CalFAT: Calibrated Federated Adversarial Training with Label Skewness

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Abstract

Recent studies have shown that, like traditional machine learning, federated learning (FL) is also vulnerable to adversarial attacks. To improve the adversarial robustness of FL, few federated adversarial training (FAT) methods have been proposed to apply adversarial training locally before global aggregation. Although these methods demonstrate promising results on independent identically distributed (IID) data, they suffer from training instability issues on non-IID data with label skewness, resulting in much degraded natural accuracy. This tends to hinder the application of FAT in real-world applications where the label distribution across the clients is often skewed. In this paper, we study the problem of FAT under label skewness, and firstly reveal one root cause of the training instability and natural accuracy degradation issues: skewed labels lead to non-identical class probabilities and heterogeneous local models. We then propose a Calibrated FAT (CalFAT) approach to tackle the instability issue by calibrating the logits adaptively to balance the classes. We show both theoretically and empirically that the optimization of CalFAT leads to homogeneous local models across the clients and better convergence point.

1 Introduction

Federated learning (FL) is a privacy-aware learning paradigm that allows multiple participants (clients) to collaboratively train a global model without sharing their private data [23]. In FL, each client follows the conventional machine learning procedure to train a local model on its own data and periodically uploads the local model updates to a central server for global aggregation. However, recent studies have shown that, like conventional machine learning, FL is also vulnerable to well-crafted adversarial examples [20, 42, 9, 40], i.e., at inference time, the attackers can add small, human-perceptible perturbations to the test examples to fool the global model to make misclassifications with high success rates. This raises security and reliability concerns on the implementation of FL in real-world scenarios where such a vulnerability could cause heavy losses [36]. For example, for cross-silo FL in biomedical domain, a vulnerable global model may cause misdiagnosis, wrong medical treatments, or even the loss of lives. Similarly, in a financial-based cross-silo FL, the lack of adversarial robustness may lead to huge financial losses. It is thus imperative to develop a robust FL method that can train adversarially robust global models resistant to different types of adversarial attacks.

In conventional machine learning, adversarial training (AT) has been shown to be one of the most effective defenses against adversarial attacks [22, 38, 4]. Since the local training in FL is the same as conventional machine learning, recent works [42, 9, 40] proposed to perform local AT to improve the adversarial robustness of the global model. These methods in general are known as Federated Adversarial Training (FAT). AT has been found to be *more* challenging than standard training [3, 39], as it generally requires more training data and larger-capacity models. Moreover,

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adversarial robustness may be at odds with accuracy [28], meaning that the increase of robustness may inevitably decrease the natural accuracy (i.e., accuracy on natural test data). As a result, the natural accuracy of AT is much lower than standard training [5]. This phenomenon also exists in FL, i.e., FAT delivers much slower convergence and lower natural accuracy than standard FL, as shown in recent studies [42, 9].

Arguably, FAT will become more challenging if the data are non-independent and identically distributed (non-IID) across the clients. One typical non-IID setting that commonly exists in real-world applications is the skewed label distribution [17], where different clients have different label distributions. In this paper, we study the problem of FAT on non-IID data with a particular focus on the challenging skewed label distribution setting (formally defined in Section 3.1). Under conventional training, Xu et.al., [35] have showed that adversarially trained models introduce severe performance disparity across different classes. And such disparity will be exacerbated under label skewness, ending up with much worse performance on the minority classes [31].

By far, a few works have studied non-IID FAT in the current literature. Zizzo et.al., [42] proposed to perform AT on only a proportion of local data for better convergence, while standard training is applied on the rest of the local data. We term this method as MixFAT. Another relevant work called FedRBN [9] tackled a different problem: how to propagate federated robustness to low-resource clients. Although MixFAT and FedRBN demonstrated promising results, they suffer from training instability issues and much lower natural accuracy compared to standard FL, as we show in Figure 1. We also compare with the other four FAT baselines that apply different adversarial training methods to FL, i.e., FedPGD, FedTRADES, FedMART, and FedGAIRAT. Unfortunately, these methods also suffer from slow convergence and much degraded final accuracy (details can be referred to Section 4.1). This motivates us to propose a novel method called *Calibrated Federated Adversarial Training* (CalFAT) for tackling FAT with label skewness. CalFAT tackles training instability caused by label skewness by calibrating the logits to give higher scores to the minority classes.

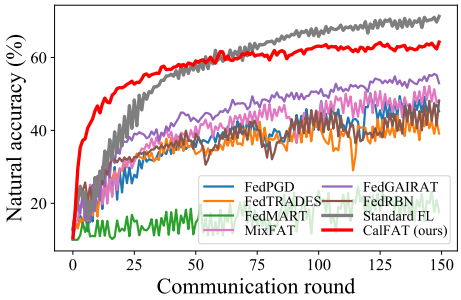

Figure 1: Natural accuracy and convergence of standard FL, our proposed CalFAT, and 6 FAT baselines (FedPGD, FedTRADES, FedMART, MixFAT [42], FedGAIRAT and FedRBN [9]) under a highly skewed label distribution with $\beta = 0.1$ (Section 4).

