Fault-Tolerant Decentralized Distributed Asynchronous Federated Learning with Adaptive Termination Detection

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Motivation

Scenario:

- **Decentralized Data**: Each hospital keeps its own patient records
- **Sensitive Data**: Cannot be shared outside the hospital
- **Insufficient Data**: One hospital alone has limited information

Challenges:

- **Privacy Restrictions**: Limits collaboration
- **Legal Compliance**: Bound by *DPDP, DISHA*
- **Fragmented Records**: Data spread across hospitals

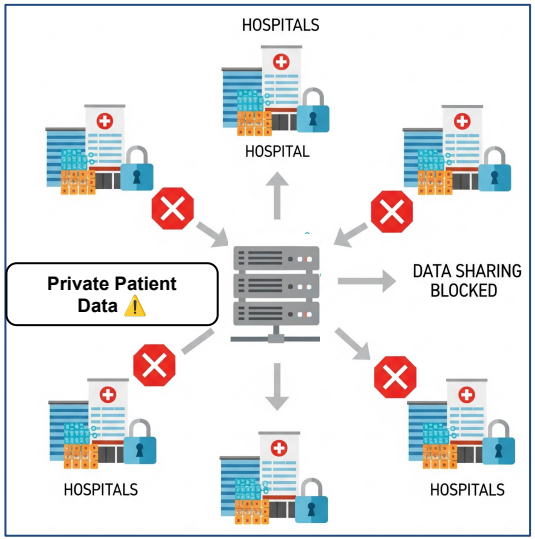


Fig. 1: Example of Real World Problem

Federated Learning

Learning without sharing personal data!

Federated Learning *is a* ***machine learning approach*** *where a shared global model is trained across multiple client devices* ***without transferring their raw data****.*

Core Features:

- *Data Privacy:* Sensitive data never leaves the source
- *Reduced Data Transfer:* Only model updates are shared
- *Utilizing Distributed Data:* Leverages data across all sites
- *Personalization:* Models adapt to local needs
- *Faster Updates:* Parallel training accelerates learning

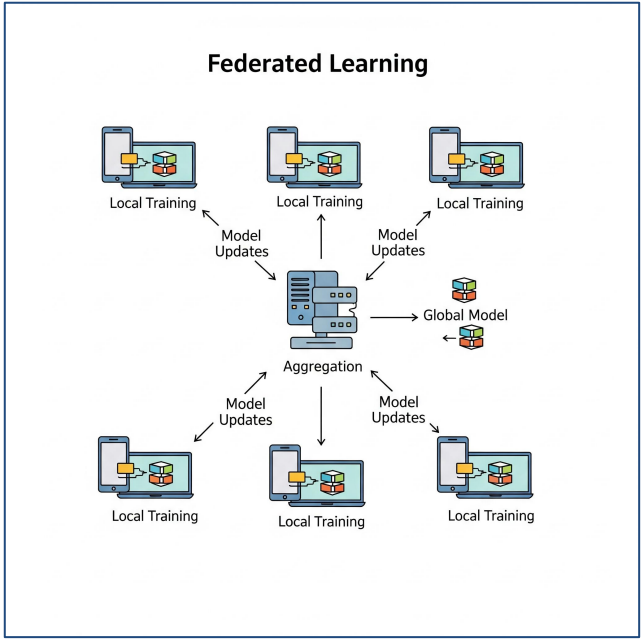


Fig. 2: Centralized Federated Learning

Synchronous Centralized FL

- **Central Server Coordination:** A global server manages model aggregation.
- **Round-based Training:** Clients train locally and send updates in fixed rounds.
- **Wait for All Clients:** Server aggregates only after selected clients finish training.
- **Global Model Synchronization:** Updated global model is shared back to all clients.
- **Most Common Setup:** Standard approach (e.g., FedAvg).

