^t=0,1\leq l\leq|\mathbf{A}^t|,\\ \mathbf{A}^{t+1},\text{otherwise,}\end{cases} \tag{20}$$

where $\complement_{\mathbf{A}^{t+1}}\{\boldsymbol{a}_l\}$ is the complement of $\{\boldsymbol{a}_l\}$ in $\mathbf{A}^{t+1}$, and the dual variable will be removed. Then master broadcasts $\mathbf{A}^{t+1}$, $\{\lambda_l^{t+1}\}$ to all workers. Details of algorithm are summarized in Algorithm 1.

5 Convergence Analysis

Definition 1 (Stationarity gap) *Following [52, 32, 53], the stationarity gap of our problem at t^{th} iteration is defined as:*

$$\nabla G^t=\begin{bmatrix}\{\frac{1}{\alpha_{\boldsymbol{w}}^t}(\boldsymbol{w}_j^t-\mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}_j^t-\alpha_{\boldsymbol{w}}^t\nabla_{\boldsymbol{w}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})))\}\\ \frac{1}{\eta_{\boldsymbol{z}}^t}(\boldsymbol{z}^t-\mathcal{P}_{\boldsymbol{\mathcal{Z}}}(\boldsymbol{z}^t-\eta_{\boldsymbol{z}}^t\nabla_{\boldsymbol{z}}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})))\\ \frac{1}{\eta_h^t}(h^t-\mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t-\eta_h^t\nabla_h L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})))\\ \{\frac{1}{\rho_1}(\lambda_l^t-\mathcal{P}_{\mathbf{\Lambda}}(\lambda_l^t+\rho_1\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})))\}\\ \{\frac{1}{\rho_2}(\boldsymbol{\phi}_j^t-\mathcal{P}_{\mathbf{\Phi}}(\boldsymbol{\phi}_j^t+\rho_2\nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})))\}\end{bmatrix}, \tag{21}$$

where ∇G^t is the simplified form of $\nabla G(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})$.

Definition 2 (ε-stationary point) $(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})$ *is an ε-stationary point ($\varepsilon\geq 0$) of a differentiable function L_p, if $||\nabla G^t||\leq\varepsilon$. $T(\varepsilon)$ is the first iteration index such that $||\nabla G^t||\leq\varepsilon$, i.e., $T(\varepsilon)=\min\{t\mid||\nabla G^t||\leq\varepsilon\}$.*

Assumption 1 (Smoothness/Gradient Lipschitz) *L_p has Lipschitz continuous gradients. We assume that there exists $L>0$ satisfying*

$$||\nabla_\theta L_p(\{\boldsymbol{w}_j\},\boldsymbol{z},h,\{\lambda_l\},\{\boldsymbol{\phi}_j\})-\nabla_\theta L_p(\{\hat{\boldsymbol{w}}_j\},\hat{\boldsymbol{z}},\hat{h},\{\hat{\lambda}_l\},\{\hat{\boldsymbol{\phi}}_j\})||$$
$$\leq L||[\boldsymbol{w}_{\text{cat}}-\hat{\boldsymbol{w}}_{\text{cat}};\boldsymbol{z}-\hat{\boldsymbol{z}};h-\hat{h};\boldsymbol{\lambda}_{\text{cat}}-\hat{\boldsymbol{\lambda}}_{\text{cat}};\boldsymbol{\phi}_{\text{cat}}-\hat{\boldsymbol{\phi}}_{\text{cat}}]||,$$

where $\theta \in \{\{\boldsymbol{w}_j\}, \boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\}\}$ *and* $[;]$ *represents the concatenation.* $\boldsymbol{w}_{\text{cat}} - \hat{\boldsymbol{w}}_{\text{cat}} = [\boldsymbol{w}_1 - \hat{\boldsymbol{w}}_1; \cdots; \boldsymbol{w}_N - \hat{\boldsymbol{w}}_N] \in \mathbb{R}^{pN}$*,* $\boldsymbol{\lambda}_{\text{cat}} - \hat{\boldsymbol{\lambda}}_{\text{cat}} = [\lambda_1 - \hat{\lambda}_1; \cdots; \lambda_{|\mathbf{A}^t|} - \hat{\lambda}_{|\mathbf{A}^t|}] \in \mathbb{R}^{|\mathbf{A}^t|}$*,* $\boldsymbol{\phi}_{\text{cat}} - \hat{\boldsymbol{\phi}}_{\text{cat}} = [\boldsymbol{\phi}_1 - \hat{\boldsymbol{\phi}}_1; \cdots; \boldsymbol{\phi}_N - \hat{\boldsymbol{\phi}}_N] \in \mathbb{R}^{pN}$*.*

Assumption 2 (Boundedness) *Before obtaining the* ε*-stationary point (i.e.,* $t \leq T(\varepsilon)-1$*), we assume variables in master satisfy that* $||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2+\sum_l ||\lambda_l^{t+1}-\lambda_l^t||^2 \geq \vartheta$*, where* $\vartheta > 0$ *is a relative small constant. The change of the variables in master is upper bounded within* τ *iterations:*

$$||\boldsymbol{z}^t - \boldsymbol{z}^{t-k}||^2 \leq \tau k_1 \vartheta, \quad ||h^t - h^{t-k}||^2 \leq \tau k_1 \vartheta, \quad \textstyle\sum_l ||\lambda_l^t - \lambda_l^{t-k}||^2 \leq \tau k_1 \vartheta, \forall 1 \leq k \leq \tau,$$

where $k_1 > 0$ *is a constant.*

Setting 1 (Bounded $|\mathbf{A}^t|$) $|\mathbf{A}^t| \leq M, \forall t$*, i.e., an upper bound is set for the number of cutting planes.*

Setting 2 (Setting of c_1^t, c_2^t) $c_1^t = \frac{1}{\rho_1 (t+1)^{\frac{1}{6}}} \geq \underline{c}_1$ *and* $c_2^t = \frac{1}{\rho_2 (t+1)^{\frac{1}{6}}} \geq \underline{c}_2$ *are nonnegative non-increasing sequences, where* $\underline{c}_1$ *and* $\underline{c}_2$ *are positive constants and meet* $M{\underline{c}_1}^2 + N{\underline{c}_2}^2 \leq \frac{\varepsilon^2}{4}$*.*

Theorem 1 (Iteration complexity) *Suppose Assumption 1 and 2 hold. We set* $\eta_{\boldsymbol{w}}^t = \eta_{\boldsymbol{z}}^t = \eta_h^t = \frac{2}{L+\rho_1|\mathbf{A}^t|L^2+\rho_2 NL^2+8(\frac{|\mathbf{A}^t|\gamma L^2}{\rho_1 (c_1^t)^2}+\frac{N\gamma L^2}{\rho_2 (c_2^t)^2})}$ *and* $\underline{\eta_{\boldsymbol{w}}} = \frac{2}{L+\rho_1 ML^2+\rho_2 NL^2+8(\frac{M\gamma L^2}{\rho_1 {\underline{c}_1}^2}+\frac{N\gamma L^2}{\rho_2 {\underline{c}_2}^2})}$*. And we set constants* $\rho_1 < \min\{\frac{2}{L+2c_1^0}, \frac{1}{15\tau k_1 NL^2}\}$ *and* $\rho_2 \leq \frac{2}{L+2c_2^0}$*, respectively. For a given* ε*, we have:*

$$T(\varepsilon) \sim \mathcal{O}(\max\{(\frac{4M{\sigma_1}^2}{{\rho_1}^2}+\frac{4N{\sigma_2}^2}{{\rho_2}^2})^3\frac{1}{\varepsilon^6}, (\frac{4(d_6+\frac{\rho_2(N-S)L^2}{2})\bar{d}^2(\bar{d}+k_d(\tau-1))d_5}{\varepsilon^2}+(T_1+\tau)^{\frac{1}{3}})^3\}), \tag{22}$$

where σ_1*,* σ_2*,* γ*,* τ*,* k_d*,* $\bar{d}$*,* d_5*,* d_6 *and* T_1 *are constants. The detailed proof is given in Appendix A.*

There exists a wide array of works regarding the convergence analysis of various algorithms for nonconvex/convex optimization problems involved in machine learning [25, 53]. Our analysis, however, differs from existing works in two aspects. First, we solve the non-convex PD-DRO in an *asynchronous distributed manner*. To our best knowledge, there are few works focusing on solving the DRO in a distributed manner. Compared to solving the non-convex PD-DRO in a centralized manner, solving it in an *asynchronous distributed manner* poses significant challenges in algorithm design and convergence analysis. Secondly, we do not assume the inner problem can be solved nearly optimally for each outer iteration, which is numerically difficult to achieve in practice [4]. Instead, ASPIRE-EASE is *single loop* and involves simple gradient projection operation at each step.

6 Experiment

In this section, we conduct experiments on four real-world datasets to assess the performance of the proposed method. Specifically, we evaluate the robustness against data heterogeneity, robustness against malicious attacks and efficiency of the proposed method. Ablation study is also carried out to demonstrate the excellent performance of ASPIRE-EASE.

6.1 Datasets and Baseline Methods

We compare the proposed ASPIRE-EASE with baseline methods based on SHL [20], Person Activity [26], Single Chest-Mounted Accelerometer (SM-AC) [9] and Fashion MNIST [51] datasets. The baseline methods include Ind_j (learning the model from an individual worker j), Mix_{Even} (learning the model from all workers with even weights using ASPIRE), FedAvg [33], AFL [35] and DRFA-Prox [16]. The detailed descriptions of datasets and baselines are given in Appendix C.

In our empirical studies, since the downstream tasks are multi-class classification, the cross entropy loss is used on each worker (*i.e.*, $\mathcal{L}_j(\cdot), \forall j$). For SHL, Person Activity, and SM-AC datasets, we adopt the deep multilayer perceptron [49] as the base model. And we use the same logistic regression model as in [35, 16] for Fashion MNIST dataset. The base models are trained with SGD. More details are given in Appendix C. Following related works in this direction [41, 35, 16], worst case performance are reported for the comparison of robustness. Specifically, we use $\mathbf{Acc}_w$ and $\mathbf{Loss}_w$ to represent the worst case test accuracy and training loss (*i.e.*, the test accuracy and training loss on the worker with worst performance), respectively. We also report the standard deviation $\mathbf{Std}$ of

Table 1: Performance comparisons based on $\mathbf{Acc}_w$ (%) ↑, $\mathbf{Loss}_w$ ↓ and $\mathbf{Std}$ ↓ (↑ and ↓ respectively denote higher scores represent better performance and lower scores represent better performance). The boldfaced digits represent the best results, "–" represents not available.

Model	SHL			Person Activity			SC-MA			Fashion MNIST		
	$\mathbf{Acc}_w$↑	$\mathbf{Loss}_w$↓	**Std**↓	$\mathbf{Acc}_w$↑	$\mathbf{Loss}_w$↓	**Std**↓	$\mathbf{Acc}_w$↑	$\mathbf{Loss}_w$↓	**Std**↓	$\mathbf{Acc}_w$↑	$\mathbf{Loss}_w$↓	**Std**↓
$\max\{\mathrm{Ind}_j\}$	19.06±0.65	–	29.1	49.38±0.08	–	8.32	22.56±0.78	–	17.5	–	–	–
$\mathrm{Mix}_{\mathrm{Even}}$	69.87±3.10	0.806±0.018	4.81	56.31±0.69	1.165±0.017	3.00	49.81±0.21	1.424±0.024	6.99	66.80±0.18	0.784±0.003	10.1
FedAvg [33]	69.96±3.07	0.802±0.023	5.21	56.28±0.63	1.154±0.019	3.13	49.53±0.96	1.441±0.015	7.17	66.58±0.39	0.781±0.002	10.2
AFL [35]	78.11±1.99	0.582±0.021	1.87	58.39±0.37	1.081±0.014	0.99	54.56±0.79	1.172±0.018	3.50	77.32±0.15	0.703±0.001	1.86
DRFA-Prox [16]	78.34±1.46	0.532±0.034	1.85	58.62±0.16	1.096±0.037	1.26	54.61±0.76	1.151±0.039	4.69	77.95±0.51	0.702±0.007	1.34
ASPIRE-EASE	**79.16±1.13**	**0.515±0.019**	**1.02**	59.43±0.44	1.053±0.010	0.82	56.31±0.29	1.127±0.021	**3.16**	**78.82±0.07**	**0.696±0.004**	**1.01**
$\text{ASPIRE-EASE}_{\text{per}}$	78.94±1.27	0.521±0.023	1.36	**59.54±0.21**	**1.051±0.016**	**0.79**	**56.71±0.16**	**1.119±0.028**	3.48	78.73±0.06	0.698±0.006	1.09

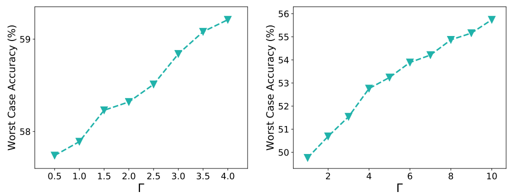
$[\mathrm{Acc}_1, \cdots, \mathrm{Acc}_\mathrm{N}]$ (the test accuracy on every worker). In the experiment, S is set as 1, that means the master will make an update once it receives a message. Each experiment is repeated 10 times, both mean and standard deviations are reported. We implement our model with PyTorch and conduct all the experiments on a server with two TITAN V GPUs.

6.2 Results

Robustness against Data Heterogeneity. We first assess the robustness of the proposed ASPIRE-EASE by comparing it with baseline methods when data are heterogeneously distributed across different workers. Specifically, we compare the $\mathbf{Acc}_w$, $\mathbf{Loss}_w$ and $\mathbf{Std}$ of different methods on all datasets. The performance comparison results are shown in Table 1. In this table, we can observe that $\max\{\mathrm{Ind}_j\}$, which represents the best performance of individual training over all workers, exhibits the worst robustness on SHL, Person Activity, and SC-MA. This is because individual training ($\max\{\mathrm{Ind}_j\}$) only learns from the data in its local worker and cannot generalize to other workers due to different data distributions. Note that $\max\{\mathrm{Ind}_j\}$ is unavailable for Fashion MNIST since each worker only contains one class of data and cross entropy loss cannot be used in this case. $\max\{\mathrm{Ind}_j\}$ also does not have $\mathbf{Loss}_w$, since Ind_j is trained only on individual worker j. The FedAvg and $\mathrm{Mix}_{\mathrm{Even}}$ exhibit better performance than $\max\{\mathrm{Ind}_j\}$ since they consider the data from all workers. Nevertheless, FedAvg and $\mathrm{Mix}_{\mathrm{Even}}$ only assign the fixed weight for each worker. AFL is more robust than FedAvg and $\mathrm{Mix}_{\mathrm{Even}}$ since it not only utilizes the data from all workers but also considers optimizing the weight of each worker. DRFA-Prox outperforms AFL since it also considers the prior distribution and regards it as a regularizer in the objective function. Finally, we can observe that the proposed ASPIRE-EASE shows excellent robustness, which can be attributed to two factors: 1) ASPIRE-EASE considers data from all workers and can optimize the weight of each worker; 2) compared with DRFA-Prox which uses prior distribution as a regularizer, the prior distribution is incorporated within the constraint in our formulation (Eq. 4), which can be leveraged more effectively. And it is seen that ASPIRE-EASE can perform periodic communication since $\text{ASPIRE-EASE}_{\text{per}}$, which represents ASPIRE-EASE with periodic communication, also has excellent performance.

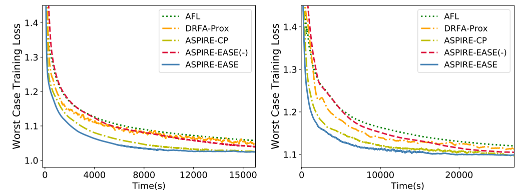
Within ASPIRE-EASE, the level of robustness can be controlled by adjusting Γ. Specially, when $\Gamma = 0$, we obtain a nominal optimization problem in which no adversarial distribution is considered. The size of the uncertainty set will increase with Γ (when $\Gamma \leq N$), which enhances the adversarial robustness of the model. As shown in Figure 1, the robustness of ASPIRE-EASE can be gradually enhanced when Γ increases. More results are available in Figure C2 of Appendix C.

Robustness against Malicious Attacks. To assess the model robustness against malicious attacks, malicious workers with backdoor attacks [1, 48], which attempt to mislead the model training process, are added to the distributed system. Following [14], we report the success attack rate of backdoor attacks for comparison. It can be calculated by checking how many instances in the backdoor dataset can be misled and categorized into the target labels. Lower success attack rates indicate more robustness against backdoor attacks. The comparison results are summarized in Table 2 and more detailed settings of backdoor attacks are available in Appendix C. In Table 2, we observe that AFL can be attacked easily since it could assign higher weights to malicious workers. Compared to AFL, FedAvg and $\mathrm{Mix}_{\mathrm{Even}}$ achieve relatively lower success attack rates since they assign equal weights to the malicious workers and other workers. DRFA-Prox can achieve even lower success attack rates since it can leverage the prior distribution to assign lower weights for malicious workers. The proposed ASPIRE-EASE achieves the lowest success attack rates since it can leverage the prior distribution more effectively. Specifically, it will assign lower weights to malicious workers with tight theoretical guarantees.



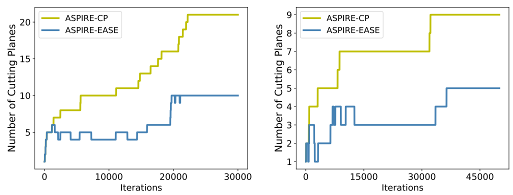
(a) Person Activity (b) SC-MA

Figure 1: Γ control the degree of robustness (worst case performance in the problem) on (a) Person Activity, (b) SC-MA datasets.



(a) Person Activity (b) SC-MA

Figure 2: Comparison of the convergence time on worst case worker on (a) Person Activity, (b) SC-MA datasets.



(a) Person Activity (b) SC-MA

Figure 3: Comparison of ASPIRE-CP and ASPIRE-EASE regarding the number of cutting planes on (a) Person Activity, (b) SC-MA datasets.

Table 2: Performance comparisons about the success attack rate (%) $\downarrow$. The boldfaced digits represent the best results.

Model	SHL	Person Activity	SC-MA	Fashion MNIST
Mix_{Even}	36.21±2.23	34.32±2.18	52.14±2.89	83.18±2.07
FedAvg [33]	38.15±3.02	33.25±2.49	55.39±3.13	82.04±1.84
AFL [35]	68.63±4.24	43.66±3.87	75.81±4.03	90.04±2.52
DRFA-Prox [16]	21.23±3.63	27.27±3.31	30.79±3.65	63.24±2.47
ASPIRE-EASE	**9.17±1.65**	**22.36±2.33**	**14.51±3.21**	**45.10±1.64**

Efficiency. In Figure 2, we compare the convergence speed of the proposed ASPIRE-EASE with AFL and DRFA-Prox by considering different communication and computation delays for each worker. The proposed ASPIRE-EASE has two variants, ASPIRE-CP (ASPIRE with cutting plane method), ASPIRE-EASE(-)(ASPIRE-EASE without asynchronous setting). More results are available in Figure C3 of Appendix C. Based on the comparison, we can observe that the proposed ASPIRE-EASE generally converges faster than baseline methods and its two variants. This is because 1) compared with AFL, DRFA-Prox, and ASPIRE-EASE(-), ASPIRE-EASE is an asynchronous algorithm in which the master updates its parameters only after receiving the updates from active workers instead of all workers; 2) unlike DRFA-Prox, the master in ASPIRE-EASE only needs to communicate with active workers once per iteration; 3) compared with ASPIRE-CP, ASPIRE-EASE utilizes active set method instead of cutting plane method, which is more efficient. It is seen from Figure 2 that, the convergence speed of ASPIRE-EASE mainly benefits from the asynchronous setting.

Ablation Study. For ASPIRE, compared with cutting plane method, EASE is more efficient since it considers removing the inactive cutting planes. To demonstrate the efficiency of EASE, we firstly compare ASPIRE-EASE with ASPIRE-CP concerning the number of cutting planes used during the training. In Figure 3, we can observe that ASPIRE-EASE uses fewer cutting planes than ASPIRE-CP, thus is more efficient. The convergence speed of ASPIRE-EASE and ASPIRE-CP in Figure 2 also suggests that ASPIRE-EASE converges much faster than ASPIRE-CP. More results are available in Figure C3 and C4, Appendix C.

7 Conclusion

In this paper, we present ASPIRE-EASE method to effectively solve the distributed distributionally robust optimization problem with non-convex objectives. In addition, CD-norm uncertainty set has been proposed to effectively incorporate the prior distribution into the problem formulation, which allows for flexible adjustment of the degree of robustness of DRO. Theoretical analysis has also been conducted to analyze the convergence properties and the iteration complexity of ASPIRE-EASE. ASPIRE-EASE exhibits strong empirical performance on multiple real-world datasets and is effective in tackling DRO problems in a fully distributed and asynchronous manner. In the future work, more uncertainty sets could be designed for our framework and more update rule for variables in ASPIRE could be considered.

Acknowledgments and Disclosure of Funding

The work of Yang Jiao and Kai Yang was supported in part by the Fundamental Research Funds for the Central Universities of China, in part by the Shenzhen Institute of Artificial Intelligence and Robotics for Society (AIRS), in part by the National Natural Science Foundation of China under Grant 61771013, and in part by the Fundamental Research Funds of Shanghai Jiading District.