In summary, our main contributions are:

- *New insight:* We study the problem of FAT on non-IID data with skewed label distribution, and reveal one root cause of the training instability and natural accuracy degradation issues: skewed labels lead to non-identical class probabilities and heterogeneous local models.
- *Novel method:* We propose a novel method called CalFAT for FAT with label skewness, and show that the optimization of CalFAT leads to homogeneous local models, and consequently, stable training, faster convergence, and better final performance.
- *Compelling results*: Extensive experiments on 4 benchmark vision datasets across various settings prove the effectiveness of our CalFAT and its superiority over existing FAT methods.

2 Notation and Preliminaries

2.1 Notation

Suppose there are m clients in FL with i denoting the i-th client, e.g., $\mathcal{D}_i$ denotes the local data of client i and θ_i denotes the parameters of its local model. We use $\hat{\theta}$ to denote the parameters of the global model. Subscript j is the sample index, e.g., (x_{ij}, y_{ij}) denotes the j-th sample of client i and its corresponding label with $y_{ij} \in \{1, \cdots, C\}$. Let $f_\theta(\cdot)$ be the local model $f(\cdot)$ (before softmax) with parameter θ. Superscript l is the class index, e.g., $f^l(\cdot)$ denotes the logit output for class l. We denote the adversarial example of clean sample x by $\widetilde{x}$. $[m]$ denotes the integer set $\{1, \cdots, m\}$.

$p_i(x, y)$ denotes the joint distribution of input x and label y at client i, and accordingly, $p_i(y)$ is the marginal distribution of label y, $p_i(y \mid x)$ is the conditional distribution of label y given input x and $p_i(x \mid y)$ is the conditional distribution of input x given label y.

2.2 Centralized Adversarial Training

Let $\mathcal{D} = \{x_j, y_j\}_{j=1}^n$ be the training dataset with n training samples. The cross-entropy loss $\ell_{ce}(f_\theta(x), y)$ for an input-label pair (x, y) is defined as $\ell_{ce}(f_\theta(x), y) = \sigma^y(f_\theta(x))$, where $\sigma^y(f) = \exp(f^y)/\sum_{l=1}^C \exp(f^l)$ is the softmax function, C is the number of classes, and f^l is the model output for class l. The objective function of the centralized adversarial training (AT) [22] can then be defined as $\min_\theta \sum_{j=1}^n \ell_{ce}(f_\theta(\widetilde{x}_j), y_j)/n$, where the adversarial example $\widetilde{x}_j$ can be generated by $\widetilde{x}_j = \arg\max_{x'_j \in \mathcal{B}_\epsilon(x_j)} \ell_{ce}(f_\theta(x'_j), y_j)$, where $\mathcal{B}_\epsilon(x_j) = \{x' \mid \|x' - x_j\|_\infty < \epsilon\}$ is the closed ball of radius $\epsilon > 0$ centered at x_j, $\|\cdot\|_\infty$ is the L_∞ norm, and $\widetilde{x}_j$ is the most adversarial sample within the ϵ-ball.

A standard centralized AT method uses Projected Gradient Decent (PGD) to generate adversarial examples [22]. In particular, PGD iteratively generates adversarial example as follows: $x_j^{(k+1)} = \Pi_{\mathcal{B}_\epsilon(x_j^{(0)})}\Big(x_j^{(k)} + \alpha\,\mathrm{sign}(\nabla_x \ell_{ce}(f_\theta(x_j^{(k)}), y_j))\Big)$, where $k = 0, \cdots, K-1$ is the step number, K is the total number of steps, $\alpha > 0$ is the step size, $x_j^{(0)}$ is the natural sample, $x_j^{(k)}$ is the adversarial example generated at step k, $\Pi_{\mathcal{B}_\epsilon(x_j^{(0)})}$ is the projection function that projects the adversarial data onto the ϵ-ball centered at $x_j^{(0)}$, and $\mathrm{sign}(\cdot)$ is the sign function. The adversarial example obtained at the final step of PGD is used as the adversarial example, i.e., $\widetilde{x}_j = x_j^{(K)}$.

By optimizing the model parameters on the adversarial examples generated by PGD, centralized AT is able to train a model that is robust against adversarial attacks.

2.3 Federated Adversarial Training

The concept of federated adversarial training (FAT) was first introduced by [42] (We term this method as MixFAT) to deal with the adversarial vulnerability of FL. MixFAT applied AT locally to improve the robustness of the global model. Suppose there are m clients and each client i has its local data $\mathcal{D}_i = \{x_{ij}, y_{ij}\}_{j=1}^{n_i}$ sampled from distribution $p_i(x, y)$ with $n_i = |\mathcal{D}_i|$ being the size of the local data. In MixFAT, each client i optimizes its local model by minimizing the following objective:

$$\min_{\theta_i} \frac{1}{n_i}\Big(\sum_{j=1}^{n'_i} \ell_{ce}(f_{\theta_i}(\widetilde{x}_{ij}), y_{ij}) + \sum_{j=n'_i+1}^{n_i} \ell_{ce}(f_{\theta_i}(x_{ij}), y_{ij})\Big), \tag{1}$$

where $\widetilde{x}_{ij}$ is the PGD adversarial example of x_{ij}, n'_i is a hyperparameter that controls the ratio of data for AT, and θ_i are the local model parameters. After training the local model for certain epochs, client i uploads its local model parameters θ_i to the central server for aggregation. Note that MixFAT only applies AT to a proportion of the local data, mainly for convergence and stability considerations.

