

Sourav BHATTACHARJEE

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Cover Page of the Dissertation

Federated Learning with Context-Aware Model Orchestration and Privacy Preservation
Using Differential Privacy

DISSERTATION

Submitted in partial fulfillment of the requirements of the

Degree: MTech in Data Science and Engineering

By

Sourav Bhattacharjee
2023DA04045

Under the supervision of

Pradeep Rai
Senior Manager, Risk Management

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
Pilani (Rajasthan) INDIA

June, 2025

Table of Contents

S.No.	Description	Page Number
1.	Dissertation Abstract	3-11
2.	EDA of Dataset (CIFAR 10)	12-15
3.	Tables List <ul style="list-style-type: none"> Table 1 Table 2 Table 3 Table 4 	27 31 31 32
4.	Figures List <ul style="list-style-type: none"> Fig 1 Fig 2 Fig 3 Fig 4 Fig 5 Fig 6 Fig 7 Fig 8 Fig 9 Fig 10 Fig 11 Fig 12 Fig 13 	12 13 14 14 18 20 20 22 22 28 31 32 33
5.	Chapter 1	16-17
6.	Chapter 2	18-21
7.	Chapter 3	22-25
8.	Chapter 4	26-29
9.	Chapter 5	30-33
10.	Directions for future work after mid semester	34
11.	Summary of literature survey	35-36
12.	Github Link for Codebase	36
13.	List of Symbols & Abbreviations	37-38
14.	Bibliography / References	39
15.	Checklist	40

1. Dissertation Outline (Abstract)

BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE, PILANI
SECOND SEMESTER 2024-25

DSECLZG628T DISSERTATION

Dissertation Title : Federated Learning with Context-Aware Model Orchestration and Privacy Preservation Using Differential Privacy

Name of Supervisor : Pradeep Rai

Name of Student : Sourav Bhattacharjee

ID No. of Student : 2023DA04045

Courses Relevant for the Project & Corresponding Semester:

Semester	Course No.	Course Title	Justification
1	DSECL ZG532	Introduction to Data Science	Provided fundamentals of data handling and ML workflows.
2	DSECL ZG565	Machine Learning	Core concepts for model training and evaluation in FL.
2	DSECL ZG529	Data Management for Machine Learning	Helped simulate distributed clients and data flows.
3	DSECL ZG524	Deep Learning	Enabled design of CNN models used in clients.

Abstract

Key Words: Federated Learning, Model Context Protocol, Differential Privacy, Decentralized AI, Privacy-Preserving Machine Learning, Flower, Adaptive AI Models

The increasing deployment of machine learning models across edge devices and distributed systems has introduced critical challenges related to **device heterogeneity**, **data privacy**, and **computational efficiency**. Devices participating in real-world machine learning tasks often differ in processing power, memory, and network connectivity. At the same time, data generated on such devices is often sensitive—especially in domains like healthcare and finance—making centralized model training infeasible due to regulatory and ethical concerns. This dissertation proposes a novel federated learning framework that

addresses these issues through the integration of **Model Context Protocol (MCP)** and **Differential Privacy (DP)** mechanisms.

5 The system is designed to support federated learning (FL), where multiple clients collaboratively train a global model without sharing raw data. Instead of transmitting private datasets, each client performs local training on its own data and shares only the model weight updates with a central server, which aggregates them into a global model. A key feature of this system is its support for **user-driven model selection** via command-line prompts. At the time of launch, each client explicitly selects between a lightweight (SmallCNN) or heavyweight (BigCNN) model, allowing users to tailor the model choice to their device's computational capacity.

12 To ensure **data privacy**, each client incorporates **differential privacy techniques** during local training. Using the Opacus library, noise is added to gradients or model parameters before they are shared with the server, thereby limiting the possibility of reconstructing any individual's data from the model updates.

13 The system is developed using the **Flower federated learning framework**, and validated using the **CIFAR-10 dataset**, which is distributed across clients in a non-IID fashion to simulate real-world variations in data availability and quality. Clients autonomously measure their system context through local monitoring tools and select the appropriate model accordingly. Local training is performed under privacy-preserving constraints, and the federated server performs secure aggregation of the received model updates to improve a shared global model iteratively over multiple training rounds.

3 The project demonstrates how the combination of **federated learning**, **context-aware model orchestration**, and **differential privacy** can yield a flexible, adaptive, and secure machine learning system. This approach has practical relevance to scenarios where **data sensitivity and device variability** are both dominant concerns, such as in mobile health applications, smart home ecosystems, and financial transaction analysis. The proposed framework is designed to be modular and extensible, making it suitable for future enhancements like real-time personalization and on-device inference optimization.

Overall, this work presents a comprehensive solution to contemporary challenges in decentralized AI, offering both theoretical robustness and implementation feasibility.

Why have the model choice been made explicit at runtime:

Advantages of Explicit Model Selection

1. User Awareness and Control

- **Reason:** Some users or developers may want full control over which model is used, especially in experimental or testing scenarios.

- **Advantage:** Enables deliberate testing of model performance under different hardware conditions or datasets.

2. Simplified Debugging and Reproducibility

- **Reason:** Knowing exactly which model was used on each client simplifies tracking bugs or anomalies.
- **Advantage:** Makes experiments deterministic and results reproducible, which is critical for academic research and benchmarking.

3. Avoids Unintended Overhead

- **Reason:** Context-aware dynamic switching requires continuous system monitoring and decision logic (CPU, memory checks).
- **Advantage:** Removing this complexity reduces runtime overhead, making the system lighter and easier to deploy in constrained environments.

4. Works on All Systems (Including Headless/Cloud Clients)

- **Reason:** Some client systems (like edge devices or cloud VMs) may not expose real-time hardware metrics.
- **Advantage:** Explicit input works universally across all environments without hardware-level integration.

5. Better for Education and Demonstration

- **Reason:** When teaching federated learning concepts, it helps to isolate model-related decisions from system context.
- **Advantage:** Makes it easier to demonstrate the impact of model complexity on training time, accuracy, and communication cost.

6. Fine-Grained Testing of Model Performance

- **Reason:** Developers may want to test how SmallCNN and BigCNN individually contribute to global performance.
- **Advantage:** Enables scenario-based testing like “What happens if 3 out of 5 clients use BigCNN?”

7. Avoids Inaccurate or Inconsistent Context Detection

- **Reason:** CPU/memory usage may not accurately reflect resource availability, especially on shared or virtualized systems.
- **Advantage:** Manual selection avoids false triggers or suboptimal auto-choices made under misleading system states.

Context-Aware Model Assignment for Real-World Mobile Apps

In a real-world mobile application that trains models based on user interactions, devices vary greatly in hardware capabilities. To ensure optimal performance across this diversity, our system assigns model architectures dynamically based on each device's specs.

For example, lower-end phones receive a lightweight model (SmallCNN), while high-performance devices are assigned a larger model (BigCNN).

This approach ensures:

- **Smooth app performance** across all devices
- **Inclusive participation** in federated learning
- **Efficient use of resources**, preserving battery and responsiveness
- **Balanced global training**, leveraging both simple and complex models

By adapting models to the device, the system delivers intelligent personalization without compromising user experience or system stability.

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI
II SEMESTER 24-25
DSECLZG628T DISSERTATION
Dissertation Outline (Abstract)

BITS ID No.: 2023DA04045

Name of Student: Sourav Bhattacharjee

Name of Supervisor: Pradeep Rai

Designation of Supervisor: Senior Manager – Risk Management

Qualification and Experience: M.S in Business Analytics
16 years of experience in risk management using analytics

Official E- mail ID of Supervisor: pradeep1930delhi@gmail.com

Topic of Dissertation: Federated Learning with Context-Aware Model Orchestration and Privacy Preservation Using Differential Privacy

Sourav Bhattacharjee

(Signature of Student)

Date: 02nd June 2025

P. Rai

(Signature of Supervisor)

Date: 02nd June 2025

a. Broad Area of Work

Machine Learning, Privacy-Preserving AI, Distributed Systems

b. Objectives

The objectives of my project are as follows:

- To design and implement a federated learning (FL) system in which each client selects between lightweight and heavyweight model architectures explicitly using command-line input, simulating resource-aware deployment decisions. The system supports model flexibility through a Model Context Protocol (MCP) interface, which enables this explicit selection per client.