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Checklist

1. For all authors...
   (a) Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope? [Yes] See Section 1.
   (b) Did you describe the limitations of your work? [Yes] See Section 7.
   (c) Did you discuss any potential negative societal impacts of your work? [N/A] There is no potential negative societal impact of our work.
   (d) Have you read the ethics review guidelines and ensured that your paper conforms to them? [Yes]
2. If you are including theoretical results...
   (a) Did you state the full set of assumptions of all theoretical results? [Yes] See Section 5.
   (b) Did you include complete proofs of all theoretical results? [Yes] See Appendix A and B.
3. If you ran experiments...
   (a) Did you include the code, data, and instructions needed to reproduce the main experimental results (either in the supplemental material or as a URL)? [Yes] The references of the data used in this paper are added in Section 6.1.
   (b) Did you specify all the training details (e.g., data splits, hyperparameters, how they were chosen)? [Yes] Section C.2.
   (c) Did you report error bars (e.g., with respect to the random seed after running experiments multiple times)? [Yes] See Section 6.
   (d) Did you include the total amount of compute and the type of resources used (e.g., type of GPUs, internal cluster, or cloud provider)? [Yes] See Section 6.1.
4. If you are using existing assets (e.g., code, data, models) or curating/releasing new assets...
   (a) If your work uses existing assets, did you cite the creators? [N/A]
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5. If you used crowdsourcing or conducted research with human subjects...
   (a) Did you include the full text of instructions given to participants and screenshots, if applicable? [N/A]
   (b) Did you describe any potential participant risks, with links to Institutional Review Board (IRB) approvals, if applicable? [N/A]
   (c) Did you include the estimated hourly wage paid to participants and the total amount spent on participant compensation? [N/A]

Appendix

A Proof of Theorem 1

Before proceeding to the detailed proofs, we provide some notations for the clarity in presentation. We use notation $< \cdot, \cdot >$ to denote the inner product and we use $||\cdot||$ to denote the l_2-norm. $|\mathbf{A}^t|$ and $|\mathbf{Q}^{t+1}|$ respectively denote the number of cutting planes and active workers in $(t+1)^{\text{th}}$ iteration.

Then, we cover some Lemmas which are useful for the deduction of Theorem 1.

Lemma 1 *Suppose Assumption 1 and 2 hold, $\forall t \geq T_1+\tau$, we have,*

$$\begin{aligned}
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})\\
&\leq \sum_{j=1}^{N}(\tfrac{L+1}{2}-\tfrac{1}{\eta_{\boldsymbol{w}}^t})||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+\tfrac{3\tau k_1 N L^2}{2}(||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2+\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2),
\end{aligned} \tag{A.1}$$

$$L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) \leq (\tfrac{L}{2}-\tfrac{1}{\eta_{\boldsymbol{z}}^t})||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2, \tag{A.2}$$

$$L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) \leq (\tfrac{L}{2}-\tfrac{1}{\eta_h^t})||h^{t+1}-h^t||^2. \tag{A.3}$$

***Proof of Lemma 1**:*

According to Assumption 1, we have,

$$\begin{aligned}
&L_p(\{\boldsymbol{w}_1^{t+1},\boldsymbol{w}_2^t,\cdots,\boldsymbol{w}_N^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})\\
&\leq \left\langle\nabla_{\boldsymbol{w}_1}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{w}_1^{t+1}-\boldsymbol{w}_1^t\right\rangle+\tfrac{L}{2}||\boldsymbol{w}_1^{t+1}-\boldsymbol{w}_1^t||^2,\\
&L_p(\{\boldsymbol{w}_1^{t+1},\boldsymbol{w}_2^{t+1},\boldsymbol{w}_3^t,\cdots,\boldsymbol{w}_N^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-L_p(\{\boldsymbol{w}_1^{t+1},\boldsymbol{w}_2^t,\cdots,\boldsymbol{w}_N^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})\\
&\leq \left\langle\nabla_{\boldsymbol{w}_2}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{w}_2^{t+1}-\boldsymbol{w}_2^t\right\rangle+\tfrac{L}{2}||\boldsymbol{w}_2^{t+1}-\boldsymbol{w}_2^t||^2,\\
&\qquad\vdots\\
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-L_p(\{\boldsymbol{w}_1^{t+1},\cdots,\boldsymbol{w}_{N-1}^{t+1},\boldsymbol{w}_N^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})\\
&\leq \left\langle\nabla_{\boldsymbol{w}_N}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{w}_N^{t+1}-\boldsymbol{w}_N^t\right\rangle+\tfrac{L}{2}||\boldsymbol{w}_N^{t+1}-\boldsymbol{w}_N^t||^2.
\end{aligned} \tag{A.4}$$

Summing up the above inequalities in Eq. (A.4), we have,

$$\begin{aligned}
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})\\
&\leq \sum_{j=1}^{N}(\left\langle\nabla_{\boldsymbol{w}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t\right\rangle+\tfrac{L}{2}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2).
\end{aligned} \tag{A.5}$$

According to $\nabla_{\boldsymbol{w}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) = \nabla_{\boldsymbol{w}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})$ and the optimal condition for Eq. (11), for active nodes, *i.e.*, $\forall j \in \mathbf{Q}^{t+1}, \forall t \geq T_1+\tau$, we have,

$$\left\langle \boldsymbol{w}_j^t-\boldsymbol{w}_j^{t+1},\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t+\underline{\eta_{\boldsymbol{w}}}\nabla_{\boldsymbol{w}_j}L_p(\{\boldsymbol{w}_j^{\widetilde{t}_j}\},\boldsymbol{z}^{\widetilde{t}_j},h^{\widetilde{t}_j},\{\lambda_l^{\widetilde{t}_j}\},\{\boldsymbol{\phi}_j^{\widetilde{t}_j}\})\right\rangle \geq 0. \tag{A.6}$$

According to Eq. (A.6), $\forall t \geq T_1+\tau$, we have,

$$\left\langle \boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t,\nabla_{\boldsymbol{w}_j}L_p(\{\boldsymbol{w}_j^{\widetilde{t}_j}\},\boldsymbol{z}^{\widetilde{t}_j},h^{\widetilde{t}_j},\{\lambda_l^{\widetilde{t}_j}\},\{\boldsymbol{\phi}_j^{\widetilde{t}_j}\})\right\rangle \leq -\frac{1}{\underline{\eta_{\boldsymbol{w}}}}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2 \leq -\frac{1}{\eta_{\boldsymbol{w}}^t}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2. \tag{A.7}$$

And according to the Cauchy-Schwarz inequality, Assumption 1 and 2, we can get,

$$
\begin{aligned}
&\Big\langle \boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t, \nabla_{\boldsymbol{w}_j} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{w}_j} L_p(\{\boldsymbol{w}_j^{\widetilde{t}_j}\},\boldsymbol{z}^{\widetilde{t}_j}, h^{\widetilde{t}_j}, \{\lambda_l^{\widetilde{t}_j}\},\{\boldsymbol{\phi}_j^{\widetilde{t}_j}\}) \Big\rangle \\
&\le \frac{1}{2}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2 + \frac{L^2}{2}(||\boldsymbol{z}^t-\boldsymbol{z}^{\widetilde{t}_j}||^2 + ||h^t-h^{\widetilde{t}_j}||^2 + \sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t-\lambda_l^{\widetilde{t}_j}||^2) \\
&\le \frac{1}{2}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2 + \frac{3\tau k_1 L^2}{2}(||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2 + ||h^{t+1}-h^t||^2 + \sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2).
\end{aligned}
\tag{A.8}
$$

Combining the above Eq. (A.5), (A.7) with Eq. (A.8), we can obtain Eq. (A.1), that is,

$$
\begin{aligned}
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) - L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) \\
&\le \sum_{j=1}^{N}(\frac{L+1}{2}-\frac{1}{\eta_{\boldsymbol{w}}^t})||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2 + \frac{3\tau k_1 N L^2}{2}(||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2 + ||h^{t+1}-h^t||^2 + \sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2).
\end{aligned}
$$

Following Assumption 1, we have,

$$
\begin{aligned}
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) - L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) \\
&\le \big\langle \nabla_{\boldsymbol{z}} L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}), \boldsymbol{z}^{t+1}-\boldsymbol{z}^t \big\rangle + \frac{L}{2}||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2.
\end{aligned}
\tag{A.9}
$$

According to $\nabla_{\boldsymbol{z}} L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) = \nabla_{\boldsymbol{z}} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})$ and the optimal condition for Eq. (12), we have,

$$
\big\langle \boldsymbol{z}^t-\boldsymbol{z}^{t+1}, \boldsymbol{z}^{t+1}-\boldsymbol{z}^t + \eta_{\boldsymbol{z}}^t \nabla_{\boldsymbol{z}} L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) \big\rangle \ge 0. \tag{A.10}
$$

Combining Eq. (A.9) with Eq. (A.10), we can obtain the Eq. (A.2), that is,

$$
L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) - L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) \le (\frac{L}{2}-\frac{1}{\eta_{\boldsymbol{z}}^t})||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2.
$$

According to Assumption 1, we have:

$$
\begin{aligned}
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) - L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) \\
&\le \big\langle \nabla_h L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}), h^{t+1}-h^t \big\rangle + \frac{L}{2}||h^{t+1}-h^t||^2.
\end{aligned}
\tag{A.11}
$$

According to $\nabla_h L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) = \nabla_h \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})$ and the optimal condition for Eq. (13), we have:

$$
\big\langle h^t-h^{t+1}, h^{t+1}-h^t + \eta_h^t \nabla_h L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) \big\rangle \ge 0. \tag{A.12}
$$

Combining Eq. (A.11) with Eq. (A.12), we can show that,

$$
L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) - L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) \le (\frac{L}{2}-\frac{1}{\eta_h^t})||h^{t+1}-h^t||^2.
$$

Lemma 2 *Suppose Assumption 1 and 2 hold,* $\forall t \ge T_1 + \tau$*, we have:*

$$
\begin{aligned}
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^{t+1}\}) - L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) \\
&\le (\frac{L+1}{2} - \frac{1}{\eta_{\boldsymbol{w}}^t} + \frac{|\mathbf{A}^t|L^2}{2a_1} + \frac{|\mathbf{Q}^{t+1}|L^2}{2a_3})\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2 + (\frac{L+3\tau k_1 N L^2}{2} - \frac{1}{\eta_{\boldsymbol{z}}^t} + \frac{|\mathbf{A}^t|L^2}{2a_1} + \frac{|\mathbf{Q}^{t+1}|L^2}{2a_3})||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2 \\
&+ (\frac{L+3\tau k_1 N L^2}{2} - \frac{1}{\eta_h^t} + \frac{|\mathbf{A}^t|L^2}{2a_1} + \frac{|\mathbf{Q}^{t+1}|L^2}{2a_3})||h^{t+1}-h^t||^2 + (\frac{a_1+3\tau k_1 N L^2}{2} - \frac{c_1^{t-1}-c_1^t}{2} + \frac{1}{2\rho_1})\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2 \\
&+ \frac{c_1^{t-1}}{2}\sum_{l=1}^{|\mathbf{A}^t|}(||\lambda_l^{t+1}||^2 - ||\lambda_l^t||^2) + \frac{1}{2\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t-\lambda_l^{t-1}||^2 + (\frac{a_3}{2} - \frac{c_2^{t-1}-c_2^t}{2} + \frac{1}{2\rho_2})\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2 \\
&+ \frac{c_2^{t-1}}{2}\sum_{j=1}^{N}(||\boldsymbol{\phi}_j^{t+1}||^2 - ||\boldsymbol{\phi}_j^t||^2) + \frac{1}{2\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2,
\end{aligned}
\tag{A.13}
$$

where $a_1 > 0$ and $a_3 > 0$ are constants.

Proof of Lemma 2:

First of all, at $(t+1)^{\text{th}}$ iteration, the following equations hold and will be used in the derivation:

$$\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2=\sum_{j\in\mathbf{Q}^{t+1}}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2,\ \sum_{j=1}^{N}(||\boldsymbol{\phi}_j^{t+1}||^2-||\boldsymbol{\phi}_j^t||^2)=\sum_{j\in\mathbf{Q}^{t+1}}(||\boldsymbol{\phi}_j^{t+1}||^2-||\boldsymbol{\phi}_j^t||^2).$$

According to Eq. (14), in $(t+1)^{\text{th}}$ iteration, $\forall\lambda\in\boldsymbol{\Lambda}$, it follows that:

$$\left\langle\lambda_l^{t+1}-\lambda_l^t-\rho_1\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda-\lambda_l^{t+1}\right\rangle\geq 0. \tag{A.14}$$

Let $\lambda=\lambda_l^t$, we can obtain:

$$\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\frac{1}{\rho_1}(\lambda_l^{t+1}-\lambda_l^t),\lambda_l^t-\lambda_l^{t+1}\right\rangle\leq 0. \tag{A.15}$$

Likewise, in t^{th} iteration, we can obtain:

$$\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\})-\frac{1}{\rho_1}(\lambda_l^t-\lambda_l^{t-1}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\leq 0. \tag{A.16}$$

$\forall t\geq T_1$, since $\widetilde{L}_p(\{\boldsymbol{w}_j\},\boldsymbol{z},h,\{\lambda_l\},\{\boldsymbol{\phi}_j\})$ is concave with respect to λ_l, we have,

$$\begin{aligned}
&\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})\\
&\leq\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\\
&\leq\sum_{l=1}^{|\mathbf{A}^t|}(\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\\
&\qquad+\tfrac{1}{\rho_1}\left\langle\lambda_l^t-\lambda_l^{t-1},\lambda_l^{t+1}-\lambda_l^t\right\rangle).
\end{aligned} \tag{A.17}$$

Denoting $\boldsymbol{v}_{1,l}^{t+1}=\lambda_l^{t+1}-\lambda_l^t-(\lambda_l^t-\lambda_l^{t-1})$, we have,

$$\begin{aligned}
&\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\\
&=\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle(1a)\\
&+\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\boldsymbol{v}_{1,l}^{t+1}\right\rangle(1b)\\
&+\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\lambda_l^t-\lambda_l^{t-1}\right\rangle(1c).
\end{aligned} \tag{A.18}$$

Firstly, we focus on the $(1a)$ in Eq. (A.18), we can write $(1a)$ as:

$$\begin{aligned}
&\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\\
&=\left\langle\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\\
&+(c_1^{t-1}-c_1^t)\left\langle\lambda_l^t,\lambda_l^{t+1}-\lambda_l^t\right\rangle\\
&=\left\langle\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\\
&+\tfrac{c_1^{t-1}-c_1^t}{2}(||\lambda_l^{t+1}||^2-||\lambda_l^t||^2)-\tfrac{c_1^{t-1}-c_1^t}{2}||\lambda_l^{t+1}-\lambda_l^t||^2.
\end{aligned} \tag{A.19}$$

And according to Cauchy-Schwarz inequality and Assumption 1, we can obtain,

$$\begin{aligned}&\left\langle\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\\&\leq\tfrac{L^2}{2a_1}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)+\tfrac{a_1}{2}||\lambda_l^{t+1}-\lambda_l^t||^2,\end{aligned} \tag{A.20}$$

where $a_1>0$ is a constant. Combining Eq. (A.19) with Eq. (A.20), we can obtain the upper bound of $(1a)$, that is,

$$\begin{aligned}&\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle\\&\leq\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{L^2}{2a_1}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)+\tfrac{a_1}{2}||\lambda_l^{t+1}-\lambda_l^t||^2\\&\qquad+\tfrac{c_1^{t-1}-c_1^t}{2}(||\lambda_l^{t+1}||^2-||\lambda_l^t||^2)-\tfrac{c_1^{t-1}-c_1^t}{2}||\lambda_l^{t+1}-\lambda_l^t||^2).\end{aligned} \tag{A.21}$$

Secondly, we focus on the $(1b)$ in Eq. (A.18). According to Cauchy-Schwarz inequality we can write the $(1b)$ as,

$$\begin{aligned}&\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\boldsymbol{v}_{1,l}^{t+1}\right\rangle\\&\leq\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{a_2}{2}||\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\})||^2+\tfrac{1}{2a_2}||\boldsymbol{v}_{1,l}^{t+1}||^2),\end{aligned} \tag{A.22}$$

where $a_2>0$ is a constant. Then, we focus on the $(1c)$ in Eq. (A.18). Firstly, $\forall\lambda_l$, we have,

$$\begin{aligned}&||\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\})||\\&=||\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^t\})-c_1^{t-1}(\lambda_l^t-\lambda_l^{t-1})||\\&\leq(L+c_1^{t-1})||\lambda_l^t-\lambda_l^{t-1}||,\end{aligned} \tag{A.23}$$

where the last inequality comes from Assumption 1 and the trigonometric inequality. Denoting $L_1{}'=L+c_1^0$, we can obtain,

$$||\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\})||\leq L_1{}'||\lambda_l^t-\lambda_l^{t-1}||. \tag{A.24}$$

Following from Eq. (A.24) and the strong concavity of $\widetilde{L}_p(\{\boldsymbol{w}_j\},\boldsymbol{z},h,\{\lambda_l\},\{\boldsymbol{\phi}_j\})$ *w.r.t* λ_l [37, 52], we can obtain the upper bound of $(1c)$:

$$\begin{aligned}&\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\lambda_l^t-\lambda_l^{t-1}\right\rangle\\&\leq\sum_{l=1}^{|\mathbf{A}^t|}(-\tfrac{1}{L_1{}'+c_1^{t-1}}||\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\})||^2\\&\qquad-\tfrac{c_1^{t-1}L_1{}'}{L_1{}'+c_1^{t-1}}||\lambda_l^t-\lambda_l^{t-1}||^2).\end{aligned} \tag{A.25}$$

In addition, the following inequality can be obtained,

$$\tfrac{1}{\rho_1}\left\langle\lambda_l^t-\lambda_l^{t-1},\lambda_l^{t+1}-\lambda_l^t\right\rangle\leq\tfrac{1}{2\rho_1}||\lambda_l^{t+1}-\lambda_l^t||^2-\tfrac{1}{2\rho_1}||\boldsymbol{v}_{1,l}^{t+1}||^2+\tfrac{1}{2\rho_1}||\lambda_l^t-\lambda_l^{t-1}||^2. \tag{A.26}$$

Combining Eq. (A.17), (A.18), (A.21), (A.22), (A.25), (A.26), $\frac{\rho_1}{2} \leq \frac{1}{L_1{}' + c_1^0}$, and setting $a_2 = \rho_1$, we have:

$$
\begin{aligned}
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^t\}) - L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}) \\
&\leq \sum_{l=1}^{|\mathbf{A}^t|} (\Big\langle \nabla_{\lambda_l} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}), \lambda_l^{t+1} - \lambda_l^t \Big\rangle \\
&+ \tfrac{1}{\rho_1} \left\langle \lambda_l^t - \lambda_l^{t-1}, \lambda_l^{t+1} - \lambda_l^t \right\rangle + \tfrac{c_1^t}{2}(||\lambda_l^{t+1}||^2 - ||\lambda_l^t||^2)) \\
&\leq \sum_{l=1}^{|\mathbf{A}^t|} (\tfrac{L^2}{2a_1}(\sum_{j=1}^{N} ||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 + ||\boldsymbol{z}^{t+1} - \boldsymbol{z}^t||^2 + ||h^{t+1} - h^t||^2) \\
&+ (\tfrac{a_1}{2} - \tfrac{c_1^{t-1} - c_1^t}{2} + \tfrac{1}{2\rho_1})||\lambda_l^{t+1} - \lambda_l^t||^2 + \tfrac{c_1^{t-1}}{2}(||\lambda_l^{t+1}||^2 - ||\lambda_l^t||^2) + \tfrac{1}{2\rho_1}||\lambda_l^t - \lambda_l^{t-1}||^2) \\
&= \tfrac{|\mathbf{A}^t| L^2}{2a_1}(\sum_{j=1}^{N} ||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 + ||\boldsymbol{z}^{t+1} - \boldsymbol{z}^t||^2 + ||h^{t+1} - h^t||^2) \\
&+ (\tfrac{a_1}{2} - \tfrac{c_1^{t-1} - c_1^t}{2} + \tfrac{1}{2\rho_1}) \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^{t+1} - \lambda_l^t||^2 + \tfrac{c_1^{t-1}}{2} \sum_{l=1}^{|\mathbf{A}^t|} (||\lambda_l^{t+1}||^2 - ||\lambda_l^t||^2) + \tfrac{1}{2\rho_1} \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^t - \lambda_l^{t-1}||^2.
\end{aligned} \tag{A.27}
$$

According to Eq. (15), $\forall \boldsymbol{\phi} \in \boldsymbol{\Phi}$, it follows that,

$$
\Big\langle \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t - \rho_2 \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^t\}), \boldsymbol{\phi} - \boldsymbol{\phi}_j^{t+1} \Big\rangle \geq 0. \tag{A.28}
$$

Choosing $\boldsymbol{\phi} = \boldsymbol{\phi}_j^t$, we can obtain,

$$
\Big\langle \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^t\}) - \frac{1}{\rho_2}(\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t), \boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t+1} \Big\rangle \leq 0. \tag{A.29}
$$

Likewise, we have,

$$
\Big\langle \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^{t-1}\}) - \frac{1}{\rho_2}(\boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}), \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t \Big\rangle \leq 0. \tag{A.30}
$$

Since $\widetilde{L}_p(\{\boldsymbol{w}_j\},\boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\})$ is concave with respect to $\boldsymbol{\phi}_j$ and follows from Eq. (A.30):

$$
\begin{aligned}
&\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^{t+1}\}) - \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^t\}) \\
&\leq \sum_{j=1}^{N} \Big\langle \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^t\}), \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t \Big\rangle \\
&\leq \sum_{j=1}^{N} (\Big\langle \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}), \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t \Big\rangle \\
&\qquad + \tfrac{1}{\rho_2} \left\langle \boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}, \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t \right\rangle).
\end{aligned} \tag{A.31}
$$

Denoting $\boldsymbol{v}_{2,l}^{t+1} = \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t - (\boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1})$, we can write the first term in the last inequality of Eq. (A.31) as

$$
\begin{aligned}
&\sum_{j=1}^{N} \Big\langle \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1},\{\lambda_l^{t+1}\}, \{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^{t-1}\}), \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t \Big\rangle \\
&= \sum_{j=1}^{N} \Big\langle \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1}, h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}), \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t \Big\rangle (2a) \\
&+ \sum_{j=1}^{N} \Big\langle \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}), \boldsymbol{v}_{2,l}^{t+1} \Big\rangle (2b) \\
&+ \sum_{j=1}^{N} \Big\langle \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}), \boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1} \Big\rangle (2c).
\end{aligned} \tag{A.32}
$$