3 Calibrated Federated Adversarial Training (CalFAT)

3.1 Skewed Label Distribution Leads to Non-identical Class Probabilities

In this paper, we focus on non-IID setting with *skewed label distribution* [19, 10], which is defined as follows.

Definition 1 (Skewed label distribution)**.** The label distribution across the clients is skewed, if for $\forall i \neq u$ and $i, u \in [m]$:

(a) there exists $y \in [C]$ such that $p_i(y) \neq p_u(y)$ and (b) $p_i(x \mid y) = p_u(x \mid y)$ for $\forall x, y$.

Condition (b) is to assume that, given a class y, x is sampled with equal probability at different clients. Note that there exist different types of non-IID: label skew, non-identical class conditional, quantity skew, to name a few (Appendix K in [10]). The class conditional is often assumed to be identical

(i.e., condition (b)) when studying the label skewness problem, which is the main focus of this work. When condition (b) does not hold, it becomes the non-identical class conditional problem.

Lemma 1 (Non-identical class probabilities)**.** *If the label distribution across the clients is skewed and the class conditionals have the same support, then the class probabilities* $\{p_i(y \mid x) \mid i \in [m]\}$ *are non-identical, i.e., for all* $i \neq u$ *and* $i, u \in [m]$*, there exist* x*,* y *such that* $p_i(y \mid x) \neq p_u(y \mid x)$*.*

The proof of Lemma 1 is given in Appendix A. Lemma 1 implies that skewed label distribution gives rise to non-identical class probabilities $\{p_i(y \mid x) \mid i \in [m]\}$.

3.2 Standard Cross-entropy Leads to Heterogeneity

From a statistical point of view, each client i in previous FAT methods estimates its local class probability $p_i(y \mid x)$ during local training [7]. More specifically, they assume that $p_i(y \mid x)$ can be parameterized by θ_i^* as:

$$p_i(y \mid x) = \hat{p}(y \mid x; \theta_i^*) = \sigma^y(f_{\theta_i^*}(x)), \tag{2}$$

where θ_i^* is the ground-truth parameters of the local class probability $p_i(y \mid x)$. According to Lemma 1, the class probabilities $\{p_i(y \mid x)\}$ are non-identical when there is a skewed label distribution. Therefore, the ground-truth parameters $\{\theta_i^* \mid i \in [m]\}$ are heterogeneous. We use the sample variance of the ground-truth parameters to measure such heterogeneity as follows:

$$(s^*)^2 = V(\theta_1^*, \ldots, \theta_m^*) = \frac{1}{m-1} \sum_{i=1}^{m} \|\theta_i^* - \frac{1}{m} \sum_{j=1}^{m} \theta_j^*\|^2. \tag{3}$$

Each client i updates its local model parameters θ_i by optimizing the standard cross-entropy (CE) loss. The updated θ_i is the maximum likelihood estimate [1] of the ground-truth parameter θ_i^* [7]. We use the sample variance [1] of local model parameters to measure heterogeneity of local models:

$$s^2 = V(\theta_1, \ldots, \theta_m). \tag{4}$$

Larger sample variance implies higher model heterogeneity.

The following proposition suggests that the heterogeneity of local models originates from the heterogeneity of local class probabilities.

Proposition 1 (Heterogeneous local models)**.** *Assume the label distribution across the clients is skewed. Let* θ_i *be the maximum likelihood estimate of* θ_i^* *in Eq. (2) given local data at client* i*. Then* s^2 *converges almost surely to a nonzero constant:*

$$s^2 \xrightarrow{a.s.} (s^*)^2 \neq 0, \tag{5}$$

where $\xrightarrow{a.s.}$ *represents the almost sure convergence.*

The proof of Proposition 1 is provided in Appendix B. $(s^*)^2$ measures the heterogeneity of ground-truth parameters $\{\theta_i^* \mid i \in [m]\}$, which reflects the class probability difference across the clients as shown in Eq. (2).

Proposition 1 implies that the local models in previous FAT methods are heterogeneous when the label distribution across the clients is skewed. Since the local models are heterogeneous, aggregating these models potentially hurts convergence or even results in divergence of the global model [17]. As shown in Figure 1, the training of previous FAT methods are unstable and have much lower natural accuracy than the standard FL.

3.3 Learning Homogeneous Local Models by Calibration

Motivated by [24], we propose to re-parameterize the class probabilities. According to Bayes' formula [12],

$$p_i(y \mid x) = \frac{p_i(x \mid y) p_i(y)}{\sum_{l=1}^{C} p_i(x \mid l) p_i(l)}. \tag{6}$$

On the right-hand side of the above equation: (1) the class priors can be easily approximated by the relative frequencies [1]; and (2) more importantly, the class conditionals $\{p_i(x \mid y) \mid i \in [m]\}$ are *identical* across different clients (see Definition 1).