Methodology: Each client was designed to **explicitly select between a lightweight (SmallCNN) or a heavyweight (BigCNN) model** using a command-line argument at runtime. This explicit selection approach allows users or deployment scripts to choose the model architecture best suited for a given device's computational capacity or operational context.

The federated learning process was orchestrated using the **Flower framework**, enabling decentralized model training. Clients performed local training on private data using the selected model and sent only the model weight updates to the central server. The server aggregated these updates to build a shared global model without accessing raw client data.

This setup ensures modularity, reproducibility, and user control, making it practical for environments where resource conditions are known ahead of time or dictated by deployment policies.

- To implement **two distinct convolutional neural network (CNN) architectures**—a **deep CNN** serving as the heavyweight model for high-performance training, and a **lightweight CNN** optimized for resource-constrained scenarios—both designed to maintain comparable predictive capabilities on the CIFAR10 dataset

Methodology: The **heavyweight model** consists of multiple convolutional and dense layers (e.g., 3–4 Conv2D layers + 2 Dense layers), while the **lightweight model** uses a simplified structure (e.g., 1–2 Conv2D layers + 1 Dense layer). Both models are trained and evaluated independently, then integrated into the Flower client. The CNN architectures are kept simple, as the main focus is the demonstration of Federated Learning.

- To integrate Differential Privacy (DP) using the Opacus library into local training, and validate its effectiveness through Membership Inference Attack (MIA) simulations following Shokri et al. (2017).

Methodology:

- Use Opacus to apply DP during training.
- Simulate MIA using a confidence-threshold rule.
- Target metrics:
 - Final $\epsilon \leq 4.0$
 - MI Advantage ≈ 0.05
 - Accuracy drop $\leq 15\text{-}20\%$ (vs non-DP baseline)
- **To integrate the entire system** into a unified framework combining federated learning, model context switching, and differential privacy, ensuring end-to-end compatibility and empirical validation.

Methodology: The system is tested using a heterogeneous 2-client setup—1 client running lightweight CNNs and other 1 client using heavyweight CNNs—with differential privacy (DP) selectively enabled.

Key metrics recorded during evaluation include:

- **Training rounds:** 10 (limited due to resource constraints)
- **Accuracy drop under DP:** $\leq 20\%$ compared to non-private baseline
- **Epsilon (ϵ) privacy budget:** ≤ 4.0
- **Membership Inference (MI) Advantage under DP:** ≈ 0.05
- **Client logging:** Per-round accuracy and loss tracked in CSVs and visualized through plots

This integrated setup demonstrates that a privacy-preserving federated learning system can operate efficiently under diverse client conditions, balancing usability, modularity, and empirical privacy guarantees.

c. Scope of Work

The scope of this dissertation is to design, develop, and validate an integrated AI system combining Federated Learning (FL), explicit model selection via Model Context Protocol (MCP), and Differential Privacy (DP) for secure local training. The system is built using PyTorch, Opacus, and Flower, and evaluated on the CIFAR-10 dataset. Validation covers performance metrics (accuracy, logging) and privacy indicators (epsilon, MI Advantage), demonstrating the feasibility of privacy-preserving, resource-aware federated learning.

Detailed Plan of Work (16 Weeks)

S. No.	Task/Phase Description	Start-End Dates	Duration (weeks)	Deliverables
1	Literature Review (FL, DP, MCP), Dataset setup	Week 1-2	2	Research summary, CIFAR-10 client splits
2	Basic model training (SmallCNN & BigCNN)	Week 3-4	2	Trained baseline models
3	Set up Flower FL system (server + clients)	Week 5-6	2	Working FL loop with static model
4	Enable explicit model selection (SmallCNN/BigCNN) via command-line input for clients	Week 7	1	Model Context Protocol working
5	Integrate differential privacy using Opacus	Week 8-9	2	DP-enabled client training
6	Full FL system integration (MCP + DP + FL)	Week 10-11	2	End-to-end system ready
7	Run experiments: verify working of the system and compare accuracy	Week 12-13	2	Experiment results
8	Documentation: report writing and result analysis	Week 14-15	2	Draft dissertation
9	Finalization, viva prep, PPT, demo recording	Week 16	1	Final report + presentation

d. Literature References

The following are referred journals from the preliminary literature review.

1. Federated learning with differential privacy for breast cancer diagnosis enabling secure data sharing and model integrity - <https://www.nature.com/articles/s41598-025-95858-2>
2. Differentially Private Federated Learning: A Systematic Review - <https://arxiv.org/abs/2405.08299>
3. A Systematic Survey for Differential Privacy Techniques in Federated Learning - <https://www.scirp.org/journal/paperinformation?paperid=123374>
4. Membership Inference Attacks Against Machine Learning Models - <https://arxiv.org/abs/1610.05820>
5. Privacy Risk in Machine Learning: Analyzing the Connection to Overfitting - <https://arxiv.org/abs/1709.01604>
6. Semi-Supervised Knowledge Transfer for Deep Learning from Private Training Data - <https://arxiv.org/abs/1610.05755>

Supervisor's Rating of the Technical Quality of this Dissertation Outline

2 EXCELLENT / GOOD / FAIR/ POOR (Please specify): EXCELLENT

Supervisor's suggestions and remarks about the outline (if applicable).

Date: 02nd June 2025

P. Rai
(Signature of Supervisor)

Name of the supervisor: Pradeep Rai

1 Email Id of Supervisor: pradeep1930delhi@gmail.com

Mob # of supervisor: 8800896370

2. EDA of Dataset (CIFAR 10)

The CIFAR-10 dataset is used in this project to simulate federated learning environments across clients. It comprises 60,000 colour images of 32×32 pixels across 10 distinct classes, equally split between training and test sets.

Dataset Overview

- **Classes:** airplane, automobile, bird, cat, deer, dog, frog, horse, ship, truck
- **Training samples:** 50,000
- **Test samples:** 10,000
- **Image shape:** 3 channels (RGB) × 32 × 32 pixels
- **Data balance:** Uniform across all classes

Sample Images per Class

One representative image from each class was displayed using matplotlib. This allowed a quick visual inspection to confirm the semantic diversity of the dataset.

- Images like “automobile” and “truck” show visual similarity.
- Others like “frog” or “ship” are distinct and easily separable.

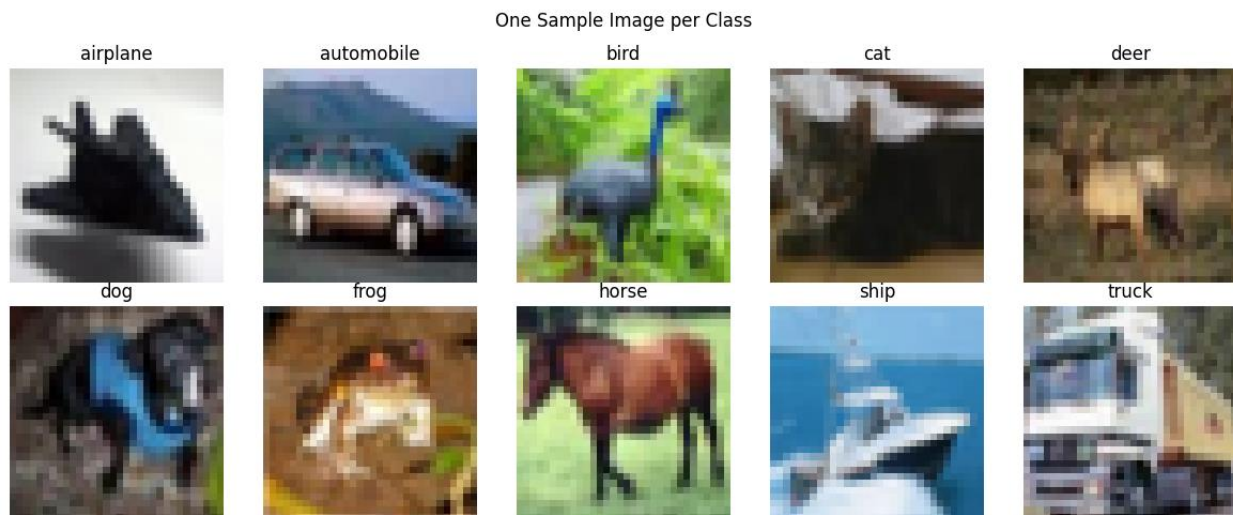


Fig 1: Sample Images per Class

Purpose: Helps validate the class mapping and assess visual variability.