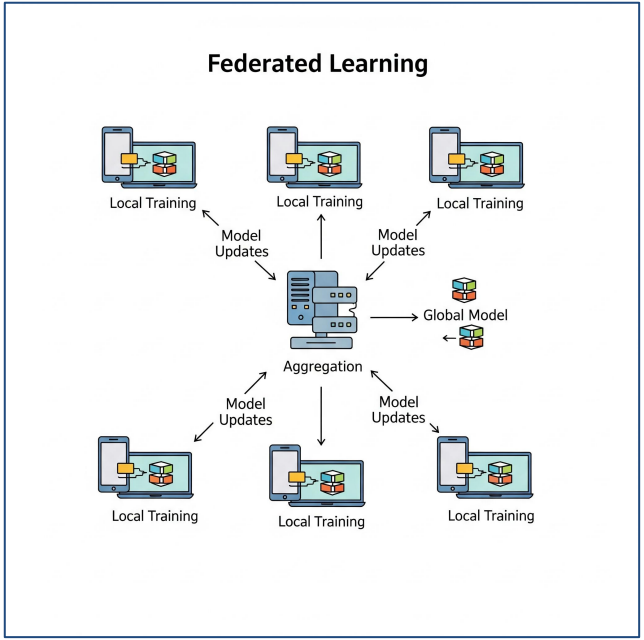


Fig. 2: Centralized Federated Learning

Limitations

Limitations of Centralized Federated Learning:

- **Reliability:** Training stops if the server fails.
- **Scalability & Efficiency:** Server becomes a bottleneck in both computation and communication as clients increase.
- **Trust & Privacy:** Centralized updates increase vulnerability to attacks or leakage.

Limitations of Synchronous Federated Learning:

- **Straggler Effect:** Slow clients delay the round, causing inefficiency.
- **Dropouts & Network Instability:** Client failures or poor connectivity disrupt training.
- **Heterogeneous Systems:** Varying resources and data make synchronization challenging.

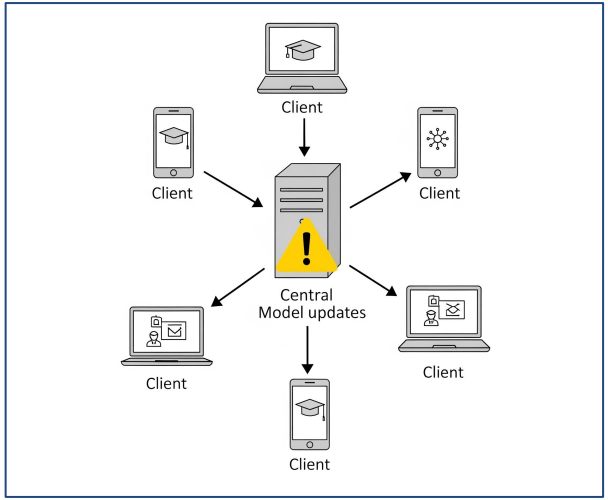


Fig. 3: Load on Central Server

Asynchronous Decentralized FL

- **Resilient to Stragglers:** Asynchronous updates keep training moving
- **No Single Point of Failure:** Not completely dependent on one server
- **Scalable by Design:** Load distributed across peers, not one server
- **Enhanced Privacy & Security:** No central aggregator, smaller attack surface

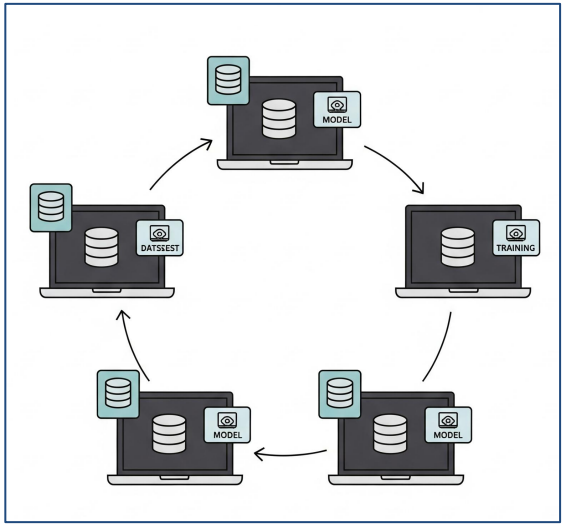


Fig. 4: Example of Decentralized FL

Faults

Definition:

A crash fault happens when a client or node unexpectedly stops working and becomes unresponsive during training or communication.