We firstly focus on the $(2a)$ in Eq. (A.32), we can write the $(2a)$ as,

$$\begin{aligned}
&\Big\langle \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\Big\rangle\\
&=\big\langle \nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\big\rangle\\
&+(c_2^{t-1}-c_2^t)\big\langle \boldsymbol{\phi}_j^t,\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\big\rangle\\
&=\big\langle \nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\big\rangle\\
&+\tfrac{c_2^{t-1}-c_2^t}{2}(||\boldsymbol{\phi}_j^{t+1}||^2-||\boldsymbol{\phi}_j^t||^2)-\tfrac{c_2^{t-1}-c_2^t}{2}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2).
\end{aligned}\tag{A.33}$$

And according to Cauchy-Schwarz inequality and Assumption 1, we can obtain,

$$\begin{aligned}
&\big\langle \nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\big\rangle\\
&=\big\langle \nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\big\rangle\\
&\le\tfrac{L^2}{2a_3}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)+\tfrac{a_3}{2}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2,
\end{aligned}\tag{A.34}$$

where $a_3>0$ is a constant. Thus, we can obtain the upper bound of $(2a)$ by combining the above Eq. (A.33) and Eq. (A.34),

$$\begin{aligned}
&\sum_{j=1}^{N}\Big\langle \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\Big\rangle\\
&=\sum_{j\in\mathbf{Q}^{t+1}}\Big\langle \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\Big\rangle\\
&\le\sum_{j\in\mathbf{Q}^{t+1}}(\tfrac{L^2}{2a_3}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)+\tfrac{a_3}{2}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2\\
&\qquad+\tfrac{c_2^{t-1}-c_2^t}{2}(||\boldsymbol{\phi}_j^{t+1}||^2-||\boldsymbol{\phi}_j^t||^2)-\tfrac{c_2^{t-1}-c_2^t}{2}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2).
\end{aligned}\tag{A.35}$$

Next we focus on the $(2b)$ in Eq. (A.32). According to Cauchy-Schwarz inequality we can write the $(2b)$ as

$$\begin{aligned}
&\sum_{j=1}^{N}\Big\langle \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}),\boldsymbol{v}_{2,l}^{t+1}\Big\rangle\\
&\le\sum_{j=1}^{N}(\tfrac{a_4}{2}||\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\})||^2+\tfrac{1}{2a_4}||\boldsymbol{v}_{2,l}^{t+1}||^2),
\end{aligned}\tag{A.36}$$

where $a_4>0$ is a constant. Then, we focus on the $(2c)$ in Eq. (A.32), we have,

$$\begin{aligned}
&||\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\})||\\
&\le||\nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\})||+c_2^{t-1}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||\\
&\le(L+c_2^{t-1})||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||,
\end{aligned}\tag{A.37}$$

where the last inequality comes from Assumption 1 and the trigonometric inequality. Denoting ${L_2}'=L+c_2^0$, we can obtain,

$$||\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\})||\le{L_2}'||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||.\tag{A.38}$$

Following Eq. (A.38) and the strong concavity of $\widetilde{L}_p(\{\boldsymbol{w}_j\},\boldsymbol{z},h,\{\lambda_l\},\{\boldsymbol{\phi}_j\})$ *w.r.t* $\boldsymbol{\phi}_j$, we can obtain the upper bound of $(2c)$,

$$\begin{aligned}
&\sum_{j=1}^{N}\left\langle \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}), \boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}\right\rangle \\
&\leq \sum_{j=1}^{N}\Big(-\tfrac{1}{L_2{'}+c_2^{t-1}}||\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\})||^2 \\
&\qquad - \tfrac{c_2^{t-1}L_2{'}}{L_2{'}+c_2^{t-1}}||\boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}||^2\Big).
\end{aligned} \tag{A.39}$$

In addition, the following inequality can also be obtained,

$$\sum_{j=1}^{N}\tfrac{1}{\rho_2}\left\langle \boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}, \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t\right\rangle \leq \sum_{j=1}^{N}\big(\tfrac{1}{2\rho_2}||\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t||^2 - \tfrac{1}{2\rho_2}||\boldsymbol{v}_{2,l}^{t+1}||^2 + \tfrac{1}{2\rho_2}||\boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}||^2\big). \tag{A.40}$$

Combining Eq. (A.31), (A.32), (A.35), (A.36), (A.39), (A.40), $\frac{\rho_2}{2} \leq \frac{1}{L_2{'}+c_2^0}$, and setting $a_4 = \rho_2$, we have,

$$\begin{aligned}
&L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^{t+1}\}) - L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\}) \\
&\leq \sum_{j=1}^{N}\Big(\left\langle \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\}) - \nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}), \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t\right\rangle \\
&\qquad + \tfrac{1}{\rho_2}\left\langle \boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}, \boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t\right\rangle + \tfrac{c_2^t}{2}(||\boldsymbol{\phi}_j^{t+1}||^2 - ||\boldsymbol{\phi}_j^t||^2)\Big) \\
&\leq \tfrac{|\mathbf{Q}^{t+1}|L^2}{2a_3}\Big(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 + ||\boldsymbol{z}^{t+1} - \boldsymbol{z}^t||^2 + ||h^{t+1} - h^t||^2\Big) \\
&+ \big(\tfrac{a_3}{2} - \tfrac{c_2^{t-1} - c_2^t}{2} + \tfrac{1}{2\rho_2}\big)\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t||^2 + \tfrac{c_2^{t-1}}{2}\sum_{j=1}^{N}(||\boldsymbol{\phi}_j^{t+1}||^2 - ||\boldsymbol{\phi}_j^t||^2) + \tfrac{1}{2\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}||^2.
\end{aligned} \tag{A.41}$$

By combining Lemma 1 with Eq. (A.27) and Eq. (A.41), we conclude the proof of Lemma 2.

Lemma 3 *Firstly, we denote S_1^{t+1}, S_2^{t+1} and F^{t+1} as,*

$$S_1^{t+1} = \frac{4}{{\rho_1}^2 c_1^{t+1}}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1} - \lambda_l^t||^2 - \frac{4}{\rho_1}\Big(\frac{c_1^{t-1}}{c_1^t} - 1\Big)\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}||^2, \tag{A.42}$$

$$S_2^{t+1} = \frac{4}{{\rho_2}^2 c_2^{t+1}}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t||^2 - \frac{4}{\rho_2}\Big(\frac{c_2^{t-1}}{c_2^t} - 1\Big)\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}||^2, \tag{A.43}$$

$$\begin{aligned}
F^{t+1} &= L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^{t+1}\}) + S_1^{t+1} + S_2^{t+1} \\
&\quad - \tfrac{7}{2\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1} - \lambda_l^t||^2 - \tfrac{c_1^t}{2}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}||^2 - \tfrac{7}{2\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t||^2 - \tfrac{c_2^t}{2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}||^2,
\end{aligned} \tag{A.44}$$

then $\forall t \geq T_1 + \tau$, *we have,*

$$
\begin{aligned}
F^{t+1}-F^t \leq & \left(\frac{L+1}{2}-\frac{1}{\eta_{\boldsymbol{w}}^t}+\frac{\rho_1|\mathbf{A}^t|L^2}{2}+\frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}+\frac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2}+\frac{8NL^2}{\rho_2(c_2^t)^2}\right)\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2 \\
& +\left(\frac{L+3\tau k_1NL^2}{2}-\frac{1}{\eta_{\boldsymbol{z}}^t}+\frac{\rho_1|\mathbf{A}^t|L^2}{2}+\frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}+\frac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2}+\frac{8NL^2}{\rho_2(c_2^t)^2}\right)||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2 \\
& +\left(\frac{L+3\tau k_1NL^2}{2}-\frac{1}{\eta_{h}^t}+\frac{\rho_1|\mathbf{A}^t|L^2}{2}+\frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}+\frac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2}+\frac{8NL^2}{\rho_2(c_2^t)^2}\right)||h^{t+1}-h^t||^2 \\
& -\left(\frac{1}{10\rho_1}-\frac{3\tau k_1NL^2}{2}\right)\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2-\frac{1}{10\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2+\frac{c_1^{t-1}-c_1^t}{2}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}||^2 \\
& +\frac{c_2^{t-1}-c_2^t}{2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}||^2+\frac{4}{\rho_1}\left(\frac{c_1^{t-2}}{c_1^{t-1}}-\frac{c_1^{t-1}}{c_1^t}\right)\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t||^2+\frac{4}{\rho_2}\left(\frac{c_2^{t-2}}{c_2^{t-1}}-\frac{c_2^{t-1}}{c_2^t}\right)\sum_{j=1}^{N}||\boldsymbol{\phi}_j^t||^2.
\end{aligned}
\tag{A.45}
$$

Proof of Lemma 3:

Let $a_1 = \frac{1}{\rho_1}$, $a_3 = \frac{1}{\rho_2}$ and substitute them into Lemma 2, $\forall t \geq T_1 + \tau$, we have,

$$
\begin{aligned}
& L_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^{t+1}\}) - L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}) \\
& \leq \left(\frac{L+1}{2}-\frac{1}{\eta_{\boldsymbol{w}}^t}+\frac{\rho_1|\mathbf{A}^t|L^2}{2}+\frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}\right)\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2 \\
& +\left(\frac{L+3\tau k_1NL^2}{2}-\frac{1}{\eta_{\boldsymbol{z}}^t}+\frac{\rho_1|\mathbf{A}^t|L^2}{2}+\frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}\right)||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2 \\
& +\left(\frac{L+3\tau k_1NL^2}{2}-\frac{1}{\eta_{h}^t}+\frac{\rho_1|\mathbf{A}^t|L^2}{2}+\frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}\right)||h^{t+1}-h^t||^2 \\
& +\left(\frac{3\tau k_1NL^2}{2}+\frac{1}{\rho_1}-\frac{c_1^{t-1}-c_1^t}{2}\right)\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2 \\
& +\frac{c_1^{t-1}}{2}\sum_{l=1}^{|\mathbf{A}^t|}(||\lambda_l^{t+1}||^2-||\lambda_l^t||^2)+\frac{1}{2\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t-\lambda_l^{t-1}||^2+\left(\frac{1}{\rho_2}-\frac{c_2^{t-1}-c_2^t}{2}\right)\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2 \\
& +\frac{c_2^{t-1}}{2}\sum_{j=1}^{N}(||\boldsymbol{\phi}_j^{t+1}||^2-||\boldsymbol{\phi}_j^t||^2)+\frac{1}{2\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2.
\end{aligned}
\tag{A.46}
$$

According to Eq. (14), in $(t+1)^{\text{th}}$ iteration, it follows that:

$$
\left\langle \lambda_l^{t+1}-\lambda_l^t-\rho_1\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^t-\lambda_l^{t+1}\right\rangle \geq 0. \tag{A.47}
$$

Similar to Eq. (A.47), in t^{th} iteration, we have,

$$
\left\langle \lambda_l^t-\lambda_l^{t-1}-\rho_1\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle \geq 0. \tag{A.48}
$$

$\forall t \geq T_1$, we can obtain the following inequality,

$$
\begin{aligned}
& \sum_{l=1}^{|\mathbf{A}^t|}\frac{1}{\rho_1}\left\langle \boldsymbol{v}_{1,l}^{t+1},\lambda_l^{t+1}-\lambda_l^t\right\rangle \\
& \leq \sum_{l=1}^{|\mathbf{A}^t|}\Big(\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\lambda_l^{t+1}-\lambda_l^t\right\rangle \\
& \quad +\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\boldsymbol{v}_{1,l}^{t+1}\right\rangle \\
& \quad +\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\}),\lambda_l^t-\lambda_l^{t-1}\right\rangle\Big).
\end{aligned}
\tag{A.49}
$$

Since we have the following equality,

$$
\frac{1}{\rho_1}\left\langle \boldsymbol{v}_{1,l}^{t+1},\lambda_l^{t+1}-\lambda_l^t\right\rangle = \frac{1}{2\rho_1}||\lambda_l^{t+1}-\lambda_l^t||^2+\frac{1}{2\rho_1}||\boldsymbol{v}_{1,l}^{t+1}||^2-\frac{1}{2\rho_1}||\lambda_l^t-\lambda_l^{t-1}||^2, \tag{A.50}
$$

it follows that,

$$\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{1}{2\rho_1}||\lambda_l^{t+1}-\lambda_l^t||^2+\tfrac{1}{2\rho_1}||\boldsymbol{v}_{1,l}^{t+1}||^2-\tfrac{1}{2\rho_1}||\lambda_l^t-\lambda_l^{t-1}||^2)$$
$$\leq\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{L^2}{2b_1^t}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)+\tfrac{b_1^t}{2}||\lambda_l^{t+1}-\lambda_l^t||^2$$
$$+\tfrac{c_1^{t-1}-c_1^t}{2}(||\lambda_l^{t+1}||^2-||\lambda_l^t||^2)-\tfrac{c_1^{t-1}-c_1^t}{2}||\lambda_l^{t+1}-\lambda_l^t||^2$$
$$+\tfrac{\rho_1}{2}||\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\})||^2+\tfrac{1}{2\rho_1}||\boldsymbol{v}_{1,l}^{t+1}||^2$$
$$-\tfrac{1}{L_1{}'+c_1^{t-1}}||\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^{t-1}\},\{\boldsymbol{\phi}_j^{t-1}\})||^2$$
$$-\tfrac{c_1^{t-1}L_1{}'}{L_1{}'+c_1^{t-1}}||\lambda_l^t-\lambda_l^{t-1}||^2), \tag{A.51}$$

where $b_1^t>0$. According to the setting that $c_1^0\leq L_1{}'$, we have $-\frac{c_1^{t-1}L_1{}'}{L_1{}'+c_1^{t-1}}\leq-\frac{c_1^{t-1}L_1{}'}{2L_1{}'}=-\frac{c_1^{t-1}}{2}\leq-\frac{c_1^t}{2}$. Multiplying both sides of the inequality Eq. (A.51) by $\frac{8}{\rho_1 c_1^t}$, we have,

$$\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{4}{\rho_1{}^2c_1^t}||\lambda_l^{t+1}-\lambda_l^t||^2-\tfrac{4}{\rho_1}(\tfrac{c_1^{t-1}-c_1^t}{c_1^t})||\lambda_l^{t+1}||^2)$$
$$\leq\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{4}{\rho_1{}^2c_1^t}||\lambda_l^t-\lambda_l^{t-1}||^2-\tfrac{4}{\rho_1}(\tfrac{c_1^{t-1}-c_1^t}{c_1^t})||\lambda_l^t||^2+\tfrac{4b_1^t}{\rho_1c_1^t}||\lambda_l^{t+1}-\lambda_l^t||^2-\tfrac{4}{\rho_1}||\lambda_l^t-\lambda_l^{t-1}||^2$$
$$+\tfrac{4L^2}{\rho_1c_1^tb_1^t}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)). \tag{A.52}$$

Setting $b_1^t=\frac{c_1^t}{2}$ in Eq. (A.52) and using the definition of S_1^t, we have,

$$S_1^{t+1}-S_1^t$$
$$\leq\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{4}{\rho_1}(\tfrac{c_1^{t-2}}{c_1^{t-1}}-\tfrac{c_1^{t-1}}{c_1^t})||\lambda_l^t||^2+\tfrac{8L^2}{\rho_1(c_1^t)^2}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)$$
$$+(\tfrac{2}{\rho_1}+\tfrac{4}{\rho_1{}^2}(\tfrac{1}{c_1^{t+1}}-\tfrac{1}{c_1^t}))||\lambda_l^{t+1}-\lambda_l^t||^2-\tfrac{4}{\rho_1}||\lambda_l^t-\lambda_l^{t-1}||^2)$$
$$=\sum_{l=1}^{|\mathbf{A}^t|}\tfrac{4}{\rho_1}(\tfrac{c_1^{t-2}}{c_1^{t-1}}-\tfrac{c_1^{t-1}}{c_1^t})||\lambda_l^t||^2+\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{2}{\rho_1}+\tfrac{4}{\rho_1{}^2}(\tfrac{1}{c_1^{t+1}}-\tfrac{1}{c_1^t}))||\lambda_l^{t+1}-\lambda_l^t||^2$$
$$-\sum_{l=1}^{|\mathbf{A}^t|}\tfrac{4}{\rho_1}||\lambda_l^t-\lambda_l^{t-1}||^2+\tfrac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2). \tag{A.53}$$

Likewise, according to Eq. (15), we have that,

$$\tfrac{1}{\rho_2}\left\langle\boldsymbol{v}_{2,l}^{t+1},\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\right\rangle$$
$$\leq\left\langle\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\right\rangle$$
$$=\left\langle\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^{t+1}\},\boldsymbol{z}^{t+1},h^{t+1},\{\lambda_l^{t+1}\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\}),\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\right\rangle$$
$$+\left\langle\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}),\boldsymbol{v}_{2,l}^{t+1}\right\rangle$$
$$+\left\langle\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\}),\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}\right\rangle. \tag{A.54}$$

In addition, since

$$\tfrac{1}{\rho_2}\left\langle\boldsymbol{v}_{2,l}^{t+1},\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t\right\rangle=\tfrac{1}{2\rho_2}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2+\tfrac{1}{2\rho_2}||\boldsymbol{v}_{2,l}^{t+1}||^2-\tfrac{1}{2\rho_2}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2, \tag{A.55}$$

it follows that,

$$\begin{aligned}&\tfrac{1}{2\rho_2}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2+\tfrac{1}{2\rho_2}||\boldsymbol{v}_{2,l}^{t+1}||^2-\tfrac{1}{2\rho_2}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2\\
&\leq \tfrac{L^2}{2b_2^t}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)+\tfrac{b_2^t}{2}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2\\
&+\tfrac{c_2^{t-1}-c_2^t}{2}(||\boldsymbol{\phi}_j^{t+1}||^2-||\boldsymbol{\phi}_j^t||^2)-\tfrac{c_2^{t-1}-c_2^t}{2}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2-\tfrac{c_2^{t-1}L_2'}{L_2'+c_2^{t-1}}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2\\
&+\tfrac{\rho_2}{2}||\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\})||^2+\tfrac{1}{2\rho_2}||\boldsymbol{v}_{2,l}^{t+1}||^2\\
&-\tfrac{1}{L_2'+c_2^{t-1}}||\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^t\})-\nabla_{\boldsymbol{\phi}_j}\widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t,h^t,\{\lambda_l^t\},\{\boldsymbol{\phi}_j^{t-1}\})||^2.\end{aligned} \tag{A.56}$$

According to the setting $c_2^0 \leq L_2{}'$, we have $-\frac{c_2^{t-1}L_2{}'}{L_2{}'+c_2^{t-1}} \leq -\frac{c_2^{t-1}L_2{}'}{2L_2{}'} = -\frac{c_2^{t-1}}{2} \leq -\frac{c_2^t}{2}$. Multiplying both sides of the inequality Eq. (A.56) by $\frac{8}{\rho_2 c_2^t}$, we have,

$$\begin{aligned}&\tfrac{4}{\rho_2{}^2c_2^t}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2-\tfrac{4}{\rho_2}(\tfrac{c_2^{t-1}-c_2^t}{c_2^t})||\boldsymbol{\phi}_j^{t+1}||^2\\
&\leq \tfrac{4}{\rho_2{}^2c_2^t}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2-\tfrac{4}{\rho_2}(\tfrac{c_2^{t-1}-c_2^t}{c_2^t})||\boldsymbol{\phi}_j^t||^2+\tfrac{4b_2^t}{\rho_2c_2^t}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2-\tfrac{4}{\rho_2}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2\\
&+\tfrac{4L^2}{\rho_2c_2^tb_2^t}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2).\end{aligned} \tag{A.57}$$

Setting $b_2^t = \frac{c_2^t}{2}$ in Eq. (A.57) and using the definition of S_2^t, we can obtain,

$$\begin{aligned}&S_2^{t+1}-S_2^t\\
&\leq \sum_{j=1}^{N}(\tfrac{4}{\rho_2}(\tfrac{c_2^{t-2}}{c_2^{t-1}}-\tfrac{c_2^{t-1}}{c_2^t})||\boldsymbol{\phi}_j^t||^2+\tfrac{8L^2}{\rho_2(c_2^t)^2}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2)\\
&+(\tfrac{2}{\rho_2}+\tfrac{2}{\rho_2{}^2}(\tfrac{1}{c_2^{t+1}}-\tfrac{1}{c_2^t}))||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2-\tfrac{4}{\rho_2}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2)\\
&=\sum_{j=1}^{N}\tfrac{4}{\rho_2}(\tfrac{c_2^{t-2}}{c_2^{t-1}}-\tfrac{c_2^{t-1}}{c_2^t})||\boldsymbol{\phi}_j^t||^2+\sum_{j=1}^{N}(\tfrac{2}{\rho_2}+\tfrac{4}{\rho_2{}^2}(\tfrac{1}{c_2^{t+1}}-\tfrac{1}{c_2^t}))||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2\\
&-\sum_{j=1}^{N}\tfrac{4}{\rho_2}||\boldsymbol{\phi}_j^t-\boldsymbol{\phi}_j^{t-1}||^2+\tfrac{8NL^2}{\rho_2(c_2^t)^2}(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2).\end{aligned} \tag{A.58}$$

According to the setting about c_1^t and c_2^t, we have $\frac{\rho_1}{10} \geq \frac{1}{c_1^{t+1}} - \frac{1}{c_1^t}$, $\frac{\rho_2}{10} \geq \frac{1}{c_2^{t+1}} - \frac{1}{c_2^t}, \forall t \geq T_1$. Using the definition of F^{t+1} and combining it with Eq. (A.53) and Eq. (A.58), $\forall t \geq T_1 + \tau$, we have,

$$\begin{aligned}&F^{t+1}-F^t\\
&\leq(\tfrac{L+1}{2}-\tfrac{1}{\eta_{\boldsymbol{w}}^t}+\tfrac{\rho_1|\mathbf{A}^t|L^2}{2}+\tfrac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}+\tfrac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2}+\tfrac{8NL^2}{\rho_2(c_2^t)^2})\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2\\
&+(\tfrac{L+3\tau k_1NL^2}{2}-\tfrac{1}{\eta_{\boldsymbol{z}}^t}+\tfrac{\rho_1|\mathbf{A}^t|L^2}{2}+\tfrac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}+\tfrac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2}+\tfrac{8NL^2}{\rho_2(c_2^t)^2})||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2\\
&+(\tfrac{L+3\tau k_1NL^2}{2}-\tfrac{1}{\eta_h^t}+\tfrac{\rho_1|\mathbf{A}^t|L^2}{2}+\tfrac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2}+\tfrac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2}+\tfrac{8NL^2}{\rho_2(c_2^t)^2})||h^{t+1}-h^t||^2\\
&-(\tfrac{1}{10\rho_1}-\tfrac{3\tau k_1NL^2}{2})\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2-\tfrac{1}{10\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2+\tfrac{c_1^{t-1}-c_1^t}{2}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}||^2\\
&+\tfrac{c_2^{t-1}-c_2^t}{2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}||^2+\tfrac{4}{\rho_1}(\tfrac{c_1^{t-2}}{c_1^{t-1}}-\tfrac{c_1^{t-1}}{c_1^t})\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t||^2+\tfrac{4}{\rho_2}(\tfrac{c_2^{t-2}}{c_2^{t-1}}-\tfrac{c_2^{t-1}}{c_2^t})\sum_{j=1}^{N}||\boldsymbol{\phi}_j^t||^2.\end{aligned} \tag{A.59}$$

Next, we will combine Lemma 1, Lemma 2 with Lemma 3 to derive Theorem 1. Firstly, we make some definitions about our problem.