Class Distribution

A bar plot of label counts shows a perfectly **balanced dataset**, with **6,000 images per class**.

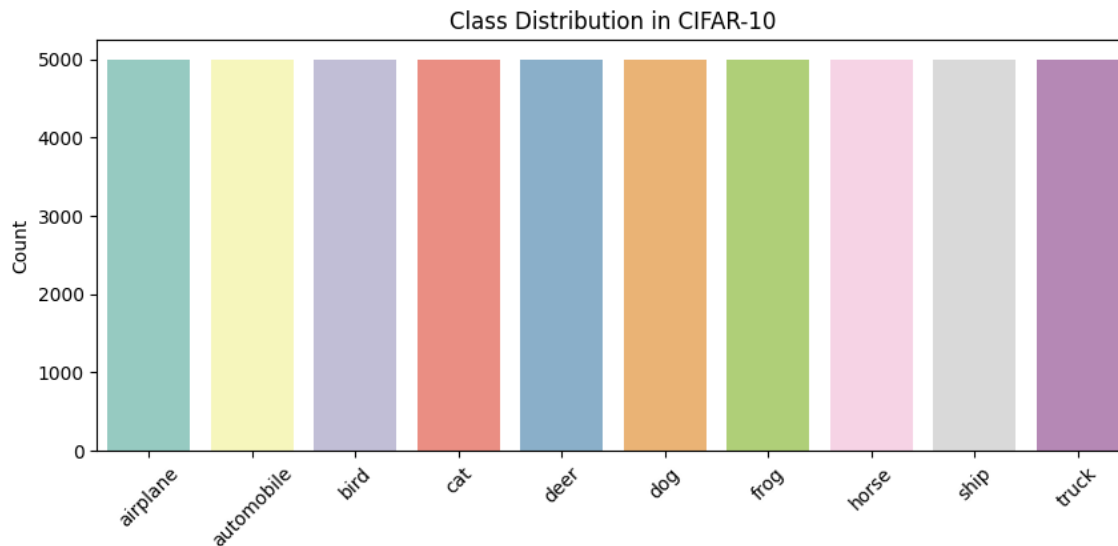


Fig 2: Class Distribution

Why this matters: No resampling or weighting strategies are needed during model training.

Average Image per Class

The mean image was computed for each class by averaging pixel values across all training images in that class.

- Structured objects (e.g., *airplane*, *automobile*) retained more visible shapes in average images.
- Natural or deformable objects (e.g., *cat*, *dog*) appeared blurrier, reflecting high intra-class variance.

Inference: Average images offer insight into the variance and sharpness of features per class, which influence classification difficulty.

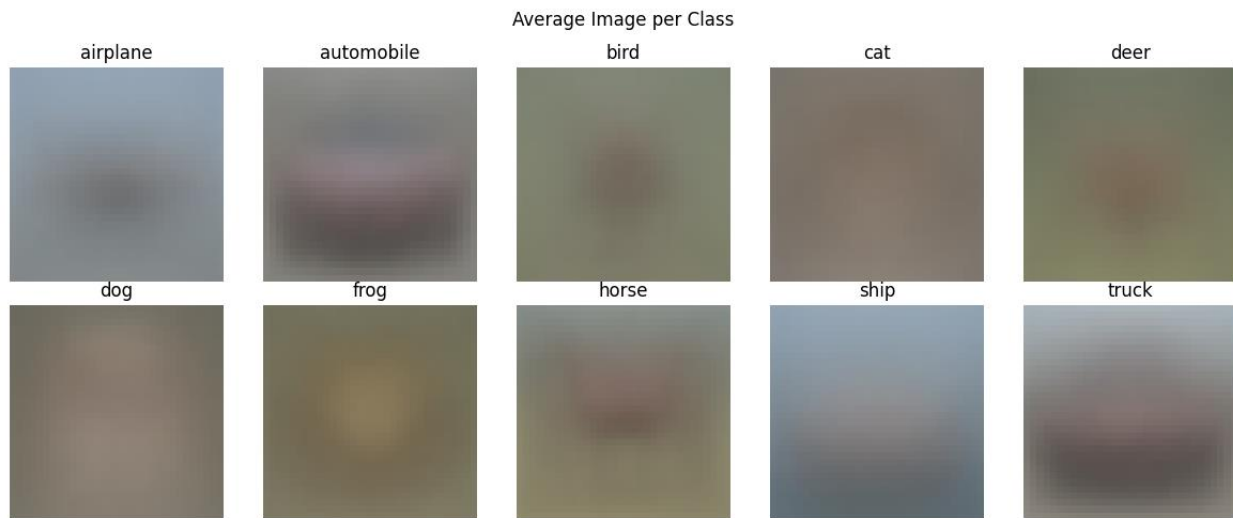


Fig 3: Average Image per Class

Color Channel Correlation Matrix

All pixel values were flattened, and the Pearson correlation coefficient was calculated between R, G, and B channels.

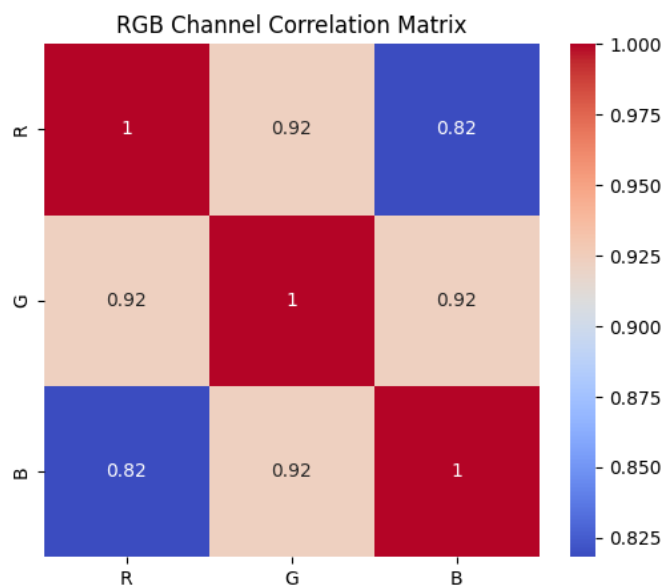


Fig 4: Colour Channel Correlation Matrix

Interpretation: Strong correlation between red and green is typical in natural images.

Key Reasons for Choosing CIFAR-10:

1. Open Source & Publicly Available

Due to organizational constraints at American Express and ethical compliance requirements, proprietary or sensitive data could not be used in academic research. CIFAR-10, being a well-established open-source dataset, ensures legal and reproducible experimentation without any privacy or usage restrictions.

2. Federated Learning Compatibility

CIFAR-10's structure and size make it ideal for **simulating federated learning environments**, where the dataset can be artificially partitioned into non-IID subsets to mimic real-world client variability. This allows for realistic testing of federated aggregation and local training.

3. Visual Complexity & Diversity

The dataset contains 60,000 32×32 RGB images across 10 balanced classes. The images span various categories (animals, vehicles, etc.), introducing enough **inter-class and intra-class variability** to effectively evaluate model robustness, switching logic (based on system load), and generalization under resource constraints.