Typical Causes:

- Device failures (battery drain, hardware crash)
- Network disconnections
- Process termination due to overload/errors

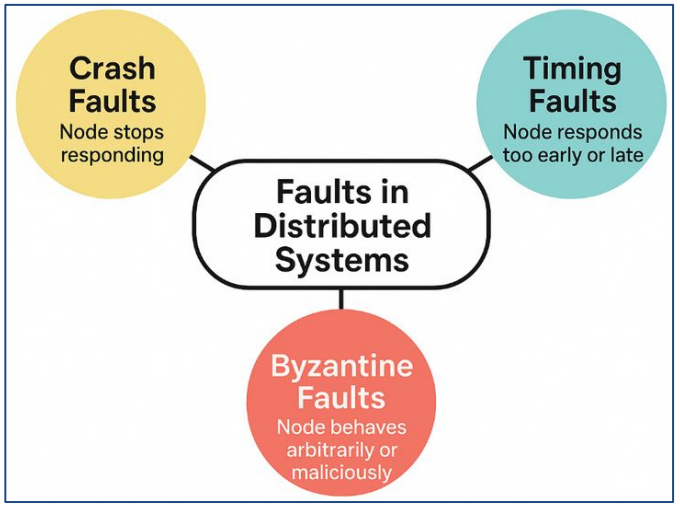


Fig. 4: Types of Faults

Crash Fault Tolerance in Asynchronous DFL

Methodology:

- **Data Preparation:** CIFAR-10, non-IID client splits, fixed samples per client
- **Model Training:** Simple CNN, local training with SGD + Cross-Entropy
- **Communication:** Clients exchange weights via TCP sockets, aggregation by weighted averaging
- **Fault Tolerance:** Simulation of crashes, detected via timeouts
- **Termination:** Triggered by stable weights over rounds, no recent crashes

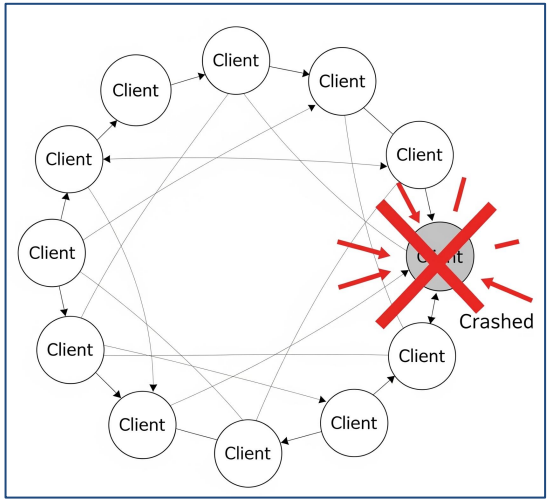


Fig. 4: Client Crash

Crash Fault Tolerance

Each Round:

- Clients train locally and broadcast updates.
- Peers wait for updates within a fixed time window.

Active Client:

- Sends update to all the clients.
- Update is included in aggregation.

Unresponsive Client:

- Misses the current round's window → update not included this round.
- Client is not marked as crashed so, can **rejoin** later

Aggregation Strategy:

- Combine all available updates + local model. (Fair Aggregation)
- Continue asynchronously without waiting for every client.

