TP2: Understanding Data Heterogeneity and Client Drift Report

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May 28, 2025

1 Federated Learning under Data Heterogeneity: Experimental Analysis

1.1 Introduction

This report analyzes the impact of data heterogeneity on the performance of three federated learning strategies: **FedAvg**, **FedProx**, and **SCAFFOLD**. The analysis is based on the training loss and test accuracy curves, as well as a summary table of key metrics, all generated from experiments with different Dirichlet α parameters (which control the degree of data heterogeneity between clients). All referenced figures can be found in the `TP2_figures` directory.

1.2 Effect of Data Heterogeneity on Federated Learning Performance

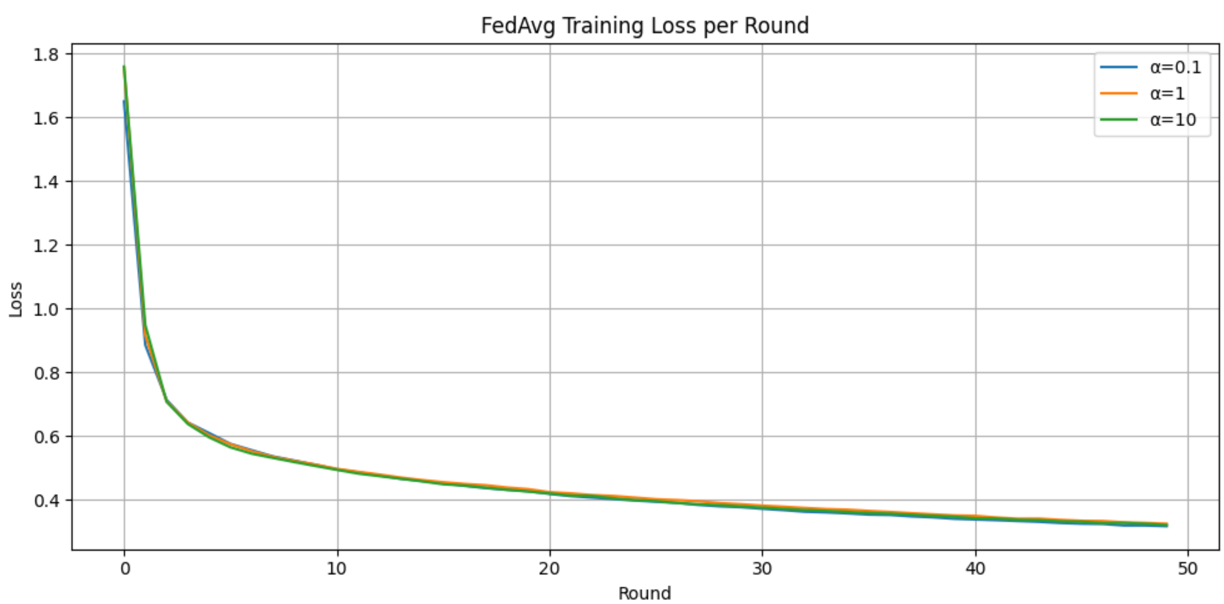

Figure 1: FedAvg Training Loss per Round for different α values

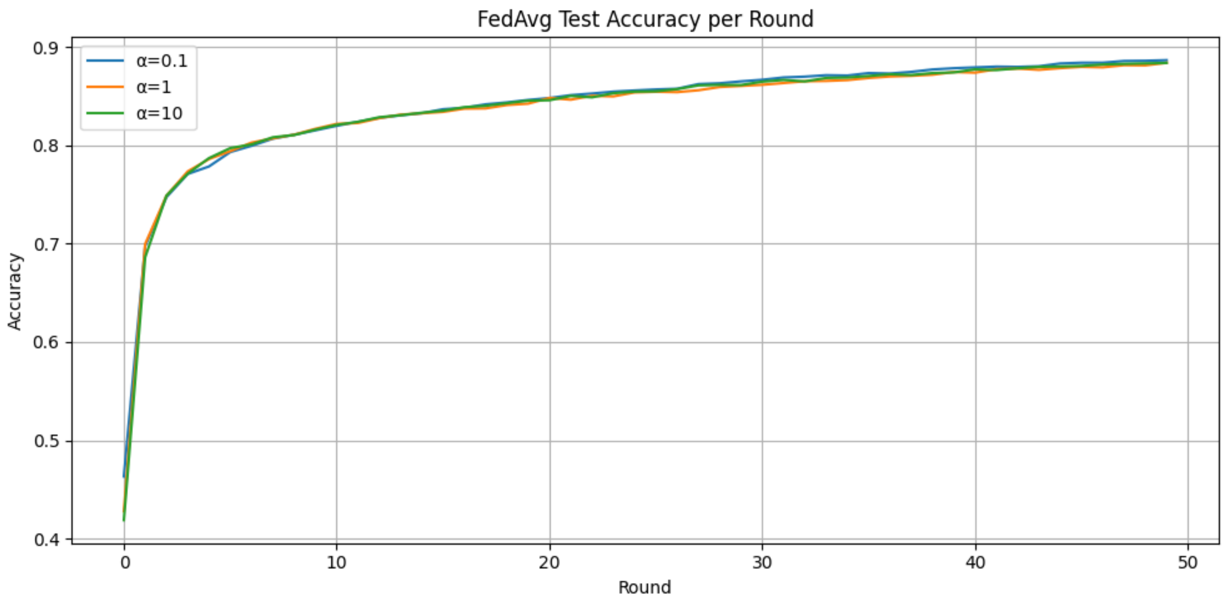

Figure 2: FedAvg Test Accuracy per Round for different α values

As shown in Figures 1 and 2, **data heterogeneity** (lower α) leads to slower convergence, higher training losses, and lower final accuracy for FedAvg. The curves for smaller α values are more oscillatory and reach lower plateaus. This suggests that the distribution of non-IID-based data among clients complicates global optimization. This is primarily due to *client drift*, where local updates deviate from the global target, leading to instability and suboptimal aggregation.