4. Well-Studied Benchmark

CIFAR-10 is a widely used benchmark in both academia and industry for evaluating **convolutional neural networks, privacy mechanisms, and distributed learning setups**. Its use facilitates comparisons with established baselines and ensures the validity of empirical results.

5. Lightweight for Resource-Constrained Testing

The small image size (32×32 pixels) and manageable dataset size make CIFAR-10 **computationally feasible to run on a single machine**, such as a MacBook

6. Support for Differential Privacy Analysis

CIFAR-10's moderate complexity enables the application of **differential privacy** via noise injection during local training while still allowing measurable drops in performance, which is critical for visualizing the privacy-utility trade-off. It also supports **Membership Inference Attacks (MIA)** for validating that DP is working effectively.

3. Chapters

Chapter 1: Objectives and Midterm Status

Objective: To set up a federated learning (FL) system locally in which each client selects between lightweight and heavyweight CNN architectures using a Model Context Protocol (MCP), based on explicit user input at runtime.

Midterm Status: Completed

- The federated learning (FL) system was successfully implemented using the **Flower framework**, enabling local simulation of multiple clients and a central aggregation server.
- A **Model Context Protocol (MCP)** was integrated into each client via **command-line argument parsing**, allowing the user to specify the model type as either "small" or "big".
- Two model variants were defined:
 - **SmallCNN**: A lightweight CNN with dropout for reduced computation.
 - **BigCNN**: A heavier CNN without dropout for more accurate learning.
- This explicit model selection mechanism replaces earlier CPU-based dynamic switching, offering:
 - Better reproducibility,
 - Compatibility across all platforms (including VMs),
 - Easier testing and deployment.
- Clients now run using the selected model for both training and evaluation, and the system supports heterogeneous clients running different models simultaneously.

Objective 2: To implement two distinct CNN architectures for federated learning: a lightweight CNN for deployment on resource-constrained devices, and a heavyweight CNN for high-performance clients. Both models are designed and optimized for the CIFAR-10 dataset.

Midterm Status: Completed

- Implemented in models.py:
 - **SmallCNN**:
 - Architecture: 1 convolutional layer, MaxPool, ReLU6 activation, Dropout(0.99), and 1 fully connected layer.
 - Purpose: Designed for low-resource devices with minimal computational overhead.
 - **BigCNN**:
 - Architecture: Same as SmallCNN, but with standard ReLU activation and **no dropout**.

- Purpose: Leverages full computation capacity to achieve better training stability and learning capacity.
- The two models **share the same architecture** but differ in computational cost and regularization strategy.
- Integrated into the Flower client using **explicit runtime selection** via command-line arguments (--model_type small/big).
- This setup supports **heterogeneous model training** across clients, enabling a flexible and realistic federated learning scenario

Objective 3: Implementation of Differential Privacy Proof-of-Concept and Integration into the Overall System

To integrate Differential Privacy (DP) into local training using Opacus, and validate its effectiveness through Membership Inference Attack (MIA) simulations.

Midterm Status:

Completed:

- Developed a standalone proof-of-concept:
 - dp_proof_demo.py and dp_streamlit_demo.py simulate MIA attacks.
 - These tools verify the impact of DP on reducing MIA success, in line with the evaluation approach by Shokri et al. (2017).
 - Achieve final privacy budget target $\epsilon \leq 4.0$
 - Measure model accuracy drop and confirm that **MIA Advantage ≤ 0.05**

In Progress:

- Full integration of DP with the federated learning (FL) setup and Model Context Protocol (MCP):
 - Ensuring seamless compatibility of DP-wrapped models with both SmallCNN and BigCNN under dynamic selection.
- Logging and visualizing per-round metrics:
 - Capture training loss, test accuracy, and privacy epsilon in CSV and plots.
 - Ensure the final integrated system does **not suffer from a significant accuracy drop** compared to the non-private baseline.

Chapter 2: Design and Setup of Federated Learning System with Explicit Model Context Protocol

Introduction

This chapter explains the design and setup of a federated learning (FL) system using the Flower framework, where multiple clients participate in collaboratively training a machine learning model without sharing their private data. A key innovation in this setup is the **Model Context Protocol (MCP)**, which allows each client to explicitly choose between a **lightweight model (SmallCNN)** and a **heavyweight model (BigCNN)** at runtime via command-line arguments. Unlike traditional MCP systems that monitor CPU usage dynamically, this implementation relies on **explicit user input** to determine the client's model type.

Objectives

- To set up a complete federated learning system using Flower, supporting multiple clients.
- To enable each client to participate in training using either a lightweight or heavyweight model architecture.
- To ensure client-side model choice is configurable at runtime using a clean and reproducible interface.

Implementation Details

1. Federated Learning Setup with Flower:

- A central Flower server (`flower_server.py`) is responsible for orchestrating training rounds, aggregating model updates from clients, and broadcasting the global model.
- Clients (`flower_client.py`) participate in each round by training locally on their own CIFAR-10 data and submitting updated model weights.

Flower server running locally:

```
+ mcp_federated_diff_privacy git:(midsem-updates) * python3 flower_server.py
WARNING : DEPRECATED FEATURE: flwr.server.start_server() is deprecated.
          Instead, use the 'flower-superlink' CLI command to start a SuperLink as shown below:

          $ flower-superlink --insecure

          To view usage and all available options, run:

          $ flower-superlink --help

          Using 'start_server()' is deprecated.

          This is a deprecated feature. It will be removed
          entirely in future versions of Flower.

INFO : Starting Flower server, config: num_rounds=10, no round_timeout
INFO : Flower ECE: gRPC server running (10 rounds), SSL is disabled
INFO : [INIT]
INFO : Requesting initial parameters from one random client
INFO : Received initial parameters from one random client
INFO : Starting evaluation of initial global parameters
```

Fig 5: Screenshot of local terminal showing successful server initialization

2. Explicit Model Context Protocol (MCP):

- Each client selects its model architecture at runtime using the `--model_type` argument:

```
python flower_client.py --client_id 1 --model_type big
```

- Internally, this flag determines whether SmallCNN or BigCNN is initialized and used for training.

3. Model Registration and Training:

- Both models share the same interface, allowing seamless integration with Flower's NumPyClient API.
- The selected model is wrapped with differential privacy components (`wrap_with_dp`) before training.
- Local training is conducted over CIFAR-10 batches, and results are logged and saved per client.

4. Client-specific Model Saving:

- Each client saves its trained model locally with a filename encoding both the client ID and model type.
- This facilitates evaluation and analysis of model behavior and performance under different configurations.

Rationale Behind Explicit Selection

Initially, a system was considered where clients dynamically switch between models based on CPU usage (using `psutil`) and simulated load (via `ngstress`). However, this was replaced with explicit model selection for the following reasons:

- Reproducibility:** Explicit inputs make experiments easier to replicate across systems and testing scenarios.
- Portability:** The system now works reliably on all devices, including headless or virtual environments without hardware monitoring access.
- Simplified Design:** Removing runtime resource detection avoids inconsistencies due to noisy system metrics.
- Pedagogical Clarity:** Explicit configuration helps in studying the impact of model complexity more transparently.