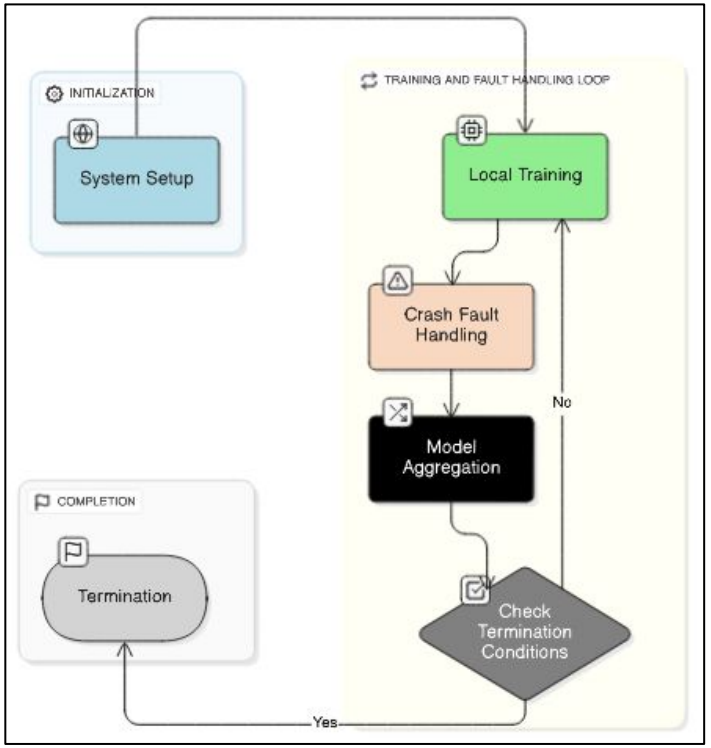
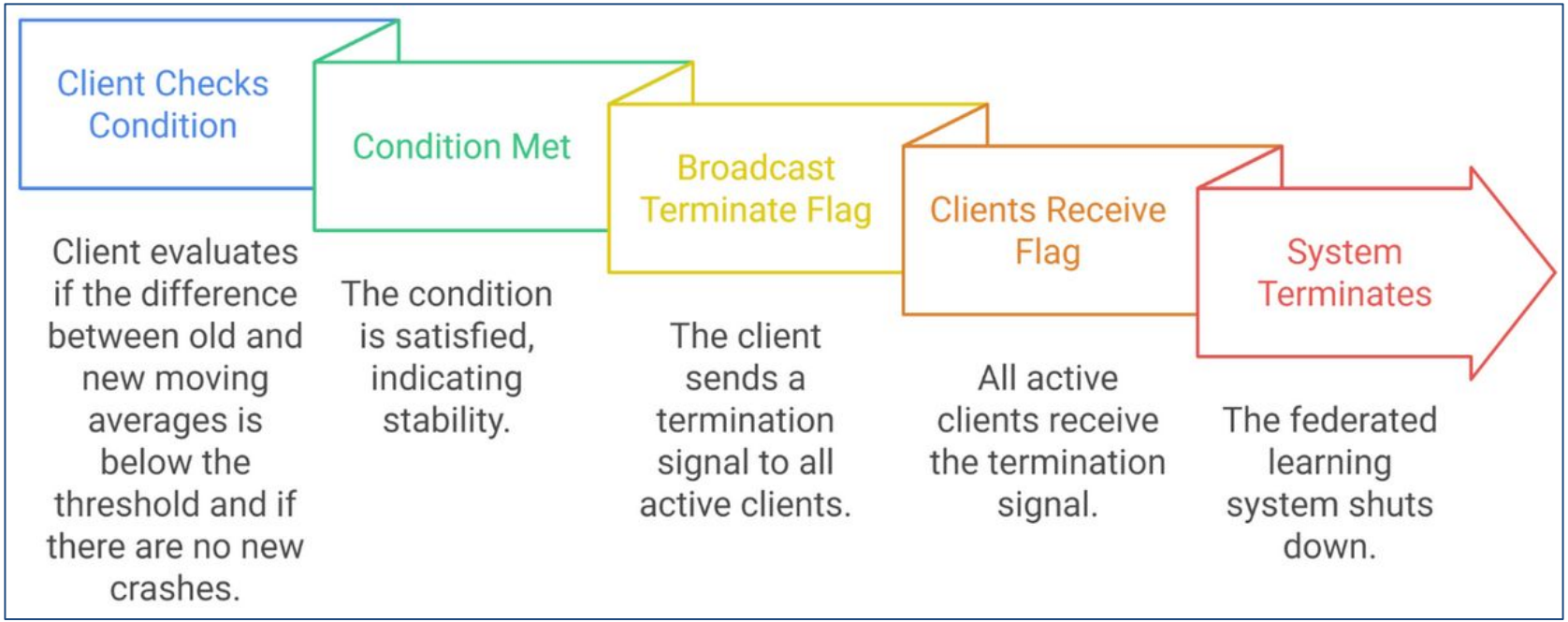