Inspired by the above observation, we propose an alternative parameterization of $p_i(y \mid x)$. Assume that for all $i \in [m]$, the class conditional $p_i(x \mid y)$ can be parameterized by θ^* as $p_i(x \mid y) = \hat{q}(x \mid y; \theta^*)$, where $\hat{q}(x \mid y; \theta^*)$ can be an arbitrary conditional probability function. Then, $p_i(y \mid x)$ can be re-parameterized by θ^* as follows:

$$p_i(y \mid x) = \hat{q}_i(y \mid x; \theta^*) \tag{7}$$

$$= \frac{\hat{q}(x \mid y; \theta^*)\pi_i^y}{\sum_{l=1}^{C} \hat{q}(x \mid l; \theta^*)\pi_i^l}. \tag{8}$$

where

$$\pi_i^y = n_i^y / n_i + \delta, y \in [C]. \tag{9}$$

Here π_i^y approximates the class prior $p_i(y)$, n_i^y is the sample size of class y on client i and $\delta > 0$ is a small constant added for numerical stability purpose. During local updates, client i uses its local data to update θ_i, which makes θ_i the maximum likelihood estimate of θ^*. The entire training procedure of our method is described in Section 3.4.

Algorithm 1 Local training of CalFAT

Input: Client i, global model parameters $\hat{\theta}$, local dataset $\mathcal{D}_i$, and local epoch number E

procedure CLIENTUPDATE
  $\theta_i \leftarrow \hat{\theta}$
  Compute π_i with $\mathcal{D}_i$ by Eq. (9)
  for local epoch=$1, \cdots, E$ **do**
    for $j = 1, \cdots, n_i$ **do**
      Sample (x_{ij}, y_{ij}) from $\mathcal{D}_i$
      Generate adversarial example $\widetilde{x}_{ij}$ by Eq. (13)
    end for
    $\theta_i \leftarrow \theta_i - \eta \frac{1}{n_i} \sum_{j=1}^{n_i} \nabla_{\theta_i} \ell_{cce}(f_{\theta_i}(\widetilde{x}_{ij}), y_{ij}, \pi_i)$
  end for
  return θ_i
end procedure

The following proposition suggests that the local models are homogeneous when trained with the above re-parameterization. The proof of Proposition 2 is provided in Appendix C.

Proposition 2 (Homogeneous local models)**.** *Assume the label distribution across the clients is skewed. Let θ_i be the maximum likelihood estimate of θ^* in Eq. (7) given local data at client i. Then s^2 converges almost surely to zero:*

$$s^2 \xrightarrow{a.s.} 0. \tag{10}$$

3.4 Details of CalFAT

The local training procedure of our proposed Calibrated Federated Adversarial Training (CalFAT) is described in Algorithm 1. Specifically, we define $\hat{q}(x \mid y; \theta^*) = \exp\left(f_{\theta^*}^y(x)\right)$. Then, we maximize the likelihood of $\hat{q}_i(y \mid x; \theta^*)$ for each client i, which is equivalent to minimizing the following objective:

$$\min_{\theta_i} \frac{1}{n_i} \sum_{j=1}^{n_i} \ell_{cce}(f_{\theta_i}(\widetilde{x}_{ij}), y_{ij}, \pi_i), \tag{11}$$

where $\ell_{cce}(\cdot, \cdot, \cdot)$ is the calibrated cross-entropy (CCE) loss and $\widetilde{x}_{ij}$ is the adversarial example of x_{ij}. The CCE loss is defined as:

$$\ell_{cce}(f_{\theta_i}(\widetilde{x}_{ij}), y_{ij}, \pi_i) = -\log \sigma^{y_{ij}}\left(f_{\theta_i}(\widetilde{x}_{ij}) + \log \pi_i\right). \tag{12}$$

As discussed in Section 3.3, minimizing the above CCE loss mitigates the heterogeneity of the local models, which can lead to improved convergence and performance of the global model.

In previous FAT methods, heterogeneous local models tend to give higher scores to the majority classes while lower scores to the minority classes. By contrast, our CalFAT encourages local models to give higher scores to the minority classes by adding a class-wise prior $\log \pi_i^l$ to the logits. Also different from MixFAT that trains the local models on both natural and adversarial data, our CalFAT trains the local models only on adversarial examples. Extensive empirical experiments are conducted in Section 4.1 to show the impact of using only adversarial data for optimization.

Adversarial example generation. Inspired by [38], we generate the adversarial examples by maximizing the following calibrated Kullback–Leibler (CKL) divergence loss:

$$\widetilde{x}_{ij} = \underset{x'_{ij} \in \mathcal{B}_\epsilon(x_{ij})}{\arg\max} \ \ell_{ckl}(f_{\theta_i}(x'_{ij}), f_{\theta_i}(x_{ij}), \pi_i), \tag{13}$$

Table 1: Natural and robust accuracy (%) on different datasets. The best results are in **bold**.