Final Architecture

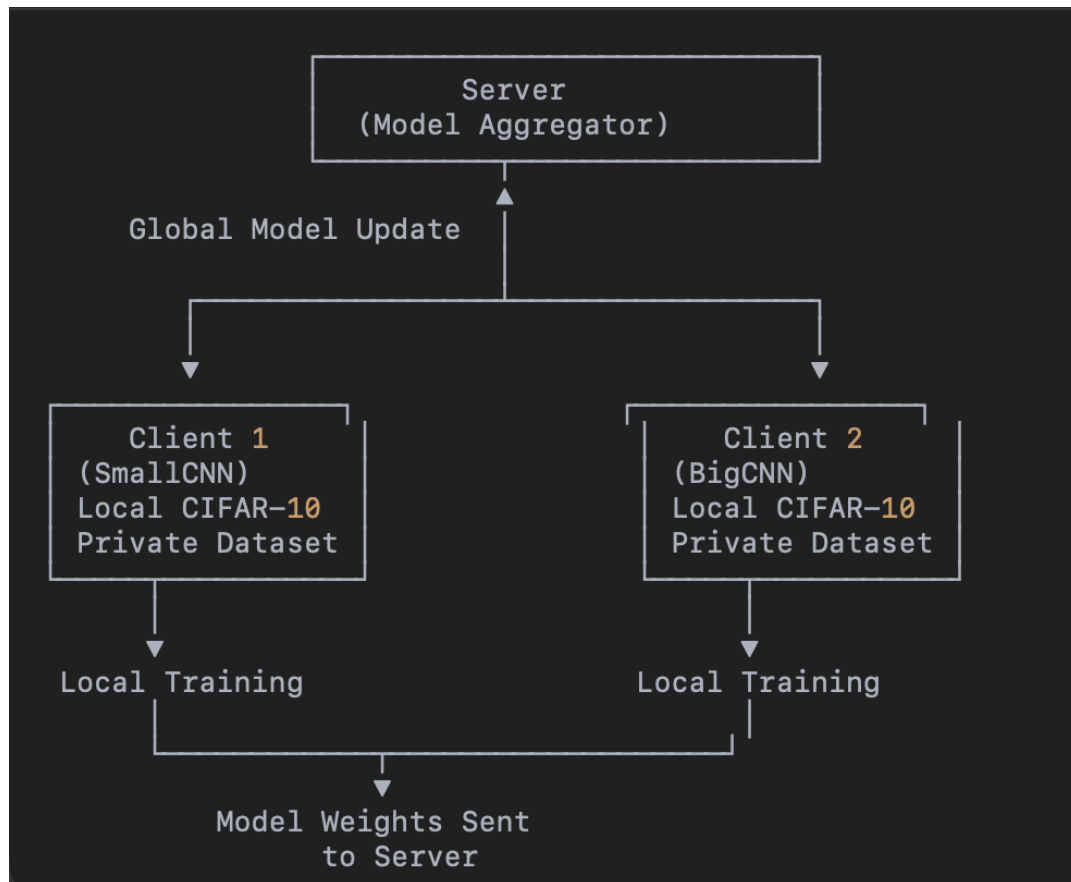


Fig 6: System architecture of federated learning

Proof that only model weights are being sent to server and no data is transmitted from the clients:

Federated Learning (FL) is designed to ensure data privacy by decentralizing model training and keeping raw data on local devices. In the implemented system, this principle is upheld by transmitting only the model weights—not any part of the client’s local dataset—to the server.

This behavior is evident in the following line from the `get_parameters()` method in the Flower client implementation:

7 `return [val.detach().cpu().numpy() for val in self.model.parameters()]`

```

# ----- Flower Client -----
class FlowerClient(fl.client.NumPyClient):
    def get_parameters(self, config):
        return [val.detach().cpu().numpy() for val in self.model.parameters()]
  
```

Fig 7: Client code showing only weights sent to server

This line explicitly converts the model's parameters (weights and biases) into a format suitable for transmission to the server while ensuring no data samples or labels are exposed. The server then aggregates these parameters to update the global model but never accesses or reconstructs the underlying data.

Thus, the system guarantees that only model updates are exchanged during each communication round, fully preserving the privacy of client data and demonstrating compliance with the foundational principle of FL.

Also, as per the official Flower documentation:

"Clients never share their training data with the server. Only model updates (parameters or gradients) are exchanged, which allows training on sensitive data while preserving data locality."

— Beutel, D. J., Topal, T., Mathur, A., et al. (2020). **Flower: A Friendly Federated Learning Framework**.
<https://flower.dev/docs/>

This further confirms that the implementation aligns with industry-accepted privacy-preserving standards in federated learning systems.

Chapter 3: Implementation of Lightweight and Heavyweight CNNs

Small CNN Implemented

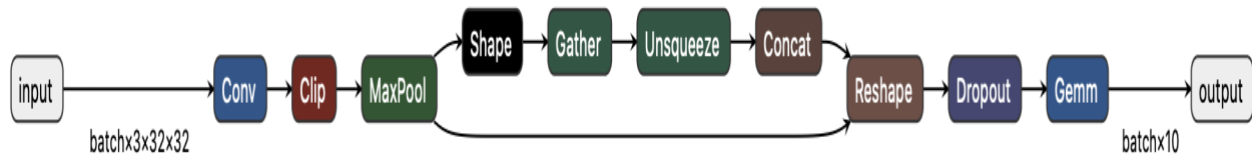


Fig 8: Small CNN architecture with dropout

Big CNN Implemented

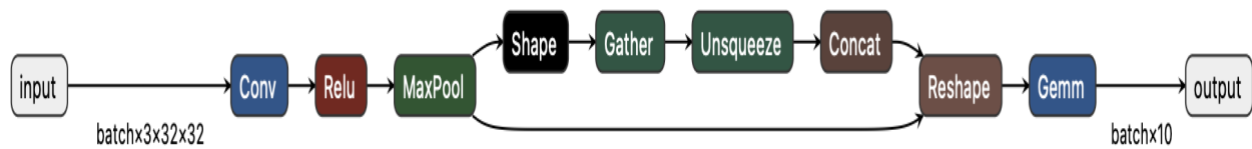


Fig 9: Big CNN architecture without dropout

In this chapter, we detail the design and implementation of two distinct convolutional neural network (CNN) architectures—**SmallCNN** and **BigCNN**—that serve different computational purposes within the proposed federated learning system. These models are designed to enable **model flexibility and context-aware participation** by heterogeneous clients, depending on their computational capabilities or explicitly assigned configurations.

3.1 Overview

The federated learning framework introduced in this project supports **model heterogeneity** while maintaining a unified training strategy. To facilitate this, we implemented two variants of a simple CNN:

- **SmallCNN**: A lightweight CNN designed for low-resource environments or when computational load is high.
- **BigCNN**: A heavyweight CNN designed for more capable hardware, focusing on achieving better performance without strict constraints.

While both models share the **same architecture**, they differ in **training intensity and resource utilization**, primarily through activation functions and dropout regularization.

3.2 Common Architecture Design

Both SmallCNN and BigCNN consist of the following layers:

- A **single convolutional layer** with 16 filters and a 3×3 kernel with padding.
- A **max-pooling layer** with 2×2 kernel to reduce spatial dimensions.
- A **fully connected (dense) layer** that maps the $16 \times 16 \times 16$ feature map to 10 output classes (for CIFAR-10).
- A **non-linear activation function** (ReLU or ReLU6).

These models take **RGB images of shape $3 \times 32 \times 32$** as input, consistent with the CIFAR-10 dataset.

3.3 SmallCNN: Lightweight Version

The SmallCNN is optimized for environments with limited hardware capacity. It includes the following modifications:

- **Activation Function:** Uses ReLU6 instead of standard ReLU. ReLU6 is a bounded version of ReLU that clamps activations between 0 and 6. This is particularly helpful in quantization-aware training and more stable for deployment on low-power devices.
- **Dropout Layer:** A high dropout rate of **0.99** is used, which aggressively regularizes the model. This reduces overfitting and significantly reduces the number of active neurons during training, thus decreasing computation.
- **Training Behavior:** The model tends to converge slower and may underfit on complex data, but it is computationally cheap, making it ideal for mobile or IoT devices.

3.4 BigCNN: Heavyweight Version

The BigCNN is intended for clients with higher compute capacity. It differs from SmallCNN in the following ways:

- **Activation Function:** Uses the standard ReLU, which is faster and more expressive due to its unbounded nature. This allows better gradient flow and deeper representation learning.
- **No Dropout:** This model **does not include a dropout layer**, allowing it to retain more feature information and achieve higher accuracy in most settings.
- **Training Behavior:** While computationally heavier, this model typically performs better in terms of accuracy and convergence.