1.3 FedProx: Mitigating Client Drift

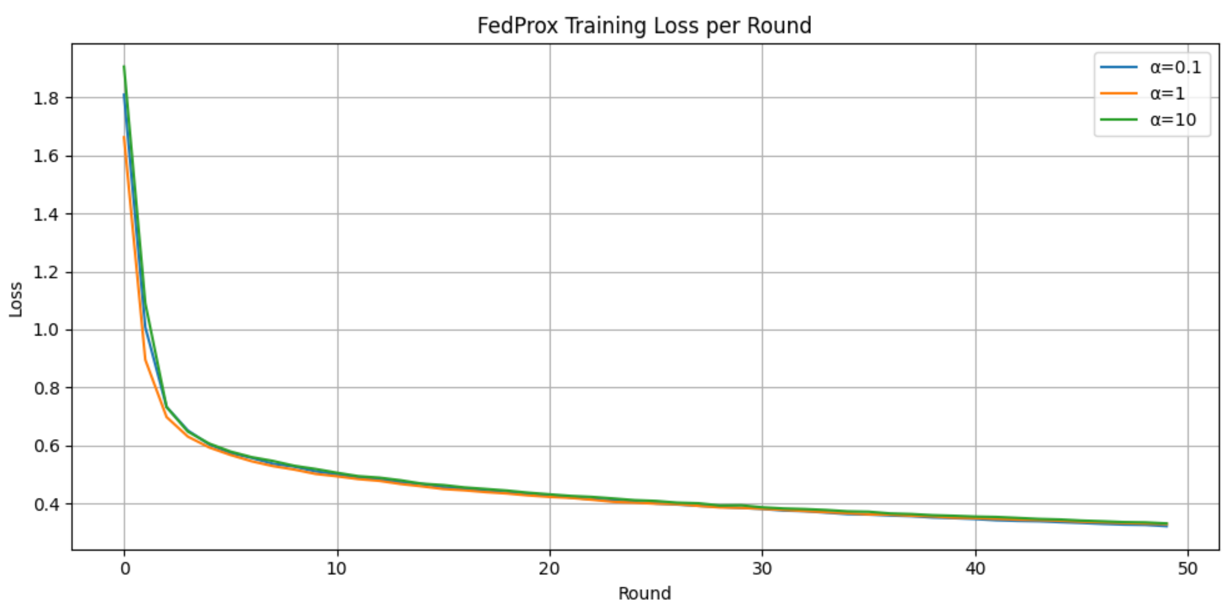

Figure 3: FedProx Training Loss per Round for different α values

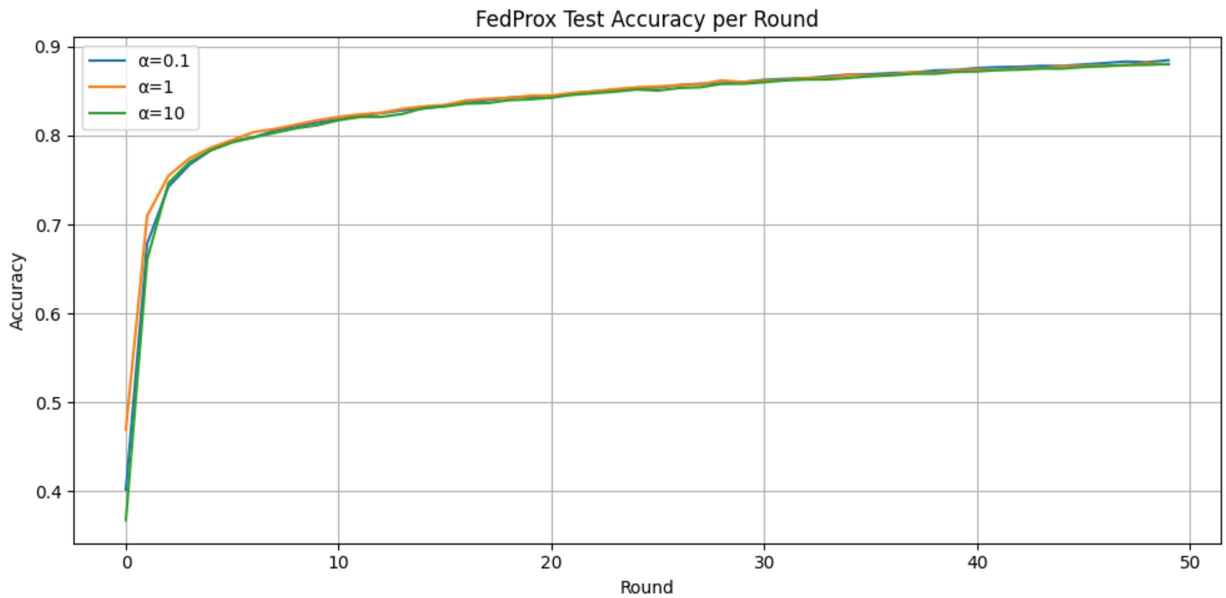

Figure 4: FedProx Test Accuracy per Round for different α values

FedProx introduces a proximal term to the local target and penalises updates that deviate too far from the global model. As can be seen in Figures 3 and 4, this results in smoother loss and accuracy curves, especially for lower α values. **FedProx** reduces oscillations and improves training stability compared to FedAvg. However, the improvement in final accuracy is small and not always consistent across all heterogeneity settings. In some cases, FedProx converges slightly faster than FedAvg, but the difference in final model performance is small.