Dataset	CIFAR10						CIFAR100					
Metric	Natural	FGSM	BIM	CW	PGD-20	AA	Natural	FGSM	BIM	CW	PGD-20	AA
MixFAT	53.35 ± 0.11	29.14 ± 0.10	26.31 ± 0.17	22.79 ± 0.12	26.27 ± 0.11	21.89 ± 0.13	34.43 ± 0.13	15.69 ± 0.13	14.60 ± 0.14	11.31 ± 0.17	14.36 ± 0.20	9.06 ± 0.11
FedPGD	46.96 ± 0.16	28.70 ± 0.19	26.59 ± 0.18	24.38 ± 0.17	26.74 ± 0.18	22.47 ± 0.11	33.96 ± 0.14	16.07 ± 0.08	14.68 ± 0.10	11.67 ± 0.10	14.67 ± 0.15	10.87 ± 0.12
FedTRADES	46.06 ± 0.12	27.75 ± 0.17	26.32 ± 0.09	22.86 ± 0.10	26.31 ± 0.12	21.70 ± 0.09	29.55 ± 0.10	15.01 ± 0.06	14.11 ± 0.11	10.58 ± 0.03	14.30 ± 0.13	9.53 ± 0.09
FedMART	25.67 ± 0.21	18.50 ± 0.18	18.21 ± 0.22	15.22 ± 0.17	18.10 ± 0.22	14.41 ± 0.20	19.96 ± 0.17	13.00 ± 0.19	12.91 ± 0.14	9.92 ± 0.21	12.83 ± 0.18	8.57 ± 0.14
FedGAIRAT	48.42 ± 0.08	29.30 ± 0.09	26.55 ± 0.07	22.78 ± 0.12	27.20 ± 0.08	21.96 ± 0.07	34.92 ± 0.05	16.18 ± 0.06	15.37 ± 0.10	11.80 ± 0.05	14.90 ± 0.03	9.41 ± 0.05
FedRBN	47.80 ± 0.06	26.87 ± 0.07	26.25 ± 0.03	22.00 ± 0.01	26.30 ± 0.09	21.33 ± 0.09	28.55 ± 0.07	14.69 ± 0.04	13.41 ± 0.08	9.71 ± 0.08	14.15 ± 0.12	8.83 ± 0.08
CalFAT (ours)	**64.69** ± 0.08	**35.03** ± 0.12	**31.50** ± 0.07	**24.69** ± 0.11	**31.12** ± 0.11	**22.91** ± 0.08	**44.57** ± 0.10	**17.63** ± 0.10	**15.60** ± 0.11	**12.01** ± 0.11	**15.21** ± 0.07	**11.49** ± 0.08
Dataset	SVHN						ImageNet subset					
Metric	Natural	FGSM	BIM	CW	PGD-20	AA	Natural	FGSM	BIM	CW	PGD-20	AA
MixFAT	19.57 ± 0.10	19.61 ± 0.12	19.66 ± 0.12	19.66 ± 0.11	19.75 ± 0.11	14.80 ± 0.07	33.53 ± 0.06	19.47 ± 0.02	18.48 ± 0.10	16.15 ± 0.07	18.39 ± 0.02	11.98 ± 0.06
FedPGD	19.55 ± 0.08	19.33 ± 0.09	19.37 ± 0.08	19.68 ± 0.05	19.52 ± 0.09	13.64 ± 0.10	30.87 ± 0.12	18.88 ± 0.13	17.95 ± 0.10	16.07 ± 0.11	18.40 ± 0.16	11.34 ± 0.08
FedTRADES	56.96 ± 0.13	36.92 ± 0.13	35.15 ± 0.05	31.08 ± 0.14	34.90 ± 0.15	30.37 ± 0.11	30.22 ± 0.14	18.67 ± 0.13	17.99 ± 0.21	16.23 ± 0.13	17.82 ± 0.12	11.81 ± 0.10
FedMART	19.85 ± 0.16	19.94 ± 0.16	19.71 ± 0.16	19.85 ± 0.15	19.79 ± 0.17	14.64 ± 0.14	26.47 ± 0.18	16.40 ± 0.18	15.53 ± 0.17	14.43 ± 0.13	15.40 ± 0.21	9.34 ± 0.14
FedGAIRAT	58.41 ± 0.11	38.30 ± 0.12	36.52 ± 0.09	31.24 ± 0.15	36.69 ± 0.13	31.63 ± 0.06	34.25 ± 0.12	19.62 ± 0.10	19.28 ± 0.14	16.78 ± 0.14	19.18 ± 0.12	11.80 ± 0.09
FedRBN	53.88 ± 0.04	34.48 ± 0.08	32.52 ± 0.02	27.99 ± 0.02	32.32 ± 0.03	28.35 ± 0.05	29.35 ± 0.09	18.76 ± 0.03	17.25 ± 0.12	15.07 ± 0.10	18.05 ± 0.09	11.42 ± 0.12
CalFAT (ours)	**84.15** ± 0.07	**48.38** ± 0.11	**42.04** ± 0.07	**31.66** ± 0.04	**41.68** ± 0.11	**32.57** ± 0.10	**49.89** ± 0.11	**22.31** ± 0.17	**19.99** ± 0.09	**17.42** ± 0.12	**19.97** ± 0.14	**12.30** ± 0.07

where $\ell_{ckl}(\cdot,\cdot,\cdot)$ is the CKL loss defined as:

$$\ell_{ckl}(f_{\theta_i}(x'_{ij}), f_{\theta_i}(x_{ij}), \pi_i) = -\sum_{y=1}^{C} \sigma^y(f_{\theta_i}(x_{ij}) + \log \pi_i) \log \sigma^y(f_{\theta_i}(x'_{ij}) + \log \pi_i), \tag{14}$$

where $\log \pi_i$ is the same as in our CCE loss. Following centralized AT [22], we also use PGD to solve Eq. (13).