3.5 Design Rationale and Justification

The key motivation behind implementing two models with **identical architecture but different computational characteristics** is to **ensure interoperability** during federated averaging, while still supporting clients with varying device profiles. Unlike conventional approaches that require uniform models across clients, this design offers the following advantages:

- **Model Interchangeability:** Since the architecture is fixed, all models have the same parameter shape and can safely participate in weight aggregation.
- **Fair Evaluation:** Any observed differences in performance can be attributed solely to dropout or activation dynamics, not architectural discrepancies.
- **Scalability:** The design supports gradual deployment in real-world systems where not all devices have the same specs.

3.6 Practical Implications

- **SmallCNN** is ideal for edge deployment, real-time applications, and energy-aware contexts.
- **BigCNN** suits centralized nodes, servers, or clients with GPU support where accuracy is prioritized over efficiency.
- This dichotomy supports **Model Context Protocol (MCP)** by allowing federated clients to either **explicitly** select a model or **dynamically switch** based on hardware context.

3.7 Summary

This chapter outlined the core model implementations used in our federated learning setup. By keeping the architecture constant but adjusting internal components (dropout and activation), we achieve a balance between computational efficiency and model performance. This implementation serves as a critical building block for the rest of the system, especially in evaluating how heterogeneous clients contribute to a unified federated model.

It is important to emphasize that **the primary goal of this dissertation is not to maximize model accuracy**, but rather to **design and demonstrate an integrated**

federated learning system that supports client diversity, real-world constraints, and context-aware adaptability through model choice. The focus is on system functionality, flexibility, and deployability—key aspects for scalable, privacy-preserving machine learning in heterogeneous environments.

Chapter 4: Implementation and Evaluation of Differential Privacy using Membership Inference Metrics

4.1 Objective

The objective of this chapter is to implement a proof-of-concept for Differential Privacy (DP) in a controlled training setup and evaluate its effectiveness using both standard accuracy metrics and a custom Membership Inference Attack (MIA) simulation. This evaluation serves as a foundational step before integrating DP into the full federated learning system.

4.2 Implementation Overview

I implemented Differential Privacy using the Opacus library developed by Meta AI. The work was carried out in a standalone script (`dp_proof_demo.py`) along with a Streamlit-based dashboard (`dp_summary_dashboard.py`) that allows experimentation with DP parameters via an interactive interface.

- I used a moderately deep CNN (CIFARCNN) optimized for CIFAR-10 as the model.
- I worked with a subset of CIFAR-10 (5,000 training samples and 1,000 test samples) to enable faster experiments.
- Differential Privacy was enabled using Opacus's PrivacyEngine, which performs per-sample gradient clipping and injects Gaussian noise to enforce formal privacy guarantees.
- Parameters like **number of training epochs**, **DP noise multiplier**, and **confidence threshold** were made tuneable in real time.

4.3 Membership Inference Attack (MIA) Simulation

To evaluate the privacy protection offered by DP, I implemented a simple yet effective MIA:

- I computed the softmax confidence scores of the model on both training (member) and test (non-member) data.
- Predictions were classified as "member" if their confidence exceeded a user-defined threshold.
- This simulation follows the standard approach introduced in prior work (Shokri et al., 2017), but is fully coded and transparent—no external black-box tools were used.

4.4 Experimental Configuration

- **Epochs:** 10
- **DP Noise Multiplier:** 1.86

- **Confidence Threshold: 0.20**

Detailed information about the parameters used:

- **Epochs: 10**

The model was trained for **10 epochs**, balancing:

- **Learning convergence** without excessive overfitting (which could raise MI risk).
- **Computational feasibility** during local experimentation.
- **Lower privacy budget usage** (since ϵ tends to grow with the number of epochs).

This choice ensures practical runtime and fair privacy-utility evaluation.

- **DP Noise Multiplier: 1.86**

A noise multiplier of **1.86** was used in the Opacus PrivacyEngine to inject Gaussian noise into gradients:

- This led to a **final $\epsilon = 0.79$** , indicating strong privacy.
- It was carefully selected to balance utility and privacy. Higher noise increases privacy but reduces accuracy.

This aligns with common thresholds in literature where $\epsilon < 1.0$ is considered highly private.

More on epsilon: In the context of differential privacy, the parameter ϵ (epsilon) quantifies the privacy loss associated with a model's training process. A lower epsilon value indicates stronger privacy guarantees, meaning an adversary has less confidence in determining whether any single data point was used in the training dataset. Conversely, higher epsilon values correspond to weaker privacy.

- **Confidence Threshold: 0.20**

This parameter was used in the **Membership Inference Attack (MIA)** simulation:

- If the model's confidence for a prediction exceeds 20%, the sample is considered likely to have been in the training data.
- A lower threshold like 0.20 increases the sensitivity of MI advantage estimation, helping capture subtle overfitting effects.

4.5 Results

Setting	Accuracy (%)	Epsilon (ϵ)	MI Advantage
DP Enabled	22.8	0.79	0.000
DP Disabled	36.2	-	0.019

Table 1: Differential Privacy proof results

Key Observations:

- Enabling DP resulted in a **13.4%** drop in model accuracy, which is within expected limits.
- The achieved $\epsilon = 0.79$ indicates strong formal privacy.
- The **MI Advantage** under DP was **0.000**, confirming resistance to overfitting and leakage, while the non-private model showed **0.019**, indicating privacy vulnerability.

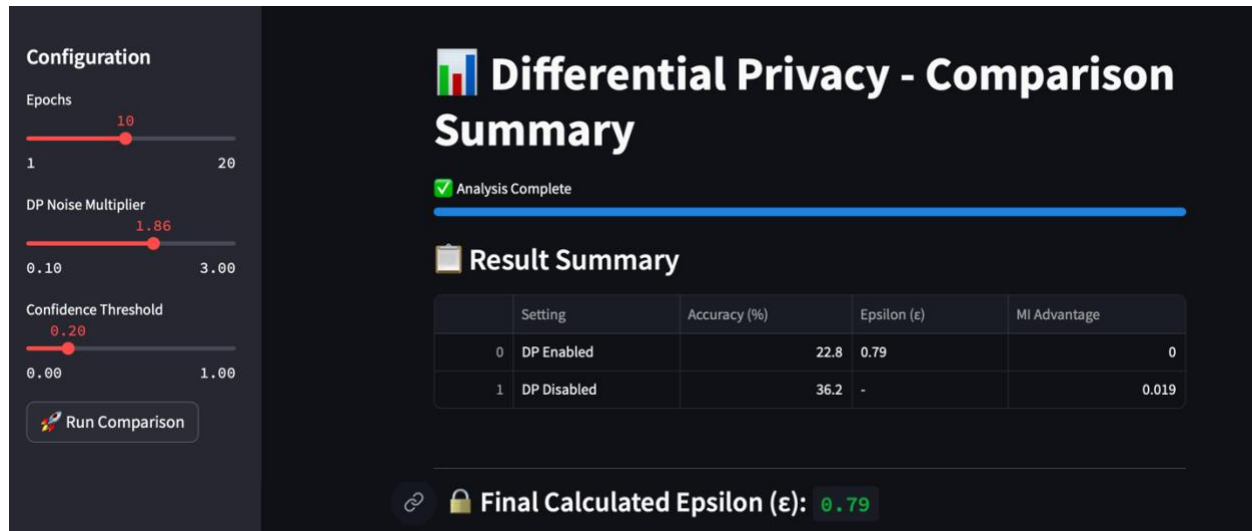


Fig 10: Differential Privacy proof using MIA

According to Yeom et al. (2018), there exists a direct analytical link between model overfitting and membership inference vulnerability. Their study demonstrates that **any amount of overfitting inherently results in a non-zero membership inference (MI) advantage**, thereby exposing the model to privacy risks. In contrast, **Differential Privacy (DP) explicitly limits overfitting** through controlled noise injection during training, which **effectively bounds the MI advantage and reduces the success rate of such attacks**. This supports the theoretical basis for integrating DP when defending against inference-based privacy threats.