Definition A.3 *The stationarity gap at t^{th} iteration is defined as:*

$$\nabla G^t = \begin{bmatrix} \{\frac{1}{\alpha_{\boldsymbol{w}}^t}(\boldsymbol{w}_j^t - \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}_j^t - \alpha_{\boldsymbol{w}}^t \nabla_{\boldsymbol{w}_j} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})))\} \\ \frac{1}{\eta_{\boldsymbol{z}}^t}(\boldsymbol{z}^t - \mathcal{P}_{\boldsymbol{\mathcal{Z}}}(\boldsymbol{z}^t - \eta_{\boldsymbol{z}}^t \nabla_{\boldsymbol{z}} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))) \\ \frac{1}{\eta_h^t}(h^t - \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))) \\ \{\frac{1}{\rho_1}(\lambda_l^t - \mathcal{P}_{\boldsymbol{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})))\} \\ \{\frac{1}{\rho_2}(\boldsymbol{\phi}_j^t - \mathcal{P}_{\boldsymbol{\Phi}}(\boldsymbol{\phi}_j^t + \rho_2 \nabla_{\boldsymbol{\phi}_j} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})))\} \end{bmatrix}. \tag{A.60}$$

And we also define:

$$\begin{aligned}
(\nabla G^t)_{\boldsymbol{w}_j} &= \tfrac{1}{\alpha_{\boldsymbol{w}}^t}(\boldsymbol{w}_j^t - \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}_j^t - \alpha_{\boldsymbol{w}}^t \nabla_{\boldsymbol{w}_j} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))), \\
(\nabla G^t)_{\boldsymbol{z}} &= \tfrac{1}{\eta_{\boldsymbol{z}}^t}(\boldsymbol{z}^t - \mathcal{P}_{\boldsymbol{\mathcal{Z}}}(\boldsymbol{z}^t - \eta_{\boldsymbol{z}}^t \nabla_{\boldsymbol{z}} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))), \\
(\nabla G^t)_h &= \tfrac{1}{\eta_h^t}(h^t - \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))), \\
(\nabla G^t)_{\lambda_l} &= \tfrac{1}{\rho_1}(\lambda_l^t - \mathcal{P}_{\boldsymbol{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))), \\
(\nabla G^t)_{\boldsymbol{\phi}_j} &= \tfrac{1}{\rho_2}(\boldsymbol{\phi}_j^t - \mathcal{P}_{\boldsymbol{\Phi}}(\boldsymbol{\phi}_j^t + \rho_2 \nabla_{\boldsymbol{\phi}_j} L_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))).
\end{aligned} \tag{A.61}$$

It follows that,

$$||\nabla G^t||^2 = \sum_{j=1}^{N} ||(\nabla G^t)_{\boldsymbol{w}_j}||^2 + ||(\nabla G^t)_{\boldsymbol{z}}||^2 + ||(\nabla G^t)_h||^2 + \sum_{l=1}^{|\mathbf{A}^t|} ||(\nabla G^t)_{\lambda_l}||^2 + \sum_{j=1}^{N} ||(\nabla G^t)_{\boldsymbol{\phi}_j}||^2. \tag{A.62}$$

Definition A.4 *At t^{th} iteration, the stationarity gap w.r.t $\widetilde{L}_p(\{\boldsymbol{w}_j\},\boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\})$ is defined as:*

$$\nabla \widetilde{G}^t = \begin{bmatrix} \{\frac{1}{\alpha_{\boldsymbol{w}}^t}(\boldsymbol{w}_j^t - \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}_j^t - \alpha_{\boldsymbol{w}}^t \nabla_{\boldsymbol{w}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})))\} \\ \frac{1}{\eta_{\boldsymbol{z}}^t}(\boldsymbol{z}^t - \mathcal{P}_{\boldsymbol{\mathcal{Z}}}(\boldsymbol{z}^t - \eta_{\boldsymbol{z}}^t \nabla_{\boldsymbol{z}} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))) \\ \frac{1}{\eta_h^t}(h^t - \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))) \\ \{\frac{1}{\rho_1}(\lambda_l^t - \mathcal{P}_{\boldsymbol{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})))\} \\ \{\frac{1}{\rho_2}(\boldsymbol{\phi}_j^t - \mathcal{P}_{\boldsymbol{\Phi}}(\boldsymbol{\phi}_j^t + \rho_2 \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\})))\} \end{bmatrix}. \tag{A.63}$$

We further define:

$$\begin{aligned}
(\nabla \widetilde{G}^t)_{\boldsymbol{w}_j} &= \tfrac{1}{\alpha_{\boldsymbol{w}}^t}(\boldsymbol{w}_j^t - \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}_j^t - \alpha_{\boldsymbol{w}}^t \nabla_{\boldsymbol{w}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))), \\
(\nabla \widetilde{G}^t)_{\boldsymbol{z}} &= \tfrac{1}{\eta_{\boldsymbol{z}}^t}(\boldsymbol{z}^t - \mathcal{P}_{\boldsymbol{\mathcal{Z}}}(\boldsymbol{z}^t - \eta_{\boldsymbol{z}}^t \nabla_{\boldsymbol{z}} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))), \\
(\nabla \widetilde{G}^t)_h &= \tfrac{1}{\eta_h^t}(h^t - \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))), \\
(\nabla \widetilde{G}^t)_{\lambda_l} &= \tfrac{1}{\rho_1}(\lambda_l^t - \mathcal{P}_{\boldsymbol{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))), \\
(\nabla \widetilde{G}^t)_{\boldsymbol{\phi}_j} &= \tfrac{1}{\rho_2}(\boldsymbol{\phi}_j^t - \mathcal{P}_{\boldsymbol{\Phi}}(\boldsymbol{\phi}_j^t + \rho_2 \nabla_{\boldsymbol{\phi}_j} \widetilde{L}_p(\{\boldsymbol{w}_j^t\},\boldsymbol{z}^t, h^t, \{\lambda_l^t\}, \{\boldsymbol{\phi}_j^t\}))).
\end{aligned} \tag{A.64}$$

It follows that,

$$||\nabla \widetilde{G}^t||^2 = \sum_{j=1}^{N} ||(\nabla \widetilde{G}^t)_{\boldsymbol{w}_j}||^2 + ||(\nabla \widetilde{G}^t)_{\boldsymbol{z}}||^2 + ||(\nabla \widetilde{G}^t)_h||^2 + \sum_{l=1}^{|\mathbf{A}^t|} ||(\nabla \widetilde{G}^t)_{\lambda_l}||^2 + \sum_{j=1}^{N} ||(\nabla \widetilde{G}^t)_{\boldsymbol{\phi}_j}||^2. \tag{A.65}$$

Definition A.5 *In our asynchronous algorithm, for the worker j in t^{th} iteration, we define the last iteration where worker j was active as $\widetilde{t}_j$. And we define the next iteration that worker j will be active as $\overline{t_j}$. For the iteration index set that worker j is active from T_1^{th} to $(T_1+T+\tau)^{th}$ iteration, we define it as $\mathcal{V}_j(T)$. And the i^{th} element in $\mathcal{V}_j(T)$ is defined as $\hat{v}_j(i)$.*

Proof of Theorem 1:

Firstly, setting:

$$a_5^t = \tfrac{4|\mathbf{A}^t|(\gamma-2)L^2}{\rho_1(c_1^t)^2} + \tfrac{4N(\gamma-2)L^2}{\rho_2(c_2^t)^2} + \tfrac{\rho_2(N-|\mathbf{Q}^{t+1}|)L^2}{2} - \tfrac{1}{2}, \tag{A.66}$$

$$a_6^t = \tfrac{4|\mathbf{A}^t|(\gamma-2)L^2}{\rho_1(c_1^t)^2} + \tfrac{4N(\gamma-2)L^2}{\rho_2(c_2^t)^2} + \tfrac{\rho_2(N-|\mathbf{Q}^{t+1}|)L^2}{2} - \tfrac{3\tau k_1 NL^2}{2}, \tag{A.67}$$

where γ is a constant which satisfies $\gamma > 2$ and $\frac{4(\gamma-2)L^2}{\rho_1(c_1^0)^2} + \frac{4N(\gamma-2)L^2}{\rho_2(c_2^0)^2} + \frac{\rho_2(N-S)L^2}{2} \geq \max\{\frac{1}{2}, \frac{3\tau k_1 NL^2}{2}\}$. It is seen that the a_5^t, a_6^t are nonnegative sequences. Since $\forall t \geq 0$, $|\mathbf{A}^0| \leq |\mathbf{A}^t|$, $(c_1^0)^2 \geq (c_1^t)^2$, $(c_2^0)^2 \geq (c_2^t)^2$, and we assume that $|\mathbf{Q}^{t+1}| = S, \forall t$, thus we have $a_5^0 \leq a_5^t, a_6^0 \leq a_6^t, \forall t$. According to the setting of $\eta_{\boldsymbol{w}}^t$, $\eta_{\boldsymbol{z}}^t$, η_h^t and c_1^t, c_2^t, we have,

$$\frac{L+1}{2} - \frac{1}{\eta_{\boldsymbol{w}}^t} + \frac{\rho_1|\mathbf{A}^t|L^2}{2} + \frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2} + \frac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2} + \frac{8NL^2}{\rho_2(c_2^t)^2} = -a_5^t, \tag{A.68}$$

$$\frac{L+3\tau k_1 NL^2}{2} - \frac{1}{\eta_{\boldsymbol{z}}^t} + \frac{\rho_1|\mathbf{A}^t|L^2}{2} + \frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2} + \frac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2} + \frac{8NL^2}{\rho_2(c_2^t)^2} = -a_6^t, \tag{A.69}$$

$$\frac{L+3\tau k_1 NL^2}{2} - \frac{1}{\eta_h^t} + \frac{\rho_1|\mathbf{A}^t|L^2}{2} + \frac{\rho_2|\mathbf{Q}^{t+1}|L^2}{2} + \frac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2} + \frac{8NL^2}{\rho_2(c_2^t)^2} = -a_6^t. \tag{A.70}$$

Combining Eq. (A.68), (A.69), (A.70) with Lemma 3, $\forall t \geq T_1 + \tau$, it follows that,

$$\begin{aligned}
& a_5^t \sum_{j=1}^{N} ||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 + a_6^t ||\boldsymbol{z}^{t+1} - \boldsymbol{z}^t||^2 + a_6^t ||h^{t+1} - h^t||^2 \\
& + (\tfrac{1}{10\rho_1} - \tfrac{3\tau k_1 NL^2}{2}) \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^{t+1} - \lambda_l^t||^2 + \tfrac{1}{10\rho_2} \sum_{j=1}^{N} ||\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t||^2 \\
& \leq F^t - F^{t+1} + \tfrac{c_1^{t-1} - c_1^t}{2} \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^{t+1}||^2 + \tfrac{c_2^{t-1} - c_2^t}{2} \sum_{j=1}^{N} ||\boldsymbol{\phi}_j^{t+1}||^2 \\
& + \tfrac{4}{\rho_1} (\tfrac{c_1^{t-2}}{c_1^{t-1}} - \tfrac{c_1^{t-1}}{c_1^t}) \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^t||^2 + \tfrac{4}{\rho_2} (\tfrac{c_2^{t-2}}{c_2^{t-1}} - \tfrac{c_2^{t-1}}{c_2^t}) \sum_{j=1}^{N} ||\boldsymbol{\phi}_j^t||^2.
\end{aligned} \tag{A.71}$$

Combining the definition of $(\nabla \widetilde{G}^t)_{\boldsymbol{w}_j}$ with trigonometric inequality, Cauchy-Schwarz inequality and Assumption 1 and 2, $\forall t \geq T_1 + \tau$, we have,

$$||(\nabla \widetilde{G}^t)_{\boldsymbol{w}_j}||^2 \leq \tfrac{2}{\underline{\eta_{\boldsymbol{w}}}^2} ||\boldsymbol{w}_j^{\overline{t_j}} - \boldsymbol{w}_j^t||^2 + 6\tau k_1 L^2 (||\boldsymbol{z}^{t+1} - \boldsymbol{z}^t||^2 + ||h^{t+1} - h^t||^2 + \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^{t+1} - \lambda_l^t||^2). \tag{A.72}$$

Combining the definition of $(\nabla \widetilde{G}^t)_{\boldsymbol{z}}$ with trigonometric inequality and Cauchy-Schwarz inequality, we can obtain the following inequality,

$$||(\nabla \widetilde{G}^t)_{\boldsymbol{z}}||^2 \leq 2L^2 \sum_{j=1}^{N} ||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 + \tfrac{2}{(\eta_{\boldsymbol{z}}^t)^2} ||\boldsymbol{z}^{t+1} - \boldsymbol{z}^t||^2. \tag{A.73}$$

Likewise, combining the definition of $(\nabla \widetilde{G}^t)_h$ with trigonometric inequality and Cauchy-Schwarz inequality, we have that,

$$||(\nabla \widetilde{G}^t)_h||^2 \leq 2L^2 (\sum_{j=1}^{N} ||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 + ||\boldsymbol{z}^{t+1} - \boldsymbol{z}^t||^2) + \tfrac{2}{(\eta_h^t)^2} ||h^{t+1} - h^t||^2. \tag{A.74}$$

Combining the definition of $(\nabla\widetilde{G}^t)_{\lambda_l}$ with trigonometric inequality and Cauchy-Schwarz inequality,

$$
\begin{aligned}
&||(\nabla\widetilde{G}^t)_{\lambda_l}||^2\\
&\leq \tfrac{3}{{\rho_1}^2}||\lambda_l^{t+1}-\lambda_l^t||^2+3L^2(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)+3(c_1^{t-1}-c_1^t)^2||\lambda_l^t||^2\\
&\leq \tfrac{3}{{\rho_1}^2}||\lambda_l^{t+1}-\lambda_l^t||^2+3L^2(\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2)+3((c_1^{t-1})^2-(c_1^t)^2)||\lambda_l^t||^2.
\end{aligned}
\tag{A.75}
$$

Combining the definition of $(\nabla\widetilde{G}^t)_{\boldsymbol{\phi}_j}$ with Cauchy-Schwarz inequality and Assumption 2, we have,

$$
\begin{aligned}
&||(\nabla\widetilde{G}^t)_{\boldsymbol{\phi}_j}||^2\\
&\leq \tfrac{3}{{\rho_2}^2}||\boldsymbol{\phi}_j^{\overline{t_j}}-\boldsymbol{\phi}_j^t||^2+3L^2(\sum_{j=1}^{N}||\boldsymbol{w}_j^{\overline{t_j}}-\boldsymbol{w}_j^t||^2+||\boldsymbol{z}^{\overline{t_j}}-\boldsymbol{z}^t||^2)+3(c_2^{\widetilde{t_j}-1}-c_2^{\overline{t_j}-1})^2||\boldsymbol{\phi}_j^t||^2\\
&\leq \tfrac{3}{{\rho_2}^2}||\boldsymbol{\phi}_j^{\overline{t_j}}-\boldsymbol{\phi}_j^t||^2+3L^2(\sum_{j=1}^{N}||\boldsymbol{w}_j^{\overline{t_j}}-\boldsymbol{w}_j^t||^2+\tau k_1(||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+||h^{t+1}-h^t||^2+\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2))\\
&\quad+3((c_2^{\widetilde{t_j}-1})^2-(c_2^{\overline{t_j}-1})^2)||\boldsymbol{\phi}_j^t||^2.
\end{aligned}
\tag{A.76}
$$

According to the Definition A.4 as well as Eq. (A.72), (A.73), (A.74), (A.75) and Eq. (A.76), $\forall t \geq T_1+\tau$, we have that,

$$
\begin{aligned}
||\nabla\widetilde{G}^t||^2 &= \sum_{j=1}^{N}||(\nabla\widetilde{G}^t)_{\boldsymbol{w}_j}||^2+||(\nabla\widetilde{G}^t)_{\boldsymbol{z}}||^2+||(\nabla\widetilde{G}^t)_h||^2+\sum_{l=1}^{|\mathbf{A}^t|}||(\nabla\widetilde{G}^t)_{\lambda_l}||^2+\sum_{j=1}^{N}||(\nabla\widetilde{G}^t)_{\boldsymbol{\phi}_j}||^2\\
&\leq (\tfrac{2}{{\underline{\eta_{\boldsymbol{w}}}}^2}+3NL^2)\sum_{j=1}^{N}||\boldsymbol{w}_j^{\overline{t_j}}-\boldsymbol{w}_j^t||^2+(4+3|\mathbf{A}^t|)L^2\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2\\
&\quad+(\tfrac{2}{(\eta_{\boldsymbol{z}}^t)^2}+(2+9\tau k_1N+3|\mathbf{A}^t|)L^2)||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+(\tfrac{2}{(\eta_h^t)^2}+(9\tau k_1N+3|\mathbf{A}^t|)L^2)||h^{t+1}-h^t||^2\\
&\quad+\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{3}{{\rho_1}^2}+9\tau k_1NL^2)||\lambda_l^{t+1}-\lambda_l^t||^2+\sum_{l=1}^{|\mathbf{A}^t|}3((c_1^{t-1})^2-(c_1^t)^2)||\lambda_l^t||^2\\
&\quad+\sum_{j=1}^{N}\tfrac{3}{{\rho_2}^2}||\boldsymbol{\phi}_j^{\overline{t_j}}-\boldsymbol{\phi}_j^t||^2+\sum_{j=1}^{N}3((c_2^{\widetilde{t_j}-1})^2-(c_2^{\overline{t_j}-1})^2)||\boldsymbol{\phi}_j^t||^2.
\end{aligned}
\tag{A.77}
$$

We set constants d_1, d_2, d_3 as,

$$
d_1 = \frac{2k_\tau\tau+(4+3M+3k_\tau\tau N)L^2{\underline{\eta_{\boldsymbol{w}}}}^2}{{\underline{\eta_{\boldsymbol{w}}}}^2(a_5^0)^2} \geq \frac{2k_\tau\tau+(4+3|\mathbf{A}^t|+3k_\tau\tau N)L^2{\underline{\eta_{\boldsymbol{w}}}}^2}{{\underline{\eta_{\boldsymbol{w}}}}^2(a_5^t)^2}, \tag{A.78}
$$

$$
d_2 = \frac{2+(2+9\tau k_1N+3M)L^2{\underline{\eta_{\boldsymbol{z}}}}^2}{{\underline{\eta_{\boldsymbol{z}}}}^2(a_6^0)^2} \geq \frac{2+(2+9\tau k_1N+3|\mathbf{A}^t|)L^2(\eta_{\boldsymbol{z}}^t)^2}{(\eta_{\boldsymbol{z}}^t)^2(a_6^t)^2}, \tag{A.79}
$$

$$
d_3 = \frac{2+(9\tau k_1N+3M)L^2{\underline{\eta_h}}^2}{{\underline{\eta_h}}^2(a_6^0)^2} \geq \frac{2+(9\tau k_1N+3|\mathbf{A}^t|)L^2(\eta_h^t)^2}{(\eta_h^t)^2(a_6^t)^2}, \tag{A.80}
$$

where k_τ, $\underline{\eta_{\boldsymbol{z}}}$ and $\underline{\eta_h}$ are positive constants. $\underline{\eta_{\boldsymbol{z}}} = \frac{2}{L+\rho_1ML^2+\rho_2NL^2+8(\frac{M\gamma L^2}{\rho_1{\underline{c_1}}^2}+\frac{N\gamma L^2}{\rho_2{\underline{c_2}}^2})} \leq \eta_{\boldsymbol{z}}^t$ and $\underline{\eta_h} = \frac{2}{L+\rho_1ML^2+\rho_2NL^2+8(\frac{M\gamma L^2}{\rho_1{\underline{c_1}}^2}+\frac{N\gamma L^2}{\rho_2{\underline{c_2}}^2})} \leq \eta_h^t, \forall t$. Thus, combining Eq. (A.77) with Eq. (A.78), (A.79), (A.80), $\forall t \geq T_1+\tau$, we have,

$$
\begin{aligned}
||\nabla\widetilde{G}^t||^2 &\leq \sum_{j=1}^{N}d_1(a_5^t)^2||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+d_2(a_6^t)^2||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+d_3(a_6^t)^2||h^{t+1}-h^t||^2\\
&\quad+\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{3}{{\rho_1}^2}+9\tau k_1NL^2)||\lambda_l^{t+1}-\lambda_l^t||^2+\sum_{l=1}^{|\mathbf{A}^t|}3((c_1^{t-1})^2-(c_1^t)^2)||\lambda_l^t||^2+\sum_{j=1}^{N}\tfrac{3}{{\rho_2}^2}||\boldsymbol{\phi}_j^{\overline{t_j}}-\boldsymbol{\phi}_j^t||^2\\
&\quad+\sum_{j=1}^{N}3((c_2^{\widetilde{t_j}-1})^2-(c_2^{\overline{t_j}-1})^2)||\boldsymbol{\phi}_j^t||^2+(\tfrac{2}{{\underline{\eta_{\boldsymbol{w}}}}^2}+3NL^2)\sum_{j=1}^{N}||\boldsymbol{w}_j^{\overline{t_j}}-\boldsymbol{w}_j^t||^2\\
&\quad-(\tfrac{2k_\tau\tau}{{\underline{\eta_{\boldsymbol{w}}}}^2}+3k_\tau\tau NL^2)\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2.
\end{aligned}
\tag{A.81}
$$