After training the local model for certain epochs following the above procedure, each client i uploads the model parameters θ_i to the server for aggregation. To be consistent with the most recent FAT methods [42, 9], we first use the most widely used FedAvg [23] as the default aggregation framework. However, we remark that our method is agnostic to FL frameworks, i.e., it is compatible with any other FL frameworks (e.g., FedProx [16] and Scaffold [11]), as shown in Section 4.1.

4 Experiments

Data configurations. Our experiments are conducted on 4 real-world datasets: CIFAR10 [13], CIFAR100 [13], SVHN [25], and ImageNet subset [6]. To simulate label skewness, we sample $p_i^l \sim Dir(\beta)$ and allocate a p_i^l proportion of the data of label l to client i, where $Dir(\beta)$ is the Dirichlet distribution with a concentration parameter β [37]. By default, we set $\beta = 0.1$ to simulate a highly skewed label distribution that widely exists in reality.

Baselines. We compare our proposed CalFAT with two state-of-the-art FAT methods: MixFAT [42] and FedRBN [9]. We also investigate the combination of the state-of-the-art centralized AT methods with FL, i.e., we apply standard PGD [22], TRADES [38], MART [32]), and GAIRAT [39] to FL, and term them as FedPGD, FedTRADES, FedMART, and FedGAIRAT.

Evaluation metrics. We report the natural test accuracy (Natural) and robust test accuracy under the most representative attacks, i.e., FGSM [33], BIM [15], PGD-20 [22], CW [2], and AA [5]. We run the experiment for 5 times and report the mean and standard deviation. More detailed experimental setup is provided in Appendix D.1.

4.1 Main Results

Evaluation on different datasets. Table 1 shows the results of all methods on CIFAR10, CIFAR100, SVHN, and ImageNet subset. From the table, we can observe that:

(1) Our CalFAT achieves the best robustness on all datasets, validating the efficacy of our CalFAT. For example, CalFAT outperforms the best baseline method (FedGAIRAT) by 10.20% on SVHN dataset under FGSM attack.

(2) Our CalFAT shows a significant improvement in natural accuracy compared to other baselines. For example, CalFAT can improve the natural accuracy of the best baseline method (FedGAIRAT) by 25.63% on SVHN dataset. We hypothesise that the reason lies in the homogeneity of local models in our CalFAT, which leads to better convergence and higher performance.

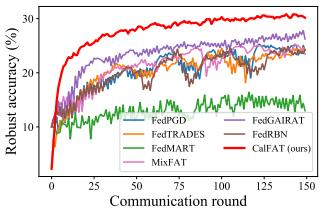

Figure 2: Robust accuracy (against PGD-20 attack) of different methods on CIFAR10 dataset.

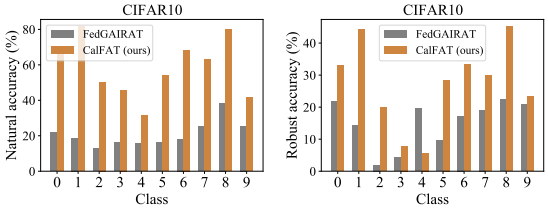

Figure 3: Per-class natural accuracy and robust accuracy (against PGD-20 attack) of CalFAT and the best baseline (FedGAIRAT) on CIFAR10 dataset.

(3) All methods demonstrate the worst performance on CIFAR100 and ImageNet subset datasets. We conjecture that this is due to the more classes in these two datasets, which makes the training hard. Nevertheless, our CalFAT still achieves the best performance.

Learning curves of different methods. To visually compare our CalFAT with all the baselines, we plot the learning curves (i.e, performance across different communication rounds) of all methods in Figure 1 and Figure 2. As shown in these figures, CalFAT achieves the best natural accuracy and robust accuracy from the beginning to the end of the training compared to the baseline FAT methods, which indicates that the design of our CalFAT is profitable across the whole training process. Moreover, our CalFAT is stable during the whole training process while the accuracy curves of other baselines oscillate strongly. Such oscillations lead to bad convergence and low performance. We hypothesise that the heterogeneity of local models in the baseline methods makes the training unstable while CalFAT learns homogeneous local models.

Combining calibration loss with other FAT methods. In this paper, we propose a calibration loss that can enhance FAT. To further show the effectiveness of our calibration loss, we combine our calibration loss with four FAT methods (MixFAT, FedPGD, FedTRADES, and FedMART) and name them MixFAT + Calibration, FedPGD + Calibration, FedTRADES + Calibration, and FedMART + Calibration, respectively. We compare these calibration loss-based FAT methods with their original version in Table 2. As shown in the table, by involving our calibration loss, all FAT methods achieve better performance. The results further confirm that our calibration loss can be combined with other FAT methods and improve their performance.

Table 2: Combining FAT methods with different losses.