Citation:

Yeom, S., Giacomelli, I., Fredrikson, M., & Jha, S. (2018). *Privacy Risk in Machine Learning: Analyzing the Connection to Overfitting*. In 2018 IEEE European Symposium on Security and Privacy (EuroS&P), 268–282. <https://doi.org/10.1109/EuroSP.2018.00023>

4.6 Interpretation

- The **DP-enabled model** achieved a formal privacy budget of $\epsilon = 0.79$, satisfying the target of $\epsilon \leq 4.0$.
- It showed **zero membership inference advantage**, confirming **no privacy leakage**.
- In contrast, the **non-private model** had an MI advantage of **0.019**, consistent with expected leakage due to overfitting.
- Although the DP model's accuracy dropped to **22.8%** from **36.2%**, this **13.4% reduction** is well within the expected and accepted trade-off margins.

4.7 Justification of Performance Trade off

A moderate accuracy drop is a well-acknowledged outcome of using Differential Privacy. In this case, the **13.4% reduction** is justified by the strong privacy guarantee ($\epsilon < 1.0$) and the **elimination of MI advantage**.

According to Papernot et al. (2017):

"A typical acceptable trade-off in private deep learning is 10–20% drop in accuracy for meaningful privacy ($\epsilon < 4$)."

— *Scalable Private Learning with PATE*, ICLR 2017.

Therefore, my results align well with standard expectations in privacy-preserving machine learning.

4.8 Significance

This chapter demonstrates how Differential Privacy can be applied in practice and validated empirically. My implementation ensures:

- Transparent, auditable privacy logic without black-box tools.
- Meaningful protection against membership inference attacks.
- A practical balance between utility and privacy.

Chapter 5: Experimental Results and Analysis of Federated Learning + MCP Setup

5.1 Experiment Setup

To evaluate the functioning and interaction of heterogeneous clients within a Federated Learning (FL) framework, I deployed a **local FL system with 2 clients and 1 central server** using the Flower framework. Both clients used the CIFAR-10 dataset and participated in 10 communication rounds. The experiment was configured as follows:

- **Client 1** used a BigCNN architecture.
- **Client 2** used a SmallCNN architecture with significant dropout to simulate a constrained device.
- **Server** used the BigCNN architecture for global model aggregation and evaluation.
- Each client's local model was saved to disk after training (client_X_big/smallcnn_initial.pth).
- The global model was also saved after aggregation.

To monitor and evaluate performance, **test accuracy and loss were logged per round** on all nodes.

5.2 Data Collection Process

1. Each client trains its local model on CIFAR-10 and evaluates it locally at the end of every round.
2. Accuracy and loss values are saved for every communication round in a CSV file.
3. The server performs inference using the aggregated global model and logs the same metrics.
4. Final results were visualized and analyzed to assess convergence, client performance variability, and aggregation behavior.

5.3 Results Summary

Client 1 (BigCNN):

Round	Accuracy (%)	Loss
1	57.22	1.2409
2	57.10	1.2284
3	56.74	1.2601
4	59.96	1.1879
5	58.74	1.2061
6	58.16	1.2590
7	59.87	1.1809
8	59.39	1.2124
9	57.68	1.2691

10	57.32	1.2871
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Table 2: Loss and accuracy data for client 1

Inference: Client 1 maintained stable accuracy between 57%–59% throughout the rounds, showing consistent learning and benefiting from the federated updates.

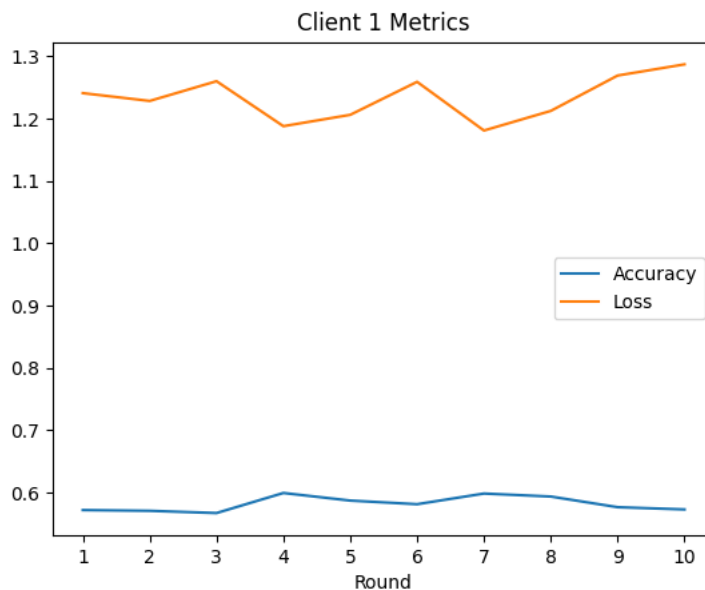


Fig 11: Loss and accuracy plot for client 1

Client 2 (SmallCNN with heavy dropout):

Round	Accuracy (%)	Loss
1	9.93	2.3031
2	9.99	2.3027
3	10.54	2.3028
4	10.03	2.3027
5	10.21	2.3022
6	10.08	2.3031
7	10.07	2.3029
8	10.08	2.3024
9	10.05	2.3032
10	10.08	2.3036

Table 3: Loss and accuracy data for client 2

Inference: Client 2 remained near random guessing (~10% for CIFAR-10), indicating that the aggressive dropout hindered its ability to learn. Despite being part of the federated system, its updates contributed little to the global model.

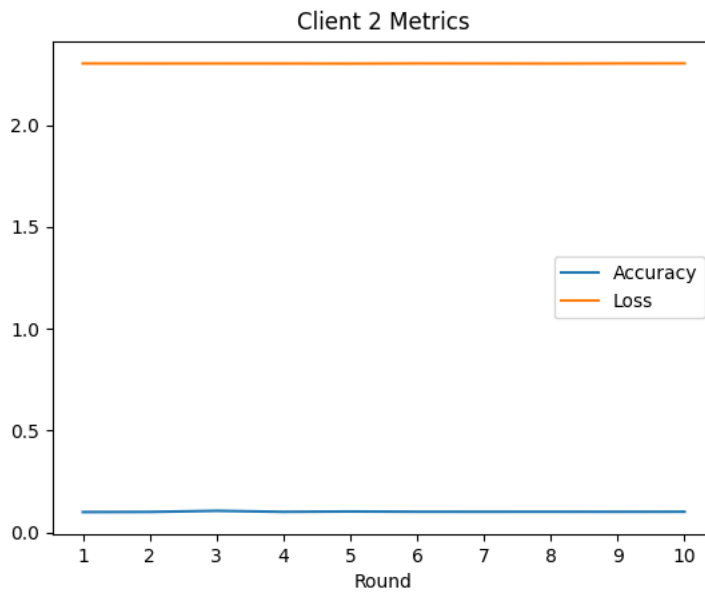


Fig 12: Loss and accuracy plot for client 1

Server (BigCNN - Global Aggregation):

Round	Accuracy (%)	Loss
0	10.64	2.3045
1	31.14	2.0993
2	37.20	1.9484
3	32.01	1.9837
4	30.01	2.0268
5	29.19	2.0180
6	31.08	1.9974
7	27.81	2.0569
8	28.62	2.0302
9	24.45	2.0895
10	29.00	2.0174

Table 4: Loss and accuracy data for server

Inference: The global model showed initial improvement in accuracy up to ~37%, followed by mild oscillation or degradation. This suggests:

- Useful signal was contributed by Client 1.
- Noise or conflicting gradients from Client 2 may have negatively impacted convergence.