Let d_4^t denote a nonnegative sequence:

$$d_4^t = \frac{1}{\max\{d_1 a_5^t, d_2 a_6^t, d_3 a_6^t, \frac{\frac{30}{\rho_1}+90\rho_1\tau k_1 NL^2}{1-15\rho_1\tau k_1 NL^2}, \frac{30\tau}{\rho_2}\}}. \tag{A.82}$$

It is seen that $d_4^0 \geq d_4^t, \forall t \geq 0$. And we denote the lower bound of d_4^t as $\underline{d_4}$, it appears that $d_4^t \geq \underline{d_4} \geq 0, \forall t \geq 0$. And we set the constant k_τ satisfies $k_\tau \geq \frac{d_4^0(\frac{2}{\underline{\eta_{\boldsymbol{w}}}^2}+3NL^2)}{\underline{d_4}(\frac{2}{\overline{\eta_{\boldsymbol{w}}}^2}+3NL^2)}$, where $\overline{\eta_{\boldsymbol{w}}}$ is the step-size in terms of $\boldsymbol{w}_j$ in the first iteration (it is seen that $\overline{\eta_{\boldsymbol{w}}} \geq \eta_{\boldsymbol{w}}^t, \forall t$). Then, $\forall t \geq T_1+\tau$, we can obtain the following inequality from Eq. (A.81) and Eq. (A.82):

$$\begin{aligned}
d_4^t||\nabla\widetilde{G}^t||^2 \leq\, & a_5^t\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2+a_6^t||\boldsymbol{z}^{t+1}-\boldsymbol{z}^t||^2+a_6^t||h^{t+1}-h^t||^2\\
&+(\tfrac{1}{10\rho_1}-\tfrac{3\tau k_1 NL^2}{2})\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2+\tfrac{1}{10\tau\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{\overline{t_j}}-\boldsymbol{\phi}_j^t||^2\\
&+3d_4^t((c_1^{t-1})^2-(c_1^t)^2)\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t||^2+3d_4^t\sum_{j=1}^{N}((c_2^{\widetilde{t_j}-1})^2-(c_2^{\overline{t_j}-1})^2)||\boldsymbol{\phi}_j^t||^2\\
&+d_4^t(\tfrac{2}{\underline{\eta_{\boldsymbol{w}}}^2}+3NL^2)\sum_{j=1}^{N}||\boldsymbol{w}_j^{\overline{t_j}}-\boldsymbol{w}_j^t||^2-d_4^t(\tfrac{2k_\tau\tau}{\underline{\eta_{\boldsymbol{w}}}^2}+3k_\tau\tau NL^2)\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2.
\end{aligned} \tag{A.83}$$

Combining Eq. (A.83) with Eq. (A.71) and according to the setting $||\lambda_l^t||^2 \leq {\sigma_1}^2$, $||\boldsymbol{\phi}_j^t||^2 \leq {\sigma_2}^2$ (where ${\sigma_1}^2 = {\alpha_3}^2$, ${\sigma_2}^2 = p{\alpha_4}^2$) and $d_4^0 \geq d_4^t \geq \underline{d_4}$, thus, $\forall t \geq T_1+\tau$, we have,

$$\begin{aligned}
& d_4^t||\nabla\widetilde{G}^t||^2\\
&\leq F^t - F^{t+1} + \tfrac{c_1^{t-1}-c_1^t}{2}M{\sigma_1}^2 + \tfrac{c_2^{t-1}-c_2^t}{2}N{\sigma_2}^2 + \tfrac{4}{\rho_1}(\tfrac{c_1^{t-2}}{c_1^{t-1}} - \tfrac{c_1^{t-1}}{c_1^t})M{\sigma_1}^2\\
&+\tfrac{4}{\rho_2}(\tfrac{c_2^{t-2}}{c_2^{t-1}} - \tfrac{c_2^{t-1}}{c_2^t})N{\sigma_2}^2 + 3d_4^0((c_1^{t-1})^2-(c_1^t)^2)M{\sigma_1}^2 + 3d_4^0\sum_{j=1}^{N}((c_2^{\widetilde{t_j}-1})^2-(c_2^{\overline{t_j}-1})^2){\sigma_2}^2\\
&+\tfrac{1}{10\tau\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{\overline{t_j}}-\boldsymbol{\phi}_j^t||^2 - \tfrac{1}{10\rho_2}\sum_{j=1}^{N}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2\\
&+d_4^0(\tfrac{2}{\underline{\eta_{\boldsymbol{w}}}^2}+3NL^2)\sum_{j=1}^{N}||\boldsymbol{w}_j^{\overline{t_j}}-\boldsymbol{w}_j^t||^2 - \underline{d_4}(\tfrac{2k_\tau\tau}{\underline{\eta_{\boldsymbol{w}}}^2}+3k_\tau\tau NL^2)\sum_{j=1}^{N}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2.
\end{aligned} \tag{A.84}$$

Denoting $\widetilde{T}(\varepsilon)$ as $\widetilde{T}(\varepsilon) = \min\{t \mid ||\nabla\widetilde{G}^{T_1+t}|| \leq \frac{\varepsilon}{2}, t \geq \tau\}$. Summing up Eq. (A.84) from $t = T_1+\tau$ to $t = T_1+\widetilde{T}(\varepsilon)$, we have,

$$\begin{aligned}
&\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} d_4^t||\nabla\widetilde{G}^t||^2\\
&\leq F^{T_1+\tau} - \underline{L} + \tfrac{4}{\rho_1}(\tfrac{c_1^{T_1+\tau-2}}{c_1^{T_1+\tau-1}} + \tfrac{c_1^{T_1+\tau-1}}{c_1^{T_1+\tau}})M{\sigma_1}^2 + \tfrac{c_1^{T_1+\tau-1}}{2}M{\sigma_1}^2 + \tfrac{7}{2\rho_1}M{\sigma_3}^2 + 3d_4^0(c_1^0)^2M{\sigma_1}^2\\
&+\tfrac{4}{\rho_2}(\tfrac{c_1^{T_1+\tau-2}}{c_1^{T_1+\tau-1}} + \tfrac{c_1^{T_1+\tau-1}}{c_1^{T_1+\tau}})N{\sigma_2}^2 + \tfrac{c_2^{T_1+\tau-1}}{2}N{\sigma_2}^2 + \tfrac{7}{2\rho_2}N{\sigma_4}^2 + \sum_{j=1}^{N}\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)}3d_4^0((c_2^{\widetilde{t_j}-1})^2-(c_2^{\overline{t_j}-1})^2){\sigma_2}^2\\
&+\tfrac{c_1^{T_1+\tau}}{2}M{\sigma_1}^2 + \tfrac{c_2^{T_1+\tau}}{2}N{\sigma_2}^2 + \tfrac{1}{10\tau\rho_2}\sum_{j=1}^{N}\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)}||\boldsymbol{\phi}_j^{\overline{t_j}}-\boldsymbol{\phi}_j^t||^2 - \tfrac{1}{10\rho_2}\sum_{j=1}^{N}\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)}||\boldsymbol{\phi}_j^{t+1}-\boldsymbol{\phi}_j^t||^2\\
&+d_4^0(\tfrac{2}{\underline{\eta_{\boldsymbol{w}}}^2}+3NL^2)\sum_{j=1}^{N}\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)}||\boldsymbol{w}_j^{\overline{t_j}}-\boldsymbol{w}_j^t||^2 - \underline{d_4}(\tfrac{2k_\tau\tau}{\overline{\eta_{\boldsymbol{w}}}^2}+3k_\tau\tau NL^2)\sum_{j=1}^{N}\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)}||\boldsymbol{w}_j^{t+1}-\boldsymbol{w}_j^t||^2,
\end{aligned} \tag{A.85}$$

where $\sigma_3 = \max\{||\lambda_1 - \lambda_2|| \,|\lambda_1, \lambda_2 \in \mathbf{\Lambda}\}$, $\sigma_4 = \max\{||\boldsymbol{\phi}_1 - \boldsymbol{\phi}_2|| \,|\boldsymbol{\phi}_1, \boldsymbol{\phi}_2 \in \mathbf{\Phi}\}$ and $\underline{L} = \min\limits_{\{\boldsymbol{w}_j \in \boldsymbol{\mathcal{W}}\}, \boldsymbol{z} \in \boldsymbol{\mathcal{Z}}, h \in \boldsymbol{\mathcal{H}}, \{\lambda_l \in \mathbf{\Lambda}\}, \{\boldsymbol{\phi}_j \in \mathbf{\Phi}\}} L_p(\{\boldsymbol{w}_j\}, \boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\})$, which satisfy that, $\forall t \geq T_1 + \tau$,

$$F^{t+1} \geq \underline{L} - \frac{4}{\rho_1} \frac{c_1^{T_1+\tau-1}}{c_1^{T_1+\tau}} M{\sigma_1}^2 - \frac{4}{\rho_2} \frac{c_2^{T_1+\tau-1}}{c_2^{T_1+\tau}} N{\sigma_2}^2 - \frac{7}{2\rho_1} M{\sigma_3}^2 - \frac{7}{2\rho_2} N{\sigma_4}^2 - \frac{c_1^{T_1+\tau}}{2} M{\sigma_1}^2 - \frac{c_2^{T_1+\tau}}{2} N{\sigma_2}^2. \tag{A.86}$$

For each worker j, the iterations between the last iteration and the next iteration where it is active is no more than τ, *i.e.*, $\overline{t_j} - \widetilde{t_j} \leq \tau$, we have,

$$\begin{aligned}
&\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} 3d_4^0((c_2^{\widetilde{t_j}-1})^2 - (c_2^{\overline{t_j}-1})^2){\sigma_2}^2 \\
&\leq \tau \sum_{\substack{\hat{v}_j(i) \in \mathcal{V}_j(\widetilde{T}(\varepsilon)), \\ T_1+\tau \leq \hat{v}_j(i) \leq T_1+\widetilde{T}(\varepsilon)}} 3d_4^0((c_2^{\hat{v}_j(i)-1})^2 - (c_2^{\hat{v}_j(i+1)-1})^2){\sigma_2}^2 \\
&\leq 3\tau d_4^0(c_2^0)^2{\sigma_2}^2.
\end{aligned} \tag{A.87}$$

Since the idle workers do not update their variables in each iteration, for any t that satisfies $\hat{v}_j(i-1) \leq t < \hat{v}_j(i)$, we have $\boldsymbol{\phi}_j^t = \boldsymbol{\phi}_j^{\hat{v}_j(i)-1}$. And for $t \notin \mathcal{V}_j(T)$, we have $||\boldsymbol{\phi}_j^t - \boldsymbol{\phi}_j^{t-1}||^2 = 0$. Combing with $\hat{v}_j(i) - \hat{v}_j(i-1) \leq \tau$, we can obtain that,

$$\begin{aligned}
\sum_{j=1}^{N} \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} ||\boldsymbol{\phi}_j^{\overline{t_j}} - \boldsymbol{\phi}_j^t||^2 &\leq \tau \sum_{j=1}^{N} \sum_{\substack{\hat{v}_j(i) \in \mathcal{V}_j(\widetilde{T}(\varepsilon)), \\ T_1+\tau+1 \leq \hat{v}_j(i)}} ||\boldsymbol{\phi}_j^{\hat{v}_j(i)} - \boldsymbol{\phi}_j^{\hat{v}_j(i)-1}||^2 \\
&= \tau \sum_{j=1}^{N} \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} ||\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t||^2 + \tau \sum_{j=1}^{N} \sum_{t=T_1+\widetilde{T}(\varepsilon)+1}^{T_1+\widetilde{T}(\varepsilon)+\tau-1} ||\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t||^2 \\
&\leq \tau \sum_{j=1}^{N} \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} ||\boldsymbol{\phi}_j^{t+1} - \boldsymbol{\phi}_j^t||^2 + 4\tau(\tau-1)N{\sigma_2}^2.
\end{aligned} \tag{A.88}$$

Similarly, for any t that satisfies $\hat{v}_j(i-1) \leq t < \hat{v}_j(i)$, we have $\boldsymbol{w}_j^t = \boldsymbol{w}_j^{\hat{v}_j(i)-1}$. And for $t \notin \mathcal{V}_j(T)$, we have $||\boldsymbol{w}_j^t - \boldsymbol{w}_j^{t-1}||^2 = 0$. Combing with $\hat{v}_j(i) - \hat{v}_j(i-1) \leq \tau$, we can obtain,

$$\begin{aligned}
\sum_{j=1}^{N} \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} ||\boldsymbol{w}_j^{\overline{t_j}} - \boldsymbol{w}_j^t||^2 &\leq \tau \sum_{j=1}^{N} \sum_{\substack{\hat{v}_j(i) \in \mathcal{V}_j(\widetilde{T}(\varepsilon)), \\ T_1+\tau+1 \leq \hat{v}_j(i)}} ||\boldsymbol{w}_j^{\hat{v}_j(i)} - \boldsymbol{w}_j^{\hat{v}_j(i)-1}||^2 \\
&= \tau \sum_{j=1}^{N} \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} ||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 + \tau \sum_{j=1}^{N} \sum_{t=T_1+\widetilde{T}(\varepsilon)+1}^{T_1+\widetilde{T}(\varepsilon)+\tau-1} ||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 \\
&\leq \tau \sum_{j=1}^{N} \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} ||\boldsymbol{w}_j^{t+1} - \boldsymbol{w}_j^t||^2 + 4\tau(\tau-1)pN{\alpha_1}^2.
\end{aligned} \tag{A.89}$$

It follows from Eq. (A.85), (A.87), (A.88), (A.89) that,

$$\begin{aligned}
&\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} d_4^t ||\nabla \widetilde{G}^t||^2 \\
&\leq F^{T_1+\tau} - \underline{L} + \tfrac{4}{\rho_1}\left(\tfrac{c_1^{T_1+\tau-2}}{c_1^{T_1+\tau-1}} + \tfrac{c_1^{T_1+\tau-1}}{c_1^{T_1+\tau}}\right)M{\sigma_1}^2 + \tfrac{c_1^{T_1+\tau-1}}{2}M{\sigma_1}^2 + \tfrac{7}{2\rho_1}M{\sigma_3}^2 + 3d_4^0(c_1^0)^2M{\sigma_1}^2 \\
&+ \tfrac{4}{\rho_2}\left(\tfrac{c_1^{T_1+\tau-2}}{c_1^{T_1+\tau-1}} + \tfrac{c_1^{T_1+\tau-1}}{c_1^{T_1+\tau}}\right)N{\sigma_2}^2 + \tfrac{c_2^{T_1+\tau-1}}{2}N{\sigma_2}^2 + \tfrac{7}{2\rho_2}N{\sigma_4}^2 + 3\tau d_4^0(c_2^0)^2N{\sigma_2}^2 \\
&+ \tfrac{c_1^{T_1+\tau}}{2}M{\sigma_1}^2 + \tfrac{c_2^{T_1+\tau}}{2}N{\sigma_2}^2 + \left(\tfrac{2N{\sigma_2}^2}{5\rho_2} + 4d_4^0\left(\tfrac{2}{\underline{\eta_{\boldsymbol{w}}}^2} + 3NL^2\right)pN{\alpha_1}^2\tau\right)(\tau-1) \\
&= \overline{d} + k_d(\tau-1),
\end{aligned} \tag{A.90}$$

where $\bar{d}$ and k_d are constants. And constant d_5 is given by,

$$\begin{aligned}
d_5 &= \max\{\tfrac{d_1}{a_6^0}, \tfrac{d_2}{a_5^0}, \tfrac{d_3}{a_5^0}, \tfrac{\frac{30}{\rho_1}+90\rho_1\tau k_1 NL^2}{(1-15\rho_1\tau k_1 NL^2)a_5^0 a_6^0}, \tfrac{30\tau}{\rho_2 a_5^0 a_6^0}\} \\
&\geq \max\{\tfrac{d_1}{a_6^t}, \tfrac{d_2}{a_5^t}, \tfrac{d_3}{a_5^t}, \tfrac{\frac{30}{\rho_1}+90\rho_1\tau k_1 NL^2}{(1-15\rho_1\tau k_1 NL^2)a_5^t a_6^t}, \tfrac{30\tau}{\rho_2 a_5^t a_6^t}\} \\
&= \tfrac{1}{d_4^t a_5^t a_6^t}.
\end{aligned} \tag{A.91}$$

Thus, we can obtain that,

$$\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} \frac{1}{d_5 a_5^t a_6^t}||\nabla \widetilde{G}^{T_1+\widetilde{T}(\varepsilon)}||^2 \leq \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} \frac{1}{d_5 a_5^t a_6^t}||\nabla \widetilde{G}^t||^2 \leq \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} d_4^t ||\nabla \widetilde{G}^t||^2 \leq \bar{d} + k_d(\tau-1). \tag{A.92}$$

And it follows from Eq. (A.92) that,

$$||\nabla \widetilde{G}^{T_1+\widetilde{T}(\varepsilon)}||^2 \leq \frac{(\bar{d} + k_d(\tau-1))d_5}{\sum\limits_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} \frac{1}{a_5^t a_6^t}}. \tag{A.93}$$

According to the setting of c_1^t, c_2^t and Eq. (A.66), (A.67), we have,

$$\frac{1}{a_5^t a_6^t} \geq \frac{1}{\left(4(\gamma-2)L^2(M\rho_1+N\rho_2)(t+1)^{\frac{1}{3}} + \frac{\rho_2(N-S)L^2}{2}\right)^2}. \tag{A.94}$$

Summing up $\frac{1}{a_5^t a_6^t}$ from $t = T_1+\tau$ to $t = T_1+\widetilde{T}(\varepsilon)$, it follows that,

$$\begin{aligned}
\sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} \tfrac{1}{a_5^t a_6^t} &\geq \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} \tfrac{1}{\left(4(\gamma-2)L^2(M\rho_1+N\rho_2)(t+1)^{\frac{1}{3}}+\frac{\rho_2(N-S)L^2}{2}\right)^2} \\
&\geq \sum_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} \tfrac{1}{\left(4(\gamma-2)L^2(M\rho_1+N\rho_2)(t+1)^{\frac{1}{3}}+\frac{\rho_2(N-S)L^2}{2}(t+1)^{\frac{1}{3}}\right)^2} \\
&\geq \tfrac{(T_1+\widetilde{T}(\varepsilon))^{\frac{1}{3}}-(T_1+\tau)^{\frac{1}{3}}}{\left(4(\gamma-2)L^2(M\rho_1+N\rho_2)+\frac{\rho_2(N-S)L^2}{2}\right)^2}.
\end{aligned} \tag{A.95}$$

The second inequality in Eq. (A.95) is due to that $\forall t \geq T_1 + \tau$, we have,

$$4(\gamma-2)L^2(M\rho_1+N\rho_2)(t+1)^{\frac{1}{3}}+\frac{\rho_2(N-S)L^2}{2} \leq (4(\gamma-2)L^2(M\rho_1+N\rho_2)+\frac{\rho_2(N-S)L^2}{2})(t+1)^{\frac{1}{3}}. \tag{A.96}$$

The last inequality in Eq. (A.95) follows from the fact that $\sum\limits_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} \frac{1}{(t+1)^{\frac{2}{3}}} \geq (T_1+\widetilde{T}(\varepsilon))^{\frac{1}{3}} - (T_1+\tau)^{\frac{1}{3}}$.

Thus, plugging Eq. (A.95) into Eq. (A.93), we can obtain:

$$||\nabla \widetilde{G}^{T_1+\widetilde{T}(\varepsilon)}||^2 \leq \frac{(\bar{d}+k_d(\tau-1))d_5}{\sum\limits_{t=T_1+\tau}^{T_1+\widetilde{T}(\varepsilon)} \frac{1}{a_5^t a_6^t}} \leq \frac{\left(4(\gamma-2)L^2(M\rho_1+N\rho_2)+\frac{\rho_2(N-S)L^2}{2}\right)^2(\bar{d}+k_d(\tau-1))d_5}{(T_1+\widetilde{T}(\varepsilon))^{\frac{1}{3}} - (T_1+\tau)^{\frac{1}{3}}}. \tag{A.97}$$

According to the definition of $\widetilde{T}(\varepsilon)$, we have:

$$T_1 + \widetilde{T}(\varepsilon) \geq \left(\frac{4\left(4(\gamma-2)L^2(M\rho_1+N\rho_2)+\frac{\rho_2(N-S)L^2}{2}\right)^2(\bar{d}+k_d(\tau-1))d_5}{\varepsilon^2} + (T_1+\tau)^{\frac{1}{3}}\right)^3. \tag{A.98}$$

Combining the definition of ∇G^t and $\nabla \widetilde{G}^t$ with trigonometric inequality, we then get:

$$||\nabla G^t|| - ||\nabla \widetilde{G}^t|| \leq ||\nabla G^t - \nabla \widetilde{G}^t|| \leq \sqrt{\sum_{l=1}^{|\mathbf{A}^t|} ||c_1^{t-1}\lambda_l^t||^2 + \sum_{j=1}^{N} ||c_2^{t-1}\boldsymbol{\phi}_j^t||^2}. \tag{A.99}$$

Denoting constant d_6 as $d_6 = 4(\gamma-2)L^2(M\rho_1 + N\rho_2)$. If $t > (\frac{4M{\sigma_1}^2}{{\rho_1}^2} + \frac{4N{\sigma_2}^2}{{\rho_2}^2})^3 \frac{1}{\varepsilon^6}$, then we have $\sqrt{\sum_{l=1}^{|\mathbf{A}^t|} ||c_1^{t-1}\lambda_l^t||^2 + \sum_{j=1}^{N} ||c_2^{t-1}\boldsymbol{\phi}_j^t||^2} \leq \frac{\varepsilon}{2}$. Combining it with Eq. (A.98), we can conclude that there exists a

$$T(\varepsilon) \sim \mathcal{O}(\max\{(\frac{4M{\sigma_1}^2}{{\rho_1}^2} + \frac{4N{\sigma_2}^2}{{\rho_2}^2})^3 \frac{1}{\varepsilon^6}, (\frac{4(d_6 + \frac{\rho_2(N-S)L^2}{2})^2(\overline{d} + k_d(\tau-1))d_5}{\varepsilon^2} + (T_1+\tau)^{\frac{1}{3}})^3\}), \tag{A.100}$$

such that $||\nabla G^t|| \leq ||\nabla \widetilde{G}^t|| + \sqrt{\sum_{l=1}^{|\mathbf{A}^t|} ||c_1^{t-1}\lambda_l^t||^2 + \sum_{j=1}^{N} ||c_2^{t-1}\boldsymbol{\phi}_j^t||^2} \leq \varepsilon$, which concludes our proof.