1.4 SCAFFOLD: Improved Convergence under High Heterogeneity

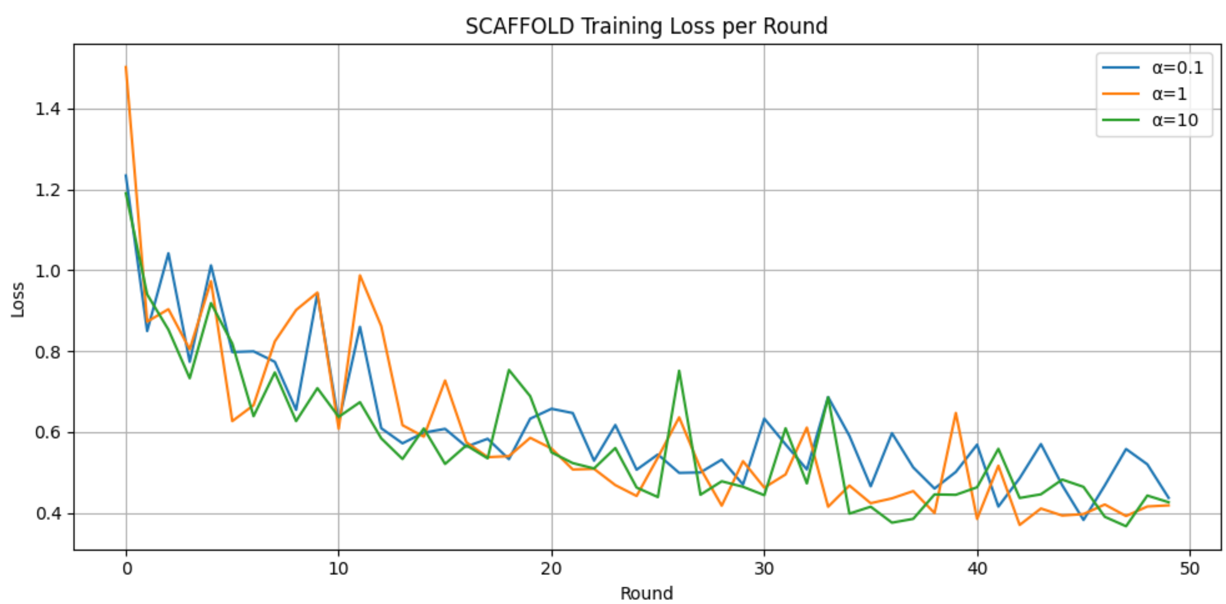

Figure 5: SCAFFOLD Training Loss per Round for different α values

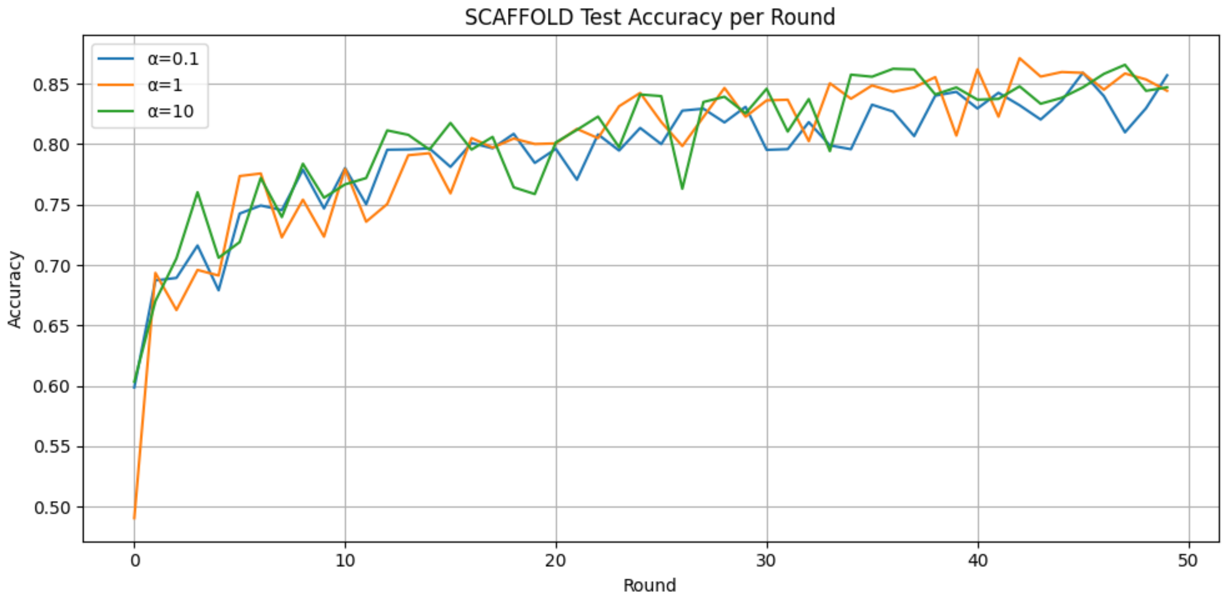

Figure 6: SCAFFOLD Test Accuracy per Round for different α values

SCAFFOLD uses control variables to correct for client drift, resulting in faster and more stable convergence, in highly heterogeneous settings (low α). Figures 5 and 6 show that SCAFFOLD achieves lower losses and higher accuracy faster than FedAvg and FedProx on highly non-IID data. The convergence speed is significantly improved, and the final accuracy is competitive or even superior, especially for $\alpha = 0.1$.

1.5 Summary Table and Comparative Analysis

Strategy	Alpha	Final Accuracy	Convergence Round	Stability (std last 10)
FedAvg	0.1	0.886617	19	0.002676
FedAvg	1.0	0.883982	19	0.002669
FedAvg	10.0	0.883791	18	0.002416
FedProx	0.1	0.884707	19	0.002842
FedProx	1.0	0.879795	17	0.002422
FedProx	10.0	0.880388	18	0.002665
SCAFFOLD	0.1	0.857039	27	0.014331
SCAFFOLD	1.0	0.844205	17	0.012602
SCAFFOLD	10.0	0.847076	13	0.009565

Figure 7: Summary Table: Final Accuracy, Convergence Speed, and Stability for all strategies and α values

Key Observations:

- **Data heterogeneity** (low α) negatively affects all strategies, but FedAvg is the most affected, with slower convergence and lower final accuracy.
- **FedProx** mitigates client drift, resulting in smoother and more stable training, but only moderately improves convergence speed and final accuracy compared to FedAvg.

- **SCAFFOLD** shows the best convergence speed and stability in highly heterogeneous settings, with competitive or superior final accuracy compared to FedAvg and FedProx.

Conclusion: While all strategies suffer from increased data heterogeneity, SCAFFOLD is the most robust and provides faster and more stable convergence. FedProx offers some improvements over FedAvg, especially in training stability. These results are visually supported by the loss and accuracy curves and the summarised table in the `TP2_figures` directory.