Metric	Natural	PGD-20
MixFAT	53.35 ± 0.11	26.27 ± 0.11
MixFAT + LogitAdj	57.53 ± 0.21	27.65 ± 0.16
MixFAT + RoBal	58.25 ± 0.13	27.86 ± 0.10
MixFAT + Calibration (ours)	**60.23** ± 0.19	**28.67** ± 0.14
FedPGD	46.96 ± 0.16	26.74 ± 0.18
FedPGD + LogitAdj	59.79 ± 0.15	28.84 ± 0.12
FedPGD + RoBal	61.48 ± 0.07	29.51 ± 0.07
FedPGD + Calibration (ours)	**63.91** ± 0.13	**30.72** ± 0.16
FedTRADES	46.06 ± 0.12	26.31 ± 0.12
FedTRADES + LogitAdj	58.26 ± 0.20	27.92 ± 0.19
FedTRADES + RoBal	59.25 ± 0.23	28.63 ± 0.08
FedTRADES + Calibration (ours)	**63.12** ± 0.10	**30.27** ± 0.23
FedMART	25.67 ± 0.21	18.10 ± 0.22
FedMART + LogitAdj	42.01 ± 0.10	24.92 ± 0.02
FedMART + RoBal	44.26 ± 0.22	25.57 ± 0.17
FedMART + Calibration (ours)	**48.85** ± 0.08	**27.19** ± 0.11
CalFAT (ours)	**64.69** ± 0.08	**31.12** ± 0.11

Comparison with state-of-the-art long-tail learning methods. We also compare our calibration loss with the losses used by long-tail learning methods LogitAdj [24] and RoBal [34]. In particular, we combine four FAT methods (MixFAT, FedPGD, FedTRADES, and FedMART) with the above three losses (LogitAdj loss, RoBal loss, and our calibration loss), and train the models following the same default setting. As shown in Table 2, both LogitAdj-based methods and RoBal-based methods have lower natural and robust accuracy than calibration loss-based methods. This indicates that in FAT our calibration loss is more suitable than other long-tail learning losses.

Table 3: Natural and robust accuracy (%) across different FL frameworks on CIFAR10 dataset.

FL framework	FedProx			Scaffold		
Metric	Natural	PGD-20	AA	Natural	PGD-20	AA
MixFAT	53.75 ± 0.16	29.61 ± 0.19	21.59 ± 0.27	55.27 ± 0.20	28.78 ± 0.15	21.26 ± 0.11
FedPGD	49.57 ± 0.18	28.48 ± 0.17	21.31 ± 0.18	49.52 ± 0.14	27.46 ± 0.21	20.27 ± 0.15
FedTRADES	48.14 ± 0.20	27.75 ± 0.17	21.13 ± 0.21	47.78 ± 0.23	27.31 ± 0.16	20.04 ± 0.16
FedMART	28.32 ± 0.22	19.32 ± 0.23	15.91 ± 0.25	27.80 ± 0.17	20.03 ± 0.26	16.85 ± 0.15
FedGAIRAT	49.61 ± 0.20	29.34 ± 0.11	21.33 ± 0.18	49.54 ± 0.21	27.23 ± 0.25	20.16 ± 0.09
FedRBN	47.26 ± 0.13	26.63 ± 0.15	20.46 ± 0.06	49.77 ± 0.09	28.37 ± 0.12	20.32 ± 0.06
CalFAT	$\mathbf{66.32} \pm 0.08$	$\mathbf{32.79} \pm 0.13$	$\mathbf{22.83} \pm 0.11$	$\mathbf{67.16} \pm 0.06$	$\mathbf{32.94} \pm 0.06$	$\mathbf{21.94} \pm 0.05$

4.2 Performance on Different Classes

We further compare the per-class performance (performance on each class) of CalFAT with the best baseline (FedGAIRAT). First, we use a well-trained model to initialize a global model. Second, the global model distributes the model parameter to all clients. Third, the local clients train their local models with their local data for 1 epoch. Then, we report the per-class average performance of all clients for each class. For fair comparisons, we use the same well-trained model for initialization and the same data partition on each client for CalFAT and FedGAIRAT.

In Figure 3, we report the per-class natural and robust accuracy of CalFAT and the best baseline (FedGAIRAT) on CIFAR10 dataset. As shown in these figures, the average performance of most classes of CalFAT is much higher than FedGAIRAT. We also report the per-class performance of each client on CIFAR10 dataset in Appendix D.2. In FedGAIRAT, due to highly skewed label distribution, the prediction of each client is highly biased to majority classes, which leads to high performance on majority classes and low performance (even 0% accuracy) on minority classes. By contrast, in CalFAT, each client has higher performance on most classes. These results show that the calibrated cross-entropy loss can indeed improve the performance on minority classes, and further improve the overall performance of the model. Moreover, we report the per-class average performance on SVHN dataset in Appendix D.3. Our CalFAT still outperforms the best baseline across most classes on SVHN dataset.

4.3 Results on Different FL Frameworks and Network Architectures

Evaluation on different FL frameworks. Besides FedAvg [23], we also conduct experiments on other FL frameworks, i.e., FedProx [16] and Scaffold [11]. The results for all methods on FedProx and Scaffold are shown in Table 3. It can be observed that CalFAT has better natural accuracy and robust accuracy than all baselines on all FL frameworks, which indicates that CalFAT can be well combined with most FL frameworks.