B Time Efficiency Comparison

In a distributed communication network, the communication and computation delays of workers are inevitable. Due to differences in system configuration, communication and computation delays vary across different workers, the existence of lagging workers (*i.e.*, stragglers and stale workers) is inevitable. For synchronous algorithm, it will lead to idling and wastage of computing resources since the master only updates the variables after receiving updates from all workers (as illustrated in Figure B1). Different from the synchronous algorithm, the asynchronous algorithm allows the master updates the variables whenever it receives updates from a subset of workers, which is more efficient. In this section, we compare the time for our asynchronous and synchronous algorithms to return an ε-stationary point.

Fact 1 *Let $\mathcal{T}_1$ and $T_1(\varepsilon)$ denote the convergence time and iterations for the proposed asynchronous algorithm. Let $\mathcal{T}_2$ and $T_2(\varepsilon)$ denote the convergence time and iterations for the synchronous algorithm, we have,*

$$\frac{\mathcal{T}_1}{\mathcal{T}_2} = \frac{T_1(\varepsilon) \times S}{T_2(\varepsilon) \times (\frac{\widetilde{d}}{\hat{d}_1} + \frac{\widetilde{d}}{\hat{d}_2} \cdots + \frac{\widetilde{d}}{\hat{d}_N})}, \tag{B.101}$$

where $\widetilde{d}$ is the maximum (computation + communication) delay of all workers.

Proof of Fact 1:

In this part, we do not consider the delays of master. Suppose that there are N workers in a distributed system and the number of active workers is S. For brevity, we assume the delay for each work remains the same during the iteration. Let $[\hat{d}_1, \hat{d}_2, \cdots \hat{d}_N] \in \mathbb{R}^N$ denote the (computation + communication) delay for N workers. And we define the maximum delay of all workers as $\widetilde{d}$. For the j^{th} worker, it has communicated with the master $\frac{\mathcal{T}_1}{d_j}$ times during time $\mathcal{T}_1$. Thus, for time $\mathcal{T}_1$, it satisfies that,

$$\frac{\mathcal{T}_1}{\hat{d}_1} + \frac{\mathcal{T}_1}{\hat{d}_2} + \cdots + \frac{\mathcal{T}_1}{\hat{d}_N} = T_1(\varepsilon) \times S. \tag{B.102}$$

For the synchronous algorithm, the time $\mathcal{T}_2$ needs to satisfy that:

$$\mathcal{T}_2 = T_2(\varepsilon) \times \widetilde{d}. \tag{B.103}$$

Thus, we have that,

$$\frac{\mathcal{T}_1}{\mathcal{T}_2} = \frac{T_1(\varepsilon) \times S}{T_2(\varepsilon) \times (\frac{\widetilde{d}}{\hat{d}_1} + \frac{\widetilde{d}}{\hat{d}_2} \cdots + \frac{\widetilde{d}}{\hat{d}_N})}. \tag{B.104}$$

For the special case that the asynchronous algorithm degrades to the synchronous algorithm, *i.e.*, the master is required to update its parameters only after receiving the updates from all workers, we have $S = N$, $T_1(\varepsilon) = T_2(\varepsilon)$ and $\hat{d}_j = \widetilde{d}, \forall j = 1, \cdots, N$ since all workers are required to wait the slowest worker. Back to Eq. (B.104), we can obtain that $\frac{\mathcal{T}_1}{\mathcal{T}_2} = 1$.

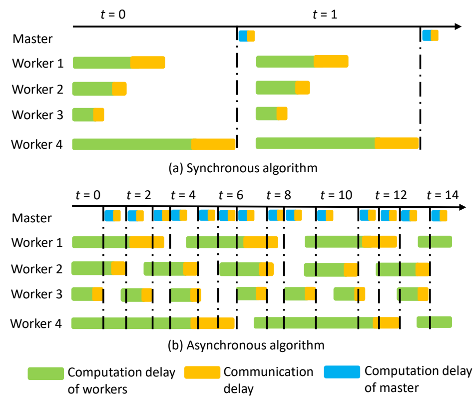
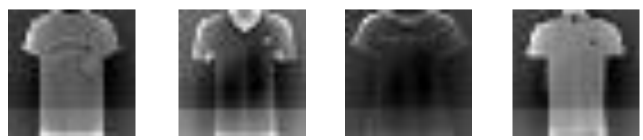


Figure B1: The illustration of synchronous and asynchronous algorithms. t represents the number of iterations. In the asynchronous algorithm (at the bottom), the master begins to update its parameters after receiving the update from one worker.

(a) Clean images whose labels are T-shirt.



(b) Attacked images whose target labels are Pullover.

Figure C1: Backdoor attacks on Fashion MNIST dataset. Through adding triggers on local patch of clean images, the attacked images are misclassified as the target labels.

C Experiments

In this section, we present the detailed results of our experiments. We first give a detailed description of the datasets and baseline methods used in our experiments.

C.1 Datasets and Baseline Methods

In this section, we provide a detailed introduction to datasets and baseline methods. The number of workers and categories of every dataset are summarized in Table C1.

Datasets:

1. **SHL dataset**: The SHL dataset was collected using four cellphones on four body locations where people usually carry cellphones. The SHL dataset provides multimodal locomotion and transportation data collected in real-world settings using eight various modes of transportation. We separated the data into six workers with varied proportions based on the four body locations of smartphones to imitate the different tendencies of workers (users) in positioning cellphones.
2. **Person Activity dataset**: Data contains recordings of five participants performing eleven different activities. Each participant wears four sensors in four different body locations (ankle left, ankle right, belt, and chest) while performing the activities. Each participant corresponds to one worker in the experiment.

Table C1: The number of workers and categories of datasets

	SHL	Person Activity	SC-MA	Fashion MNIST
Number of workers	6	5	15	3
Number of categories	8	11	7	3

Table C2: Model structure that used for SHL dataset.

No.	Layer type	Number of neurons	Activation
1	Fully-connected	96	ReLU
2	Fully-connected	48	ReLU
3	Fully-connected	24	ReLU
4	Output	8	Softmax

3. **Single Chest-Mounted Accelerometer dataset**: Data was collected from fifteen participants engaged in seven distinct activities. Each participant (worker) wears an accelerometer mounted on the chest.
4. **Fashion MNIST**: Similar to MNIST, Fashion MNIST is a dataset where images are grouped into ten categories of clothing. The subset of the data labeled with Pullover, Shirt and T-shirt are extracted as three workers and each worker consists of one class of clothing.

Baseline Methods:

1. **Ind**$_j$: It learns the model from an individual worker j.
2. **Mix**$_{\mathrm{Even}}$: It learns the model from all workers with even weights using the proposed distributed algorithm.
3. **FedAvg**: It learns the model from all workers with even weights. It aggregates the local model parameters from workers through using model averaging.
4. **AFL**: It aims to address the fairness issues in federated learning. AFL adopts the strategy that alternately update the model parameters and the weight of each worker through alternating projected gradient descent/ascent.
5. **DRFA-Prox**: It aims to mitigate the data heterogeneity issue in federated learning. Compared with AFL, it is communication-efficient which requires fewer communication rounds. Moreover, it leverages the prior distribution and introduces it as a regularizer in the objective function.
6. **ASPIRE-EASE(-)**: The proposed ASPIRE-EASE without asynchronous setting.
7. **ASPIRE-CP**: The proposed ASPIRE with cutting plane method.
8. **ASPIRE-EASE**$_{\mathrm{per}}$: The proposed ASPIRE-EASE with periodic communication.

C.2 Training Details

In our empirical studies, since the downstream tasks are multi-class classification, the cross entropy loss is used on each worker (*i.e.*, $\mathcal{L}_j(\cdot), \forall j$). For SHL, Person Activity and SM-AC datasets, we adopt the deep multilayer perceptron [49] as the base model. Specifically, we exhibit the model structures that are used for SHL, Person Activity and SM-AC datasets in Table C2, Table C3 and Table C4. And we use the same logistic regression model as in [35, 16] for the Fashion MNIST dataset. In the experiments, we use the SGD optimizer for model training, and we implement our model with PyTorch and conduct all the experiments on a server with two TITAN V GPUs.

C.3 Additional Results

We first show the detailed experiment settings about robustness against malicious attacks. We conduct experiments in the setting where there are malicious workers which attempt to mislead the model

Table C3: Model structure that used for Peson Activity dataset.

No.	Layer type	Number of neurons	Activation
1	Fully-connected	64	ReLU
2	Fully-connected	32	ReLU
3	Fully-connected	16	ReLU
4	Output	11	Softmax

Table C4: Model structure that used for SC-MA dataset.

No.	Layer type	Number of neurons	Activation
1	Fully-connected	32	ReLU
2	Fully-connected	16	ReLU
3	Output	7	Softmax

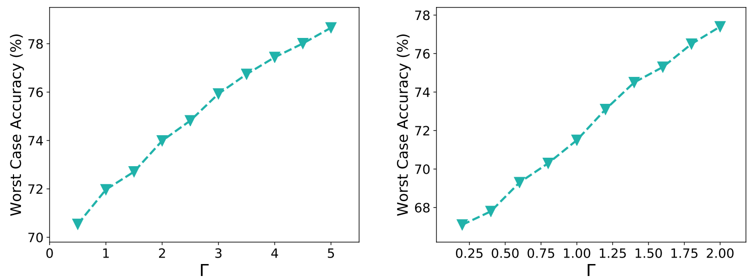
training process. The backdoor attack [1, 48] is adopted in the experiment which aims to bury the backdoor during the training phase of the model. The buried backdoor will be activated by the preset trigger. When the backdoor is not activated, the attacked model performs normally to other local models. When the backdoor is activated, the output of the attack model is misled as the target label which is pre-specified by the attacker. In the experiment, one worker is chosen as the malicious worker. We add triggers to a small part of the data and change their primal labels to target labels (*e.g.*, triggers are added on the local patch of clean images on the Fashion MNIST dataset, which are shown in Figure C1). Furthermore, the malicious worker can purposefully raise the training loss to mislead the master. To evaluate the model's robustness against malicious attacks, following [14], we calculate the success attack rate of the backdoor attacks. The success attack rate can be calculated by checking how many instances in the backdoor dataset can be misled into the target labels. The lower success attack rate indicates better robustness against backdoor attacks. The success attack rates of different models on three datasets are reported in Table 2. In Table 2, we observe that AFL can be attacked easily since it could assign higher weights to malicious workers. Compared to AFL, FedAvg and $\mathrm{Mix}_{\mathrm{Even}}$ achieve relatively lower success attack rates since they assign equal weights to the malicious workers and other workers. DRFA-Prox can achieve even lower success attack rates since it can leverage the prior distribution to assign lower weights for malicious workers. The proposed ASPIRE-EASE achieves the lowest success attack rates since it can leverage the prior distribution more effectively. Specifically, it will assign lower weights to malicious workers with tight theoretical guarantees.

We also report additional experiment results on SHL and Fashion MNIST datasets. We first show that the proposed ASPIRE-EASE can flexibly control the level of robustness by adjusting Γ, which is presented in Figure C2. It is seen that the robustness of ASPIRE-EASE can be gradually enhanced when Γ increases. Next, the comparison of convergence speed by considering different communication and computation delays for each worker is exhibited in Figure C3. We can observe that the proposed ASPIRE-EASE is generally the most efficient since the ASPIRE is an asynchronous algorithm and the proposed EASE is effective. Finally, to further demonstrate the efficiency of EASE, we compare ASPIRE-EASE with ASPIRE-CP concerning the number of cutting planes used during the training. As shown in Theorem 1, a smaller number of cutting planes (which corresponds to a smaller M) will need fewer iterations to achieve convergence. In Figure C4, we can see that ASPIRE-EASE uses fewer cutting planes and thus is more efficient.

D Solve PD-DRO in Centralized Manner

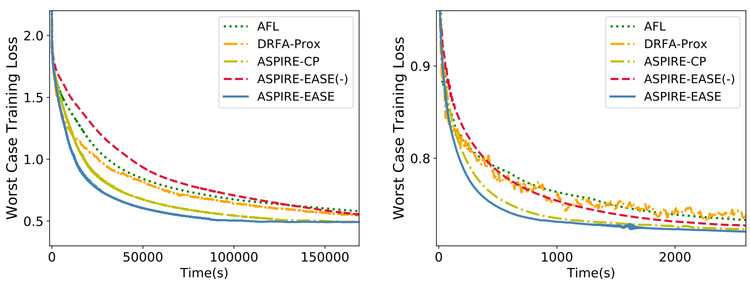
Considering to solve the PD-DRO problem in Eq. (4) in centralized manner, we can rewrite the problem in Eq. (4) as:

$$\min_{\boldsymbol{w}\in\boldsymbol{\mathcal{W}}} \max_{\mathbf{p}\in\boldsymbol{\mathcal{P}}} \sum_{j=1}^{N} p_j f_j(\boldsymbol{w}) \tag{D.105}$$



(a) SHL (b) Fashion MNIST

Figure C2: Γ control the degree of robustness (worst case performance in the problem) on (a) SHL, (b) Fashion MNIST datasets.



(a) SHL (b) Fashion MNIST

Figure C3: Comparison of the convergence time on worst case worker on (a) SHL, (b) Fashion MNIST datasets.

where $\boldsymbol{w} \in \mathbb{R}^p$ is the model parameter. Utilizing the cutting plane method, we can obtain the approximate problem of Eq. (D.105),

$$
\begin{aligned}
&\min_{\boldsymbol{w}\in\boldsymbol{\mathcal{W}},h\in\boldsymbol{\mathcal{H}}} \quad h \\
&\text{s.t.} \sum_{j=1}^{N}(\bar{p}+a_{l,j})f_j(\boldsymbol{w})-h\le 0, \forall \boldsymbol{a}_l \in \mathbf{A}^t, \\
&\quad \text{var.} \quad \boldsymbol{w}, h.
\end{aligned} \tag{D.106}
$$

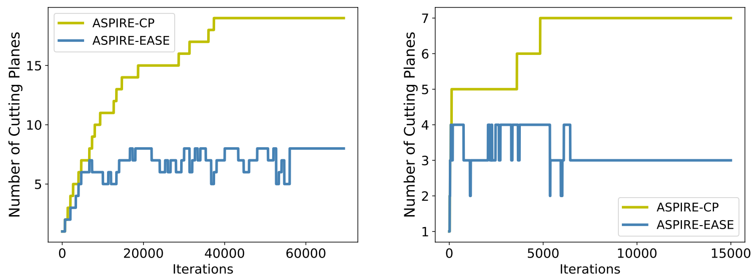
Thus, the Lagrangian function of Eq. (D.106) can be written as:

$$
L_p(\boldsymbol{w},h,\{\lambda_l\}) = h+\sum_{l=1}^{|\mathbf{A}^t|}\lambda_l(\sum_{j=1}^{N}(\bar{p}+a_{l,j})f_j(\boldsymbol{w})-h). \tag{D.107}
$$

Following [52], the regularized version of (D.107) is employed to update all variables as follows,

$$
\widetilde{L}_p(\boldsymbol{w},h,\{\lambda_l\}) = h+\sum_{l=1}^{|\mathbf{A}^t|}\lambda_l(\sum_{j=1}^{N}(\bar{p}+a_{l,j})f_j(\boldsymbol{w})-h) - \sum_{l=1}^{|\mathbf{A}^t|}\frac{c_1^t}{2}||\lambda_l||^2, \tag{D.108}
$$

where c_1^t denotes the regularization term in $(t+1)^{\text{th}}$ iteration. To avoid enumerating the whole dataset, the mini-batch loss $\hat{f}_j(\boldsymbol{w}) = \sum_{i=1}^{m}\frac{1}{m}\mathcal{L}_j(\mathbf{x}_j^i, y_j^i; \boldsymbol{w})$ can be used, where m is the mini-batch size. It is evident that $\mathbb{E}[\hat{f}_j(\boldsymbol{w})] = f_j(\boldsymbol{w})$ and $\mathbb{E}[\nabla\hat{f}_j(\boldsymbol{w})] = \nabla f_j(\boldsymbol{w})$. The centralized algorithm, which aims to solve problem in Eq. (4) in centralized manner, proceeds as follows in $(t+1)^{\text{th}}$ iteration:



(a) SHL (b) Fashion MNIST

Figure C4: Comparison of ASPIRE-CP and ASPIRE-EASE regarding the number of cutting planes on (a) SHL, (b) Fashion MNIST datasets. ASPIRE-CP represents ASPIRE with cutting plane method.

1. Updating the model parameter $\boldsymbol{w}$ as follows,

$$\boldsymbol{w}^{t+1} = \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}^t - \eta_{\boldsymbol{w}}^t \nabla_{\boldsymbol{w}} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\})), \tag{D.109}$$

where $\eta_{\boldsymbol{w}}^t$ represents the step-size and $\mathcal{P}_{\boldsymbol{\mathcal{W}}}$ represents the projection onto the convex set $\boldsymbol{\mathcal{W}}$.

2. Updating the additional variable h as follows,

$$h^{t+1} = \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^t, \{\lambda_l^t\})), \tag{D.110}$$

where η_h^t represents the step-size and $\mathcal{P}_{\boldsymbol{\mathcal{H}}}$ represents the projection onto the convex set $\boldsymbol{\mathcal{H}}$.

3. Updating the dual variable λ_l as follows,

$$\lambda_l^{t+1} = \mathcal{P}_{\boldsymbol{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\})),\ l = 1,\cdots,|\mathbf{A}^t|, \tag{D.111}$$

where ρ_1 represents the step-size and $\mathcal{P}_{\boldsymbol{\Lambda}}$ represents the projection onto the convex set $\boldsymbol{\Lambda}$.

Then, during T_1 iterations, EASE is utilized to update the set $\mathbf{A}^{t+1}$ every k iterations.

Definition D.1 *Following [52, 32, 53], the stationarity gap at t^{th} iteration is defined as,*

$$\nabla G^t = \begin{bmatrix} \frac{1}{\eta_{\boldsymbol{w}}^t}(\boldsymbol{w}^t - \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}^t - \eta_{\boldsymbol{w}}^t \nabla_{\boldsymbol{w}} L_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}))) \\ \frac{1}{\eta_h^t}(h^t - \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h L_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}))) \\ \{\frac{1}{\rho_1}(\lambda_l^t - \mathcal{P}_{\boldsymbol{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} L_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\})))\} \end{bmatrix}. \tag{D.112}$$

And we also define:

$$\begin{aligned} (\nabla G^t)_{\boldsymbol{w}} &= \tfrac{1}{\eta_{\boldsymbol{w}}^t}(\boldsymbol{w}^t - \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}^t - \eta_{\boldsymbol{w}}^t \nabla_{\boldsymbol{w}} L_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}))), \\ (\nabla G^t)_h &= \tfrac{1}{\eta_h^t}(h^t - \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h L_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}))), \\ (\nabla G^t)_{\lambda_l} &= \tfrac{1}{\rho_1}(\lambda_l^t - \mathcal{P}_{\boldsymbol{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} L_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}))). \end{aligned} \tag{D.113}$$

It follows that:

$$||\nabla G^t||^2 = ||(\nabla G^t)_{\boldsymbol{w}}||^2 + ||(\nabla G^t)_h||^2 + \sum_{l=1}^{|\mathbf{A}^t|} ||(\nabla G^t)_{\lambda_l}||^2. \tag{D.114}$$

Definition D.2 *At t^{th} iteration, the stationarity gap w.r.t $\widetilde{L}_p(\boldsymbol{w}, h, \{\lambda_l\})$ is defined as:*

$$\nabla \widetilde{G}^t = \begin{bmatrix} \frac{1}{\eta_{\boldsymbol{w}}^t}(\boldsymbol{w}^t - \mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}^t - \eta_{\boldsymbol{w}}^t \nabla_{\boldsymbol{w}} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}))) \\ \frac{1}{\eta_h^t}(h^t - \mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t - \eta_h^t \nabla_h \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}))) \\ \{\frac{1}{\rho_1}(\lambda_l^t - \mathcal{P}_{\boldsymbol{\Lambda}}(\lambda_l^t + \rho_1 \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\})))\} \end{bmatrix}. \tag{D.115}$$

And we also define:

$$
\begin{aligned}
&(\nabla\widetilde{G}^t)_{\boldsymbol{w}}=\tfrac{1}{\eta_{\boldsymbol{w}}^t}(\boldsymbol{w}^t-\mathcal{P}_{\boldsymbol{\mathcal{W}}}(\boldsymbol{w}^t-\eta_{\boldsymbol{w}}^t\nabla_{\boldsymbol{w}}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\}))),\\
&(\nabla\widetilde{G}^t)_h=\tfrac{1}{\eta_h^t}(h^t-\mathcal{P}_{\boldsymbol{\mathcal{H}}}(h^t-\eta_h^t\nabla_h\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\}))),\\
&(\nabla\widetilde{G}^t)_{\lambda_l}=\tfrac{1}{\rho_1}(\lambda_l^t-\mathcal{P}_{\mathbf{\Lambda}}(\lambda_l^t+\rho_1\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\}))).
\end{aligned}
\tag{D.116}
$$

It follows that:

$$
||\nabla\widetilde{G}^t||^2=||(\nabla\widetilde{G}^t)_{\boldsymbol{w}}||^2+||(\nabla\widetilde{G}^t)_h||^2+\sum_{l=1}^{|\mathbf{A}^t|}||(\nabla\widetilde{G}^t)_{\lambda_l}||^2. \tag{D.117}
$$

Assumption D.1 *L_p has Lipschitz continuous gradients. We assume that there exists $L>0$ satisfying that,*

$$
||\nabla_\theta L_p(\boldsymbol{w},h,\{\lambda_l\})-\nabla_\theta L_p(\hat{\boldsymbol{w}},\hat{h},\{\hat{\lambda}_l\})||\le L||[\boldsymbol{w}-\hat{\boldsymbol{w}};h-\hat{h};\boldsymbol{\lambda}_{\text{cat}}-\hat{\boldsymbol{\lambda}}_{\text{cat}}]||,
$$

where $\theta\in\{\boldsymbol{w},h,\{\lambda_l\}\}$, $[;]$ represents the concatenation and $\boldsymbol{\lambda}_{\text{cat}}-\hat{\boldsymbol{\lambda}}_{\text{cat}}=[\lambda_1-\hat{\lambda}_1;\cdots;\lambda_{|\mathbf{A}^t|}-\hat{\lambda}_{|\mathbf{A}^t|}]\in\mathbb{R}^{|\mathbf{A}^t|}$.