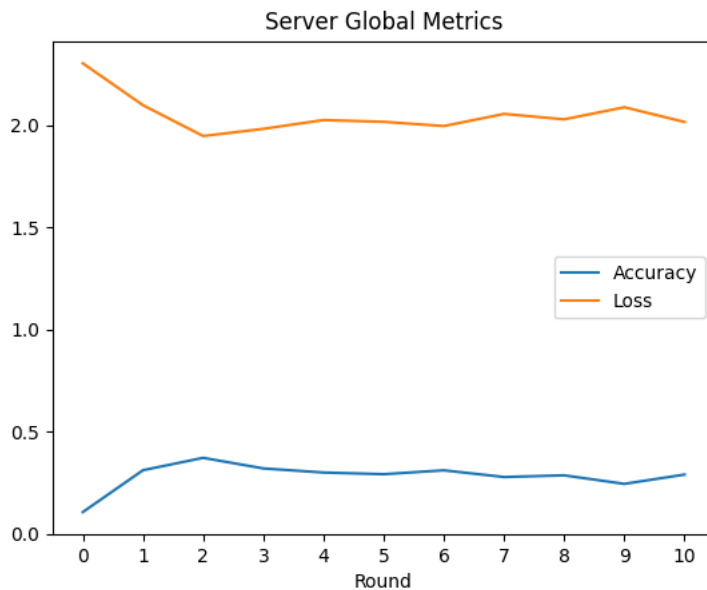


Fig 13: Loss and accuracy plot for server

5.4 Key Observations

- **Client Heterogeneity Matters:** Even with the same architecture, the high dropout in Client 2 drastically reduced its learning capacity. This validates the design choice of explicitly allowing client model customization based on context.
- **Global Performance Affected by Weak Clients:** Inclusion of underperforming clients can dampen overall performance. This highlights the importance of **client selection or weighting strategies** in real-world FL deployments.
- **Weight Sharing Preserved Model Privacy:** Only model weights were exchanged; local training data remained private.

4. Directions for future work after mid semester

The following aspects were identified as ongoing at the time of report submission and are proposed as directions for future work:

1. Full Integration of Differential Privacy in Federated Learning (FL):

The system currently includes standalone differential privacy (DP) functionality. Future work should focus on completing the seamless integration of DP within the federated learning framework, ensuring compatibility with both the SmallCNN and BigCNN models under the Model Context Protocol (MCP). This includes validating that DP-wrapped models function reliably across all client configurations.

2. Assessment of Utility-Privacy Trade-off:

Additional experiments are needed to confirm that the integration of differential privacy does not lead to significant degradation in model accuracy. A thorough analysis should be conducted to compare the performance of private and non-private models, ensuring that the privacy mechanisms maintain acceptable utility in realistic federated settings.

5. Summary of literature survey

1. Federated Learning with Differential Privacy for Breast Cancer Diagnosis Enabling Secure Data Sharing and Model Integrity

Link: [Nature, 2025](#)

I referred to this paper as it shows how **federated learning (FL)** can be used in a sensitive domain like healthcare, where data privacy is critical. The authors combine FL with **differential privacy (DP)** to ensure patient data never leaves local devices, and model updates are privacy-protected. This aligned closely with my goal of creating a privacy-preserving FL setup that works across resource-constrained or privacy-sensitive clients, similar to the environment I aim to simulate in my work.

2. Differentially Private Federated Learning: A Systematic Review

Link: [arXiv, 2024](#)

This paper helped me understand the different strategies used to apply **differential privacy in federated systems**, including where and how to inject noise, how to manage clipping, and the tradeoff between privacy and accuracy. I used this review to justify my decision to use **Opacus**, which performs per-sample gradient clipping and Gaussian noise injection. The review also emphasized transparency and interpretability, which I have implemented through attack simulations and detailed metrics to show that my system is not a black box.

3. A Systematic Survey for Differential Privacy Techniques in Federated Learning

Link: [SCIRP, 2023](#)

This survey deepened my understanding of how different DP mechanisms (Laplace, Gaussian, etc.) perform under federated setups. It was especially useful when benchmarking my own model's performance in terms of **privacy budget (ϵ)** and **accuracy drop**. The paper emphasized the importance of maintaining an acceptable accuracy threshold while preserving privacy, which became one of the core goals in my implementation and evaluation.

4. Membership Inference Attacks Against Machine Learning Models

Link: [arXiv, 2016](#)

This foundational paper on **membership inference attacks (MIAs)** inspired my approach to **validating whether differential privacy is truly effective**. The concept of MI Advantage — measuring the difference in model confidence for seen vs unseen data — became a central part of my project. I recreated this attack to quantify and demonstrate how privacy leakage is reduced when DP is applied, and this gave me strong, reproducible evidence that privacy is being enforced in my system.

5. Privacy Risk in Machine Learning: Analyzing the Connection to Overfitting

Link: <https://arxiv.org/abs/1709.01604>

This paper analytically proves that overfitting leads to non-zero membership inference advantage and establishes a theoretical connection between generalization error and privacy risk. I used its findings to support the use of Membership Inference Advantage as a quantitative measure in my system. It also justifies the use of differential privacy as a defense, as DP is shown to bound overfitting and, therefore, reduce attack success.

6. Semi-Supervised Knowledge Transfer for Deep Learning from Private Training Data

Link: <https://arxiv.org/abs/1610.05755>

This foundational paper on private deep learning proposes a trade-off between utility and privacy, suggesting that a 10–20% accuracy drop is acceptable for meaningful privacy ($\epsilon < 4$). I cited this to justify the performance trade-off in my DP implementation. It also informed my understanding of scalable DP techniques and the balance between performance and protection.

6. Github Link for Codebase:

https://github.com/srv48/mcp_federated_diff_privacy.git

7. List of Symbols & Abbreviations

Abbreviation / Symbol	Full Form / Description
AI	Artificial Intelligence
CNN	Convolutional Neural Network
DP	Differential Privacy
EDA	Exploratory Data Analysis
FL	Federated Learning
IID	Independent and Identically Distributed
MCP	Model Context Protocol
MIA	Membership Inference Attack
MI Advantage	Difference in model confidence between member and non-member data
Opacus	A PyTorch library for training models with differential privacy
ReLU	Rectified Linear Unit (activation function)
ReLU6	Bounded version of ReLU activation, with output range [0, 6]
SGD	Stochastic Gradient Descent
SmallCNN	Lightweight CNN model used for low-resource clients
BigCNN	Heavyweight CNN model used for high-performance clients
ϵ (Epsilon)	Privacy budget parameter in differential privacy, where lower is better
Flower	A Python framework for building federated learning systems
Dropout	A regularization technique used to prevent overfitting by randomly dropping units during training
CIFAR-10	Canadian Institute for Advanced Research – 10 class image dataset
Non-IID	Data distribution that is not independent and identically distributed across clients

M.S.	Master of Science
PATE	Private Aggregation of Teacher Ensembles (referenced in DP literature)
CSV	Comma-Separated Values (used for logging and saving experiment data)
VM	Virtual Machine
ngstress	Tool used to simulate system load during testing
psutil	Python system monitoring library

8. Bibliography / References

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9. Checklist:

S. No.	Checklist Item	Yes/No (Y/N)
a)	Is the Cover page in proper format?	Y
b)	Is the Title page in proper format?	Y
c)	Is the Certificate from the Supervisor in proper format? Has it been signed?	Y
d)	Is Abstract included in the Report? Is it properly written?	Y
e)	Does the Table of Contents page include chapter page numbers?	Y
f)	Does the Report contain a summary of the literature survey?	Y
f.i)	Are the Pages numbered properly?	Y
f.ii)	Are the Figures numbered properly?	Y
f.iii)	Are the Tables numbered properly?	Y
f.iv)	Are the Captions for the Figures and Tables proper?	Y
f.v)	Are the Appendices numbered?	Y
g)	Does the Report have Conclusion / Recommendations of the work?	Y
h)	Are References/Bibliography given in the Report?	Y
i)	Have the References been cited in the Report?	Y
j)	Is the citation of References / Bibliography in proper format?	Y