Evaluation on different network architectures. We also compare CalFAT with baselines on different network architectures, i.e., CNN [23], VGG-8 [27], and ResNet-18 [8]. For CNN, we use the same architecture as [23]. VGG-8 and ResNet-18 are two widely used architectures in deep learning. The results on CIFAR10 dataset are shown in Appendix D.4. CalFAT outperforms all baselines, which further validates the superiority of CalFAT under different network architectures.

4.4 Feature Visualization

To better illustrate the efficacy of CalFAT, we visualize the learned features extracted from the second last layer of FedTRADES (the best baseline) and CalFAT trained on SVHN dataset in Appendix D.5. The extracted features are visualized in a 2-dimensional space by t-SNE [29]. The visualization results show that data from different classes are mixed together in FedTRADES, resulting in low performance. For instance, Class 6 (pink) and Class 8 (khaki) are hard to be separated in FedTRADES while these 2 classes can be well separated in CalFAT. This illustration further verifies that the server cannot learn a good global model from the heterogeneous local models. By contrast, CalFAT can well separate different classes and achieve better performance.

4.5 Results under IID settings

Besides the non-IID setting, we also conduct an experiment under the IID setting. The results are shown in Appendix D.6 where it shows that our CalFAT achieves the best robustness (under PGD-20 attack). Compared to the non-IID setting, all FAT methods demonstrate much better performance under the IID setting. This indicates that existing FAT methods can easily handle IID data yet facing substantial challenge on non-IID data.

4.6 Ablation Studies

Impact of the number of clients. To show the capability of CalFAT, we train CalFAT with different number of clients m. Table 7 in Appendix D.7 reports all the results across $m = \{20, 50, 100\}$. As expected, CalFAT achieves the best performance across all m. As m increases, the performance of all methods decreases. We conjecture that the reason is that more clients in FAT make the model harder to converge. However, our CalFAT can still achieve 41.23% natural accuracy when there are 100 clients, which outperforms other baselines by a large margin.

Impact of skewed label distribution. We find that the performance of these FAT methods is closely related to label skewness. We investigate the impact of skewed label distribution by varying the Dirichlet parameter $\beta = \{0.05, 0.2, 0.3\}$ and report the results on CIFAR10 dataset in Table 8 in Appendix D.8. Not surprisingly, our CalFAT outperforms all baselines under all β's. This further verifies the consistent effectiveness of CalFAT under label skewness.

Note that as β decreases (i.e., the labels on each client are more imbalanced), the performance of all methods drops rapidly. For example, the natural accuracy of FedMART drops from 38.38% to 29.84% as β decreases from 0.2 to 0.05. This indicates that all methods are hard to train a good model in extremely skewed label distribution scenarios. However, our CalFAT still achieves 61.00% natural accuracy and 32.40% robust accuracy (against FGSM attack) when $\beta = 0.05$, which are much higher than all the baselines.

Contribution of the calibrated loss functions. As shown in Eq. (12) and Eq. (14), for each client i, we have two new loss functions: a CCE loss $\ell_{cce}(\cdot,\cdot,\cdot)$ for optimization and a CKL loss $\ell_{ckl}(\cdot,\cdot,\cdot)$ to generate adversarial data. This naturally raises a question: how do these two loss functions contribute to CalFAT? To answer this question, we conduct leave-one-out tests by removing the CCE loss (w/o $\ell_{cce}(\cdot,\cdot,\cdot)$) and removing the CKL loss (w/o $\ell_{ckl}(\cdot,\cdot,\cdot)$). As illustrated in Appendix D.9, w/o $\ell_{cce}(\cdot,\cdot,\cdot)$ leads to poor performance, which implies that CCE loss plays an important role in enhancing CalFAT. Besides, if we use only the CCE loss (i.e., w/o $\ell_{ckl}(\cdot,\cdot,\cdot)$), we can achieve a much better performance, but still underperforms CalFAT. All these results indicate that the CCE loss is the most important part in CalFAT, and the CKL loss can further increase the performance of CalFAT. The combination of both loss functions leads to the best performance.

Impact of the ratio of adversarial data. To investigate the impact of adversarial data, we conduct experiments with different ratios of adversarial data on CalFAT. Appendix D.10 shows the robust accuracy (against PGD-20 attack) of CalFAT with different ratios of adversarial data. Ratio r=0 and r=1 stand for training the model with only natural data and with only adversarial data, respectively. As expected, r=1 achieves the best performance, which further verifies that training with only adversarial data can better enhance adversarial robustness in CalFAT.

5 Conclusion

In this paper, we studied the challenging problem of Federated Adversarial Training (FAT) with label skewness and proposed a novel Calibrated Federated Adversarial Training (CalFAT) to achieve stable training, better convergence, and natural accuracy and robustness in FL. CalFAT calibrates the model prediction and trains homogeneous local models across different clients by giving higher scores to minority classes, thus delivering a better global model in FAT. Extensive experiments across representative vision datasets under various settings validate the effectiveness of our proposed method. We envision our work as a milestone for more accurate and robust federated adversarial training. As future work, we will continue to improve FAT under other non-IID settings such as feature skewness, quantity skewness and temporal skewness [10, 41], etc.

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1. For all authors...
   (a) Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope? [Yes]
   (b) Did you describe the limitations of your work? [Yes]
   (c) Did you discuss any potential negative societal impacts of your work? [No]
   (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]
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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]
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