Setting D.1 *$|\mathbf{A}^t|\le M,\forall t$, i.e., an upper bound is set for the number of cutting planes.*

Setting D.2 *$c_1^t=\frac{1}{\rho_1(t+1)^{\frac{1}{4}}}\ge\underline{c}_1$ is nonnegative non-increasing sequence, where $\underline{c}_1>0$ meets $\underline{c}_1{}^2\le\frac{\varepsilon^2}{4M}$.*

Theorem D.1 *Suppose Assumption D.1 holds. We set $\eta_{\boldsymbol{w}}^t=\eta_h^t=\frac{2}{L+\rho_1|\mathbf{A}^t|L^2+8\frac{|\mathbf{A}^t|\gamma L^2}{\rho_1(c_1^t)^2}}$, and we set constant $\rho_1\le\frac{2}{L+2c_1^0}$. For a given ε, we have:*

$$
T(\varepsilon)\sim\mathcal{O}(\max\{(\frac{16(\gamma-2)L^2M\rho_1\,\overline{d}\,d_5}{\varepsilon^2}+(T_1+2)^{\frac{1}{2}})^2,\frac{16M^2{\sigma_1}^4}{{\rho_1}^4}\frac{1}{\varepsilon^4}\}), \tag{D.118}
$$

where σ_1, γ, $\overline{d}$, d_5 and T_1 are constants.

Lemma D.1 *Suppose Assumption D.1 holds, we have:*

$$
L_p(\boldsymbol{w}^{t+1},h^t,\{\lambda_l^t\})-L_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})\le(\tfrac{L}{2}-\tfrac{1}{\eta_{\boldsymbol{w}}^t})||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2, \tag{D.119}
$$

$$
L_p(\boldsymbol{w}^{t+1},h^{t+1},\{\lambda_l^t\})-L_p(\boldsymbol{w}^{t+1},h^t,\{\lambda_l^t\})\le(\tfrac{L}{2}-\tfrac{1}{\eta_h^t})||h^{t+1}-h^t||^2. \tag{D.120}
$$

Proof:

According to Assumption D.1, we have,

$$
\begin{aligned}
&L_p(\boldsymbol{w}^{t+1},h^t,\{\lambda_l^t\})-L_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})\\
&\le\left\langle\nabla_{\boldsymbol{w}}L_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\}),\boldsymbol{w}^{t+1}-\boldsymbol{w}^t\right\rangle+\tfrac{L}{2}||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2.
\end{aligned}
\tag{D.121}
$$

According to the optimal condition for Eq. (D.109) and $\nabla_{\boldsymbol{w}}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})=\nabla_{\boldsymbol{w}}L_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})$, we have,

$$
\left\langle\boldsymbol{w}^{t+1}-\boldsymbol{w}^t,\nabla_{\boldsymbol{w}}L_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\}\right\rangle\le-\tfrac{1}{\eta_{\boldsymbol{w}}^t}||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2. \tag{D.122}
$$

Combining Eq. (D.121) with Eq. (D.122), we have that,

$$
L_p(\boldsymbol{w}^{t+1},h^t,\{\lambda_l^t\})-L_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})\le(\tfrac{L}{2}-\tfrac{1}{\eta_{\boldsymbol{w}}^t})||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2.
$$

Similar to Eq. (D.119), we can easily have Eq. (D.120).

Lemma D.2 *Suppose Assumption D.1 holds,* $\forall t \geq T_1$, *we have:*

$$
\begin{aligned}
& L_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}) - L_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}) \\
\leq & (\tfrac{L}{2} - \tfrac{1}{\eta_{\boldsymbol{w}}^t} + \tfrac{|\mathbf{A}^t|L^2}{2a_1})||\boldsymbol{w}^{t+1} - \boldsymbol{w}^t||^2 + (\tfrac{L}{2} - \tfrac{1}{\eta_h^t} + \tfrac{|\mathbf{A}^t|L^2}{2a_1})||h^{t+1} - h^t||^2 \\
+ & (\tfrac{a_1}{2} - \tfrac{c_1^{t-1} - c_1^t}{2} + \tfrac{1}{2\rho_1})\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1} - \lambda_l^t||^2 + \tfrac{c_1^{t-1}}{2}\sum_{l=1}^{|\mathbf{A}^t|}(||\lambda_l^{t+1}||^2 - ||\lambda_l^t||^2) + \tfrac{1}{2\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t - \lambda_l^{t-1}||^2.
\end{aligned}
\tag{D.123}
$$

Proof:

According to Eq. (D.111), in $(t+1)^{\text{th}}$ iteration, $\forall \lambda \in \boldsymbol{\Lambda}$, it follows that,

$$
\left\langle \lambda_l^{t+1} - \lambda_l^t - \rho_1 \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}), \lambda - \lambda_l^{t+1} \right\rangle \geq 0. \tag{D.124}
$$

Let $\lambda = \lambda_l^t$, we can obtain,

$$
\left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}) - \frac{1}{\rho_1}(\lambda_l^{t+1} - \lambda_l^t), \lambda_l^t - \lambda_l^{t+1} \right\rangle \leq 0. \tag{D.125}
$$

Likewise, in t^{th} iteration, we have that,

$$
\left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}) - \frac{1}{\rho_1}(\lambda_l^t - \lambda_l^{t-1}), \lambda_l^{t+1} - \lambda_l^t \right\rangle \leq 0. \tag{D.126}
$$

$\forall t \geq T_1$, since $\widetilde{L}_p(\boldsymbol{w}, h, \{\lambda_l\})$ is concave with respect to λ_l, we have,

$$
\begin{aligned}
& \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^{t+1}\}) - \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}) \\
\leq & \sum_{l=1}^{|\mathbf{A}^t|} \left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}), \lambda_l^{t+1} - \lambda_l^t \right\rangle \\
\leq & \sum_{l=1}^{|\mathbf{A}^t|} (\left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}), \lambda_l^{t+1} - \lambda_l^t \right\rangle \\
& \quad + \tfrac{1}{\rho_1} \left\langle \lambda_l^t - \lambda_l^{t-1}, \lambda_l^{t+1} - \lambda_l^t \right\rangle).
\end{aligned}
\tag{D.127}
$$

Denoting $\boldsymbol{v}_{1,l}^{t+1} = \lambda_l^{t+1} - \lambda_l^t - (\lambda_l^t - \lambda_l^{t-1})$, we have,

$$
\begin{aligned}
& \sum_{l=1}^{|\mathbf{A}^t|} (\left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}), \lambda_l^{t+1} - \lambda_l^t \right\rangle \\
= & \sum_{l=1}^{|\mathbf{A}^t|} \left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}), \lambda_l^{t+1} - \lambda_l^t \right\rangle (1a) \\
+ & \sum_{l=1}^{|\mathbf{A}^t|} \left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}), \boldsymbol{v}_{1,l}^{t+1} \right\rangle (1b) \\
+ & \sum_{l=1}^{|\mathbf{A}^t|} \left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}), \lambda_l^t - \lambda_l^{t-1} \right\rangle (1c).
\end{aligned}
\tag{D.128}
$$

We firstly focus on $(1a)$ in Eq. (D.128). According to the Cauchy-Schwarz inequality and Assumption D.1, we have,

$$
\begin{aligned}
& \sum_{l=1}^{|\mathbf{A}^t|} \left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}), \lambda_l^{t+1} - \lambda_l^t \right\rangle \\
\leq & \sum_{l=1}^{|\mathbf{A}^t|} (\tfrac{L^2}{2a_1}(||\boldsymbol{w}^{t+1} - \boldsymbol{w}^t||^2 + ||h^{t+1} - h^t||^2) + \tfrac{a_1}{2}||\lambda_l^{t+1} - \lambda_l^t||^2 \\
& \quad + \tfrac{c_1^{t-1} - c_1^t}{2}(||\lambda_l^{t+1}||^2 - ||\lambda_l^t||^2) - \tfrac{c_1^{t-1} - c_1^t}{2}||\lambda_l^{t+1} - \lambda_l^t||^2),
\end{aligned}
\tag{D.129}
$$

where $a_1 > 0$ is a constant. Secondly, according to Cauchy-Schwarz inequality we write $(1b)$ in Eq. (D.128) as,

$$\begin{aligned}&\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^{t-1}\}),\boldsymbol{v}_{1,l}^{t+1}\right\rangle\\&\leq\sum_{l=1}^{|\mathbf{A}^t|}(\tfrac{a_2}{2}||\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^{t-1}\})||^2+\tfrac{1}{2a_2}||\boldsymbol{v}_{1,l}^{t+1}||^2),\end{aligned}\tag{D.130}$$

where $a_2 > 0$ is a constant. Then, we focus on the $(1c)$ in Eq. (D.128). Denoting $L_1{}' = L + c_1^0$, according to Assumption D.1, trigonometric inequality and the strong concavity of $\widetilde{L}_p(\boldsymbol{w},h,\{\lambda_l\})$ *w.r.t* λ_l [37, 52], we have,

$$\begin{aligned}&\sum_{l=1}^{|\mathbf{A}^t|}\left\langle\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^{t-1}\}),\lambda_l^t-\lambda_l^{t-1}\right\rangle\\&\leq\sum_{l=1}^{|\mathbf{A}^t|}(-\tfrac{1}{L_1{}'+c_1^{t-1}}||\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})-\nabla_{\lambda_l}\widetilde{L}_p(\boldsymbol{w}^t,h^t,\{\lambda_l^{t-1}\}),\boldsymbol{v}_{1,l}^{t+1}||^2-\tfrac{c_1^{t-1}L_1{}'}{L_1{}'+c_1^{t-1}}||\lambda_l^t-\lambda_l^{t-1}||^2).\end{aligned}\tag{D.131}$$

In addition, we can obtain the following inequality,

$$\tfrac{1}{\rho_1}\left\langle\lambda_l^t-\lambda_l^{t-1},\lambda_l^{t+1}-\lambda_l^t\right\rangle\leq\tfrac{1}{2\rho_1}||\lambda_l^{t+1}-\lambda_l^t||^2-\tfrac{1}{2\rho_1}||\boldsymbol{v}_{1,l}^{t+1}||^2+\tfrac{1}{2\rho_1}||\lambda_l^t-\lambda_l^{t-1}||^2.\tag{D.132}$$

Combining Eq. (D.127), (D.129), (D.130), (D.131), (D.132) with $\frac{\rho_1}{2}\leq\frac{1}{L_1{}'+c_1^0}$, and setting $a_2=\rho_1$, $\forall t\geq T_1$, we have,

$$\begin{aligned}&L_p(\boldsymbol{w}^{t+1},h^{t+1},\{\lambda_l^{t+1}\})-L_p(\boldsymbol{w}^{t+1},h^{t+1},\{\lambda_l^t\})\\&\leq\tfrac{|\mathbf{A}^t|L^2}{2a_1}(||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2+||h^{t+1}-h^t||^2)+(\tfrac{a_1}{2}-\tfrac{c_1^{t-1}-c_1^t}{2}+\tfrac{1}{2\rho_1})\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2\\&+\tfrac{c_1^{t-1}}{2}\sum_{l=1}^{|\mathbf{A}^t|}(||\lambda_l^{t+1}||^2-||\lambda_l^t||^2)+\tfrac{1}{2\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t-\lambda_l^{t-1}||^2.\end{aligned}\tag{D.133}$$

By combining Lemma D.1 with Eq. (D.133), we conclude the proof of Lemma D.2.

Lemma D.3 *Denote:*

$$S_1^{t+1}=\frac{4}{\rho_1{}^2c_1^{t+1}}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2-\frac{4}{\rho_1}(\frac{c_1^{t-1}}{c_1^t}-1)\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}||^2,\tag{D.134}$$

$$F^{t+1}=L_p(\boldsymbol{w}^{t+1},h^{t+1},\{\lambda_l^{t+1}\})+S_1^{t+1}-\tfrac{7}{2\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2-\tfrac{c_1^t}{2}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}||^2,\tag{D.135}$$

then $\forall t\geq T_1$*, we have:*

$$\begin{aligned}&F^{t+1}-F^t\\&\leq(\tfrac{L}{2}-\tfrac{1}{\eta_{\boldsymbol{w}}^t}+\tfrac{\rho_1|\mathbf{A}^t|L^2}{2}+\tfrac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2})||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2+(\tfrac{L}{2}-\tfrac{1}{\eta_h^t}+\tfrac{\rho_1|\mathbf{A}^t|L^2}{2}+\tfrac{8|\mathbf{A}^t|L^2}{\rho_1(c_1^t)^2})||h^{t+1}-h^t||^2\\&-\tfrac{1}{10\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2+\tfrac{c_1^{t-1}-c_1^t}{2}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}||^2+\tfrac{4}{\rho_1}(\tfrac{c_1^{t-2}}{c_1^{t-1}}-\tfrac{c_1^{t-1}}{c_1^t})\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t||^2.\end{aligned}\tag{D.136}$$

Proof:

Let $a_1=\frac{1}{\rho_1}$ and substitute it into Lemma D.2, $\forall t\geq T_1$, we have,

$$\begin{aligned}&L_p(\boldsymbol{w}^{t+1},h^{t+1},\{\lambda_l^{t+1}\})-L_p(\boldsymbol{w}^t,h^t,\{\lambda_l^t\})\\&\leq(\tfrac{L}{2}-\tfrac{1}{\eta_{\boldsymbol{w}}^t}+\tfrac{\rho_1|\mathbf{A}^t|L^2}{2})||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2+(\tfrac{L}{2}-\tfrac{1}{\eta_h^t}+\tfrac{\rho_1|\mathbf{A}^t|L^2}{2})||h^{t+1}-h^t||^2\\&+(-\tfrac{c_1^{t-1}-c_1^t}{2}+\tfrac{1}{\rho_1})\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2+\tfrac{c_1^{t-1}}{2}\sum_{l=1}^{|\mathbf{A}^t|}(||\lambda_l^{t+1}||^2-||\lambda_l^t||^2)+\tfrac{1}{2\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t-\lambda_l^{t-1}||^2.\end{aligned}\tag{D.137}$$

Firstly, $\forall t \geq T_1$, we can obtain the following inequality,

$$\begin{aligned}
&\sum_{l=1}^{|\mathbf{A}^t|} \frac{1}{\rho_1} \left\langle \boldsymbol{v}_{1,l}^{t+1}, \lambda_l^{t+1} - \lambda_l^t \right\rangle \\
&\leq \sum_{l=1}^{|\mathbf{A}^t|} (\left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^{t+1}, h^{t+1}, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}), \lambda_l^{t+1} - \lambda_l^t \right\rangle \\
&\quad\quad + \left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}), \boldsymbol{v}_{1,l}^{t+1} \right\rangle \\
&\quad\quad + \left\langle \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}), \lambda_l^t - \lambda_l^{t-1} \right\rangle).
\end{aligned} \tag{D.138}$$

Since

$$\frac{1}{\rho_1} \left\langle \boldsymbol{v}_{1,l}^{t+1}, \lambda_l^{t+1} - \lambda_l^t \right\rangle = \frac{1}{2\rho_1} ||\lambda_l^{t+1} - \lambda_l^t||^2 + \frac{1}{2\rho_1} ||\boldsymbol{v}_{1,l}^{t+1}||^2 - \frac{1}{2\rho_1} ||\lambda_l^t - \lambda_l^{t-1}||^2, \tag{D.139}$$

it follows that,

$$\begin{aligned}
&\sum_{l=1}^{|\mathbf{A}^t|} (\frac{1}{2\rho_1} ||\lambda_l^{t+1} - \lambda_l^t||^2 + \frac{1}{2\rho_1} ||\boldsymbol{v}_{1,l}^{t+1}||^2 - \frac{1}{2\rho_1} ||\lambda_l^t - \lambda_l^{t-1}||^2) \\
&\leq \sum_{l=1}^{|\mathbf{A}^t|} (\frac{L^2}{2b_1^t} (||\boldsymbol{w}^{t+1} - \boldsymbol{w}^t||^2 + ||h^{t+1} - h^t||^2) + \frac{b_1^t}{2} ||\lambda_l^{t+1} - \lambda_l^t||^2 \\
&\quad + \frac{c_1^{t-1} - c_1^t}{2} (||\lambda_l^{t+1}||^2 - ||\lambda_l^t||^2) - \frac{c_1^{t-1} - c_1^t}{2} ||\lambda_l^{t+1} - \lambda_l^t||^2 \\
&\quad + \frac{\rho_1}{2} ||\nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}), \boldsymbol{v}_{1,l}^{t+1}||^2 + \frac{1}{2\rho_1} ||\boldsymbol{v}_{1,l}^{t+1}||^2 \\
&\quad - \frac{1}{L_1' + c_1^{t-1}} ||\nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^t\}) - \nabla_{\lambda_l} \widetilde{L}_p(\boldsymbol{w}^t, h^t, \{\lambda_l^{t-1}\}), \boldsymbol{v}_{1,l}^{t+1}||^2 - \frac{c_1^{t-1} L_1'}{L_1' + c_1^{t-1}} ||\lambda_l^t - \lambda_l^{t-1}||^2),
\end{aligned} \tag{D.140}$$

where $b_1^t > 0$. According to the setting that $c_1^0 \leq L_1'$, we have $-\frac{c_1^{t-1} L_1'}{L_1' + c_1^{t-1}} \leq -\frac{c_1^{t-1} L_1'}{2L_1'} = -\frac{c_1^{t-1}}{2} \leq -\frac{c_1^t}{2}$. Multiplying both sides of the inequality Eq. (D.140) by $\frac{8}{\rho_1 c_1^t}$ and setting $b_1^t = \frac{c_1^t}{2}, \forall t \geq T_1$, we have,

$$\begin{aligned}
S_1^{t+1} - S_1^t \leq &\sum_{l=1}^{|\mathbf{A}^t|} \frac{4}{\rho_1} (\frac{c_1^{t-2}}{c_1^{t-1}} - \frac{c_1^{t-1}}{c_1^t}) ||\lambda_l^t||^2 + \sum_{l=1}^{|\mathbf{A}^t|} (\frac{2}{\rho_1} + \frac{4}{\rho_1{}^2} (\frac{1}{c_1^{t+1}} - \frac{1}{c_1^t})) ||\lambda_l^{t+1} - \lambda_l^t||^2 \\
&- \sum_{l=1}^{|\mathbf{A}^t|} \frac{4}{\rho_1} ||\lambda_l^t - \lambda_l^{t-1}||^2 + \frac{8|\mathbf{A}^t| L^2}{\rho_1 (c_1^t)^2} (||\boldsymbol{w}^{t+1} - \boldsymbol{w}^t||^2 + ||h^{t+1} - h^t||^2).
\end{aligned} \tag{D.141}$$

According to the setting about c_1^t, we have $\frac{\rho_1}{10} \geq \frac{1}{c_1^{t+1}} - \frac{1}{c_1^t}, \forall t \geq T_1$. Using the definition of F^{t+1} and combining it with Eq. (D.141) and Eq. (D.137), $\forall t \geq T_1$, we have,

$$\begin{aligned}
&F^{t+1} - F^t \\
&\leq (\frac{L}{2} - \frac{1}{\eta_{\boldsymbol{w}}^t} + \frac{\rho_1 |\mathbf{A}^t| L^2}{2} + \frac{8|\mathbf{A}^t| L^2}{\rho_1 (c_1^t)^2}) ||\boldsymbol{w}^{t+1} - \boldsymbol{w}^t||^2 + (\frac{L}{2} - \frac{1}{\eta_h^t} + \frac{\rho_1 |\mathbf{A}^t| L^2}{2} + \frac{8|\mathbf{A}^t| L^2}{\rho_1 (c_1^t)^2}) ||h^{t+1} - h^t||^2 \\
&- \frac{1}{10\rho_1} \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^{t+1} - \lambda_l^t||^2 + \frac{c_1^{t-1} - c_1^t}{2} \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^{t+1}||^2 + \frac{4}{\rho_1} (\frac{c_1^{t-2}}{c_1^{t-1}} - \frac{c_1^{t-1}}{c_1^t}) \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^t||^2.
\end{aligned}$$

Proof of Theorem D.1:

Firstly, we set that $a_5^t = \frac{4|\mathbf{A}^t|(\gamma-2)L^2}{\rho_1 (c_1^t)^2}$, where $\gamma > 2$ is a constant. According to the setting of $\eta_{\boldsymbol{w}}^t$, η_h^t and c_1^t, we have,

$$\frac{L}{2} - \frac{1}{\eta_{\boldsymbol{w}}^t} + \frac{\rho_1 |\mathbf{A}^t| L^2}{2} + \frac{8|\mathbf{A}^t| L^2}{\rho_1 (c_1^t)^2} = -a_5^t, \quad \frac{L}{2} - \frac{1}{\eta_h^t} + \frac{\rho_1 |\mathbf{A}^t| L^2}{2} + \frac{8|\mathbf{A}^t| L^2}{\rho_1 (c_1^t)^2} = -a_5^t. \tag{D.142}$$

Combining with Lemma D.3, $\forall t \geq T_1$, it follows that,

$$\begin{aligned}
&a_5^t ||\boldsymbol{w}^{t+1} - \boldsymbol{w}^t||^2 + a_5^t ||h^{t+1} - h^t||^2 + \frac{1}{10\rho_1} \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^{t+1} - \lambda_l^t||^2 \\
&\leq F^t - F^{t+1} + \frac{c_1^{t-1} - c_1^t}{2} \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^{t+1}||^2 + \frac{4}{\rho_1} (\frac{c_1^{t-2}}{c_1^{t-1}} - \frac{c_1^{t-1}}{c_1^t}) \sum_{l=1}^{|\mathbf{A}^t|} ||\lambda_l^t||^2.
\end{aligned} \tag{D.143}$$

According to the definition of $(\nabla\widetilde{G}(t))_{\boldsymbol{w}}$, we have,

$$||(\nabla\widetilde{G}^t)_{\boldsymbol{w}}||^2 \leq \frac{1}{(\eta_{\boldsymbol{w}}^t)^2}||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2. \tag{D.144}$$

Combining the definition of $(\nabla\widetilde{G}(t))_h$ with trigonometric, Cauchy-Schwarz inequality and Assumption D.1, we have,

$$||(\nabla\widetilde{G}^t)_h||^2 \leq 2L^2||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2+\frac{2}{(\eta_h^t)^2}||h^{t+1}-h^t||^2. \tag{D.145}$$

Combining the definition of $(\nabla\widetilde{G}^t)_{\lambda_l}$ with trigonometric inequality and Cauchy-Schwarz inequality,

$$||(\nabla\widetilde{G}^t)_{\lambda_l}||^2 \leq \frac{3}{{\rho_1}^2}||\lambda_l^{t+1}-\lambda_l^t||^2+3L^2(||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2+||h^{t+1}-h^t||^2)+3((c_1^{t-1})^2-(c_1^t)^2)||\lambda_l^t||^2. \tag{D.146}$$

According to the Definition D.2 as well as Eq. (D.144), (D.145) and Eq. (D.146), we can obtain,

$$\begin{aligned}||\nabla\widetilde{G}^t||^2 \leq{}& (\frac{1}{(\eta_{\boldsymbol{w}}^t)^2}+2L^2+3|\mathbf{A}^t|L^2)||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2+(\frac{2}{(\eta_h^t)^2}+3|\mathbf{A}^t|L^2)||h^{t+1}-h^t||^2\\ &+\sum_{l=1}^{|\mathbf{A}^t|}\frac{3}{{\rho_1}^2}||\lambda_l^{t+1}-\lambda_l^t||^2+\sum_{l=1}^{|\mathbf{A}^t|}3((c_1^{t-1})^2-(c_1^t)^2)||\lambda_l^t||^2.\end{aligned} \tag{D.147}$$

We set constants d_1, d_2 as

$$d_1=\frac{1+(2+3M)L^2\underline{\eta_{\boldsymbol{w}}}^2}{\underline{\eta_{\boldsymbol{w}}}^2(a_5^0)^2} \geq \frac{1+(2+3|\mathbf{A}^t|)L^2(\eta_{\boldsymbol{w}}^t)^2}{(\eta_{\boldsymbol{w}}^t)^2(a_5^t)^2}, \tag{D.148}$$

$$d_2=\frac{2+3ML^2\underline{\eta_h}^2}{\underline{\eta_h}^2(a_5^0)^2} \geq \frac{2+3|\mathbf{A}^t|L^2(\eta_h^t)^2}{(\eta_h^t)^2(a_5^t)^2}, \tag{D.149}$$

where $\underline{\eta_{\boldsymbol{w}}}=\frac{2}{L+\rho_1ML^2+8\frac{M\gamma L^2}{\rho_1\underline{c}_1^2}} \leq \eta_{\boldsymbol{w}}^t$ and $\underline{\eta_h}=\frac{2}{L+\rho_1ML^2+8\frac{M\gamma L^2}{\rho_1\underline{c}_1^2}} \leq \eta_h^t, \forall t$ are positive constants. Thus, combining Eq. (D.147) with Eq. (D.148) and Eq. (D.149), we can obtain,

$$\begin{aligned}||\nabla\widetilde{G}^t||^2 \leq{}& d_1(a_5^t)^2||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2+d_2(a_5^t)^2||h^{t+1}-h^t||^2\\ &+\sum_{l=1}^{|\mathbf{A}^t|}\frac{3}{{\rho_1}^2}||\lambda_l^{t+1}-\lambda_l^t||^2+\sum_{l=1}^{|\mathbf{A}^t|}3((c_1^{t-1})^2-(c_1^t)^2)||\lambda_l^t||^2.\end{aligned} \tag{D.150}$$

Let d_3^t denote a nonnegative sequence, $d_3^t=\frac{1}{\max\{d_1a_5^t,d_2a_5^t,\frac{30}{\rho_1}\}}$, and we have,

$$\begin{aligned}d_3^t||\nabla\widetilde{G}^t||^2 \leq{}& a_5^t||\boldsymbol{w}^{t+1}-\boldsymbol{w}^t||^2+a_5^t||h^{t+1}-h^t||^2\\ &+\frac{1}{10\rho_1}\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^{t+1}-\lambda_l^t||^2+3d_3^t((c_1^{t-1})^2-(c_1^t)^2)\sum_{l=1}^{|\mathbf{A}^t|}||\lambda_l^t||^2.\end{aligned} \tag{D.151}$$

Combining Eq. (D.151) with Eq. (D.143) and according to the setting $||\lambda_l^t||^2 \leq {\sigma_1}^2$ (where ${\sigma_1}^2={\alpha_3}^2$) and $d_3^0 \geq d_3^t, \forall t \geq T_1$, we have that,

$$d_3^t||\nabla\widetilde{G}^t||^2 \leq F^t-F^{t+1}+\frac{c_1^{t-1}-c_1^t}{2}M{\sigma_1}^2+\frac{4}{\rho_1}(\frac{c_1^{t-2}}{c_1^{t-1}}-\frac{c_1^{t-1}}{c_1^t})M{\sigma_1}^2+3d_3^0((c_1^{t-1})^2-(c_1^t)^2)M{\sigma_1}^2. \tag{D.152}$$

Denoting $\widetilde{T}(\varepsilon)$ as $\widetilde{T}(\varepsilon)=\min\{t \mid \ ||\nabla\widetilde{G}^{T_1+t}|| \leq \frac{\varepsilon}{2}, t \geq 2\}$. Summing up Eq. (D.152) from $t=T_1+2$ to $t=T_1+\widetilde{T}(\varepsilon)$, we have,

$$\begin{aligned}\sum_{t=T_1+2}^{T_1+\widetilde{T}(\varepsilon)}d_3^t||\nabla\widetilde{G}^t||^2 \leq{}& F^{T_1+2}-\underline{L}+\frac{4}{\rho_1}(\frac{c_1^{T_1}}{c_1^{T_1+1}}+\frac{c_1^{T_1+1}}{c_1^{T_1+2}})M{\sigma_1}^2+\frac{c_1^{T_1+1}}{2}M{\sigma_1}^2\\ &+\frac{7}{2\rho_1}M{\sigma_3}^2+\frac{c_1^{T_1+2}}{2}M{\sigma_1}^2+3d_3^0(c_1^0)^2M{\sigma_1}^2\\ ={}& \bar{d},\end{aligned} \tag{D.153}$$

where $\sigma_3 = \max\{||\lambda_1 - \lambda_2|| \,|\lambda_1, \lambda_2 \in \mathbf{\Lambda}\}$ and $\underline{L} = \min\limits_{\boldsymbol{w}\in\boldsymbol{\mathcal{W}}, h\in\boldsymbol{\mathcal{H}}, \{\lambda_l\in\mathbf{\Lambda}\}} L_p(\boldsymbol{w}, h, \{\lambda_l\})$, which satisfy that,

$$F^{t+1} \geq \underline{L} - \frac{4}{\rho_1}\frac{c_1^{T_1+1}}{c_1^{T_1+2}} M{\sigma_1}^2 - \frac{7}{2\rho_1} M{\sigma_3}^2 - \frac{c_1^{T_1+2}}{2} M{\sigma_1}^2, \; \forall t \geq T_1 + 2, \tag{D.154}$$

and $\bar{d}$ is a constant. Constant d_5 is given by,

$$d_5 = \max\{d_1, d_2, \tfrac{30}{\rho_1 a_5^0}\} \geq \max\{d_1, d_2, \tfrac{30}{\rho_1 a_5^t}\} = \tfrac{1}{d_3^t a_5^t} \;\; . \tag{D.155}$$

Thus, we can obtain that,

$$\sum_{t=T_1+2}^{T_1+\widetilde{T}(\varepsilon)} \frac{1}{d_5 a_5^t} ||\nabla \widetilde{G}^{T_1+\widetilde{T}(\varepsilon)}||^2 \leq \sum_{t=T_1+2}^{T_1+\widetilde{T}(\varepsilon)} d_3^t ||\nabla \widetilde{G}^t||^2 \leq \bar{d} \,. \tag{D.156}$$

Summing up $\frac{1}{a_5^t}$ from $t = T_1 + 2$ to $t = T_1 + \widetilde{T}(\varepsilon)$, it follows that,

$$\sum_{t=T_1+2}^{T_1+\widetilde{T}(\varepsilon)} \tfrac{1}{a_5^t} \geq \sum_{t=T_1+2}^{T_1+\widetilde{T}(\varepsilon)} \tfrac{1}{4(\gamma-2)L^2 M \rho_1 (t+1)^{\frac{1}{2}}} \geq \tfrac{(T_1+\widetilde{T}(\varepsilon))^{\frac{1}{2}} - (T_1+2)^{\frac{1}{2}}}{4(\gamma-2)L^2 M \rho_1}. \tag{D.157}$$

Combining Eq. (D.156), (D.157) with the definition of $\widetilde{T}(\varepsilon)$, we have that,

$$T_1 + \widetilde{T}(\varepsilon) \geq (\frac{16(\gamma-2)L^2 M \rho_1 \,\bar{d}\, d_5}{\varepsilon^2} + (T_1+2)^{\frac{1}{2}})^2. \tag{D.158}$$

According to trigonometric inequality, we then get $||\nabla G^t|| - ||\nabla \widetilde{G}^t|| \leq ||\nabla G^t - \nabla \widetilde{G}^t|| \leq \sqrt{\sum\limits_{l=1}^{|\mathbf{A}^t|} ||c_1^{t-1}\lambda_l^t||^2}$. If $t > \frac{16M^2{\sigma_1}^4}{{\rho_1}^4}\frac{1}{\varepsilon^4}$, we have $\sqrt{\sum\limits_{l=1}^{|\mathbf{A}^t|} ||c_1^{t-1}\lambda_l^t||^2} \leq \frac{\varepsilon}{2}$. Combining it with Eq. (D.158), we can conclude that there exists a

$$T(\varepsilon) \sim \mathcal{O}(\max\{(\frac{16(\gamma-2)L^2 M \rho_1 \,\bar{d}\, d_5}{\varepsilon^2} + (T_1+2)^{\frac{1}{2}})^2, \frac{16M^2{\sigma_1}^4}{{\rho_1}^4}\frac{1}{\varepsilon^4}\}), \tag{D.159}$$

such that $||\nabla G^t|| \leq \varepsilon$, which concludes our proof.

E Convergence Rate Analysis

In this section, we compare the convergence results of the proposed method against the existing methods in the literature (with centralized and distributed setting). GDmax [25] is proposed recently, which can be utilized to solve the nonconvex-concave minimax problems (related to the setting of our problem) with iteration complexity $\mathcal{O}(\frac{1}{\varepsilon^6})$ to obtain the ε-stationary point (*i.e.*, $||\Phi(\cdot)||^2 \leq \varepsilon^2$, where $\Phi(\cdot) = \max_y f(\cdot, y)$). However, GDmax is nested-loop which has to solve the inner subproblem every iteration [52]. Gradient descent-ascent (GDA) method [31] is proposed, which performs alternating gradient descent-ascent every iteration. The iteration complexity of GDA to obtain the ε-stationary point (*i.e.*, $||\Phi(\cdot)||^2 \leq \varepsilon^2$) for nonconvex-concave minimax problems is upper bounded by $\mathcal{O}(\frac{1}{\varepsilon^6})$. COVER [38] is proposed to solve the distributionally robust optimization with nonconvex objectives, which can obtain the ε-stationary point (*i.e.*, $||\mathcal{G}_\eta(\cdot)||^2 \leq \varepsilon^2$, where $\mathcal{G}_\eta$ is a proximal gradient measure) with the complexity $\mathcal{O}(\frac{1}{\varepsilon^3})$. Nevertheless, all the algorithms mentioned above do not discuss about the distributed algorithms. Recently, GCIVR [22] is proposed to solve the distributionally robust optimization problem in centralized and distributed manners. GCIVR is effective, which can respectively obtain the ε-stationary point (*i.e.*, $||\mathcal{G}_\eta(\cdot)||^2 \leq \varepsilon^2$) with the complexity $\mathcal{O}(\min\{\frac{\sqrt{N}}{\varepsilon^2}, \frac{1}{\varepsilon^3}\})$ and $\mathcal{O}(\min\{\frac{\sqrt{N}}{p\varepsilon^2} + \frac{\sqrt{N}}{\varepsilon^2}, \frac{1}{p\varepsilon^3} + \frac{1}{\varepsilon^3}\})$ (p is the number of workers, in this problem $p = N$) in centralized and distributed manners when the objective is nonconvex.

Table E1: Convergence rate of algorithms related to our work (with centralized and distributed setting).

Method	Centralized	Synchronous (Distributed)	Asynchronous (Distributed)
GDmax [25]	$\mathcal{O}(\frac{1}{\varepsilon^6})^{1,3}$	NA[5]	NA[5]
GDA [31]	$\mathcal{O}(\frac{1}{\varepsilon^6})^{1}$	NA[5]	NA[5]
COVER [38]	$\mathcal{O}(\frac{1}{\varepsilon^3})^{2}$	NA[5]	NA[5]
GCIVR [22]	$\mathcal{O}(\min\{\frac{\sqrt{N}}{\varepsilon^2}, \frac{1}{\varepsilon^3}\})^2$	$\mathcal{O}(\min\{\frac{\sqrt{N}}{p\varepsilon^2}+\frac{\sqrt{N}}{\varepsilon^2}, \frac{1}{p\varepsilon^3}+\frac{1}{\varepsilon^3}\})^{2,4}$	NA[5]
ASPIRE-EASE	$\mathcal{O}(\frac{1}{\varepsilon^4})$	NA[5]	$\mathcal{O}(\frac{1}{\varepsilon^6})$

[1] This complexity is to find an ε-stationary point of $\Phi(\cdot) = \max_y f(\cdot, y)$, that is $||\Phi(\cdot)||^2 \leq \varepsilon^2$.
[2] This complexity is to find an ε-stationary point such that $||\mathcal{G}_\eta(\cdot)||^2 \leq \varepsilon^2$, where $\mathcal{G}_\eta$ is a proximal gradient measure.
[3] This complexity corresponds to the number of iterations to solve the inner subproblem. It does not consider the complexity of solving the inner subproblem.
[4] p is the number of workers, in this problem $p = N$.
[5] NA represents not applicable.

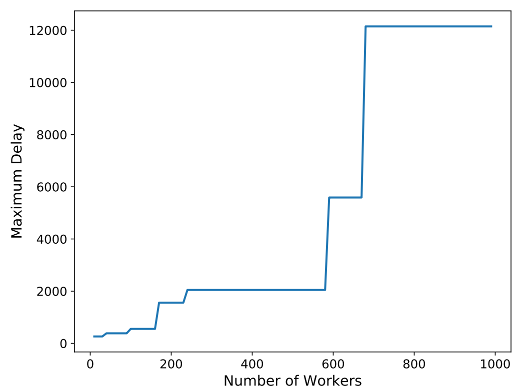


Figure E1: With the increase of the number of workers in the distributed system, the maximum delay would increase dramatically. The delay follows log-normal distribution LN(1, 0.4) in the experiment.

The proposed algorithm differs significantly from the aforementioned methods because it is designed for solving the PD-DRO problem in Eq. (4) in an *asynchronous distributed manner*. The asynchronous distributed algorithm does not suffer from the straggler problem [24] and therefore is critical for large scale distributed optimization in practice. On the contrary, synchronous distributed algorithm suffers from the straggler problem, *i.e.*, its speed is limited by the worker with maximum delay [10] and may not scale well with the size of a distributed system. For instance, we assume that the delays of workers follow a heavy-tailed distribution as given in [12]. With the increase of the number of workers in the distributed system, the maximum delay may increase dramatically as shown in Figure E1. Hence, the synchronous algorithm may incur huge delays and become practically infeasible for a large-scale distributed systems with tens of thousands of workers. Moreover, if a few workers fail to respond, which is very common in real-world large-scale data centers, the synchronous algorithm will come to an immediate halt [58]. Therefore, the asynchronous algorithm is strongly preferred in practice.

The asynchronous setting is considered when we design the distributed algorithm. Compared with centralized algorithm, the asynchronous distributed algorithm is more complicated, which pose the major challenge against the theoretical analysis. In the future work, how to improve the iteration complexity will be taken into consideration. And we summarize the convergence results of different methods in Table E1.

F Explanation about Assumption

The gradient Lipschitz (or smoothness) is a common assumption that has been widely used [16, 38, 31]. In some other works [47, 59], if the function L_p is $\widetilde{L}$-smooth, it has to satisfy,

$$
\begin{aligned}
&||\nabla_\theta L_p(\{\boldsymbol{w}_j\}, \boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\}) - \nabla_\theta L_p(\{\hat{\boldsymbol{w}}_j\}, \hat{\boldsymbol{z}}, \hat{h}, \{\hat{\lambda}_l\}, \{\hat{\boldsymbol{\phi}}_j\})|| \\
&\leq \widetilde{L}(\sum_{j=1}^{N} ||\boldsymbol{w}_j - \hat{\boldsymbol{w}}_j|| + ||\boldsymbol{z} - \hat{\boldsymbol{z}}|| + ||h - \hat{h}|| + \sum_{l=1}^{M} ||\lambda_l - \hat{\lambda}_l|| + \sum_{j=1}^{N} ||\boldsymbol{\phi}_j - \hat{\boldsymbol{\phi}}_j||),
\end{aligned}
\tag{F.160}
$$

where $\theta \in \{\{\boldsymbol{w}_j\}, \boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\}\}$ and we demonstrate L_p that satisfies Eq. (F. 160) is also satisfied with our Assumption 1.

From Eq. (F. 160) and according to Cauchy-Schwarz inequality, we can obtain,

$$
\begin{aligned}
&||\nabla_\theta L_p(\{\boldsymbol{w}_j\}, \boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\}) - \nabla_\theta L_p(\{\hat{\boldsymbol{w}}_j\}, \hat{\boldsymbol{z}}, \hat{h}, \{\hat{\lambda}_l\}, \{\hat{\boldsymbol{\phi}}_j\})||^2 \\
&\leq (2N + M + 2)\widetilde{L}^2(\sum_{j=1}^{N} ||\boldsymbol{w}_j - \hat{\boldsymbol{w}}_j||^2 + ||\boldsymbol{z} - \hat{\boldsymbol{z}}||^2 + ||h - \hat{h}||^2 + \sum_{l=1}^{M} ||\lambda_l - \hat{\lambda}_l||^2 + \sum_{j=1}^{N} ||\boldsymbol{\phi}_j - \hat{\boldsymbol{\phi}}_j||^2).
\end{aligned}
\tag{F.161}
$$

Let $L = \sqrt{(2N + M + 2)}\widetilde{L}$, we can obtain,

$$
\begin{aligned}
&||\nabla_\theta L_p(\{\boldsymbol{w}_j\}, \boldsymbol{z}, h, \{\lambda_l\}, \{\boldsymbol{\phi}_j\}) - \nabla_\theta L_p(\{\hat{\boldsymbol{w}}_j\}, \hat{\boldsymbol{z}}, \hat{h}, \{\hat{\lambda}_l\}, \{\hat{\boldsymbol{\phi}}_j\})|| \\
&\leq L||[\boldsymbol{w}_{\text{cat}} - \hat{\boldsymbol{w}}_{\text{cat}}; \boldsymbol{z} - \hat{\boldsymbol{z}}; h - \hat{h}; \boldsymbol{\lambda}_{\text{cat}} - \hat{\boldsymbol{\lambda}}_{\text{cat}}; \boldsymbol{\phi}_{\text{cat}} - \hat{\boldsymbol{\phi}}_{\text{cat}}]||.
\end{aligned}
\tag{F.162}
$$

G Discussion about CD-norm Uncertainty Set

In this paper, we utilize the CD-norm uncertainty set in our framework. Compared with ellipsoid and KL-divergence uncertainty sets, whose cutting plane generation subproblems are respectively a second-order cone optimization (SOCP) problem and a relative entropy programming (REP) problem, the cutting plane generation subproblem (Eq. (17)) is an LP-type problem when utilizing CD-norm uncertainty set. Please note that the LP-type problem in Eq. (17) can be efficiently solved by merge sort. Therefore, the cutting plane generation subproblem with CD-norm uncertainty set is much easier to solve than those with the ellipsoid and KL-divergence uncertainty sets.