Fig. 5: High Level flow of current setup

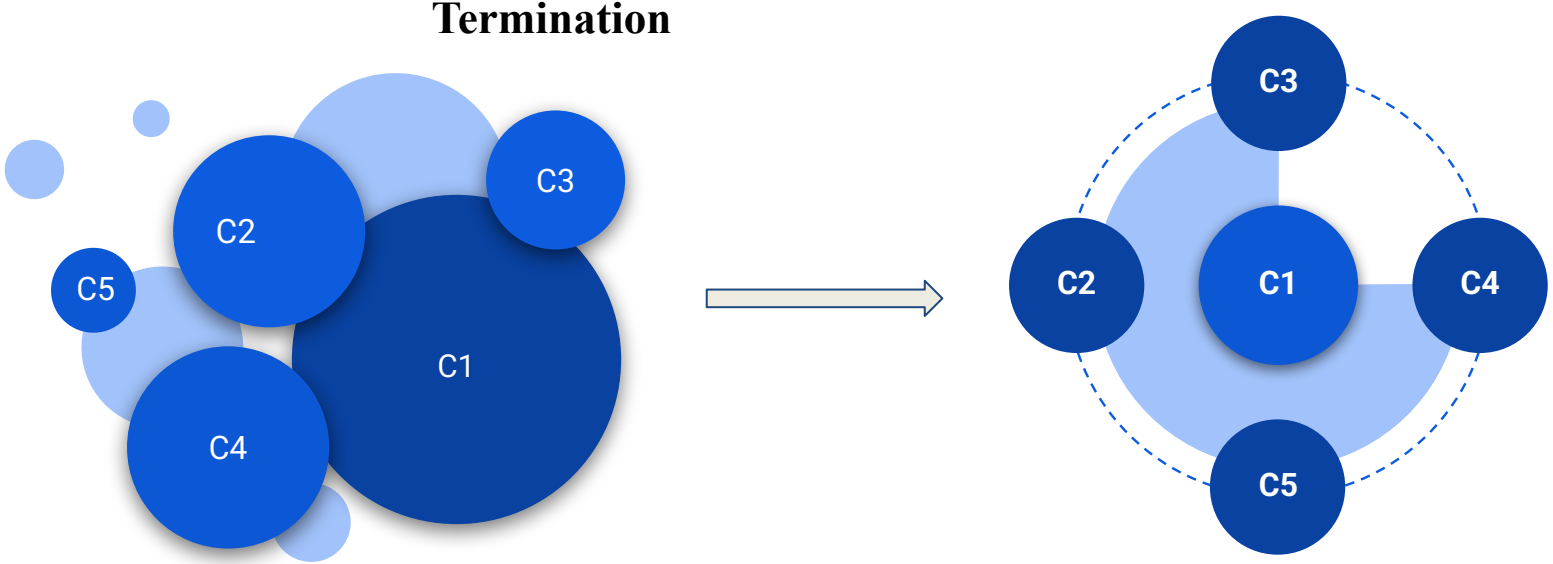
Novel Termination

1. Client-Confident Convergence



Novel Termination

2. Client Responsive Termination



All the active clients after receiving the termination signal, alters their own termination flags, complete the current round, broadcast their new model along with termination flag and safely terminates.

Experimental Setup

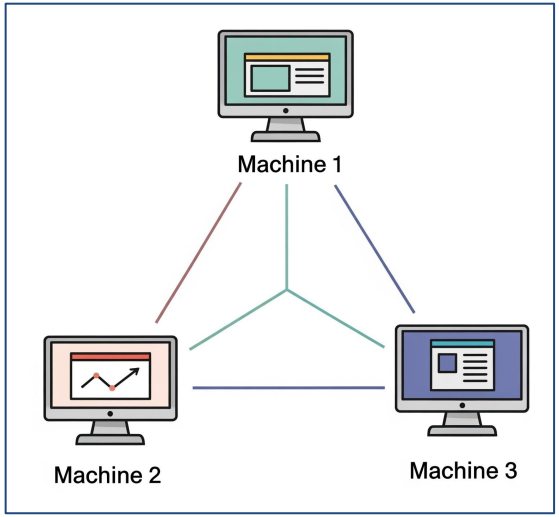
System Specifications:

- **Machine 1:** Ubuntu 18.04.6, 376 GiB RAM, 56 cores @ 4.0 GHz
- **Machine 2:** Ubuntu 22.04.5, 251 GiB RAM, 112 cores @ 2.0 GHz
- **Machine 3:** Ubuntu 22.04.5, 188 GiB RAM, 52 cores @ 3.5 GHz

To simulate the complications of real time scenario, we have done all the experiments in multi machine, multi client setup

Federated Learning Configuration:

- **Framework:** Custom asynchronous decentralized FL (Python, PyTorch)
- **Dataset:** CIFAR-10 (non-IID split using Dirichlet distribution)
- **Model:** Simple CNN (2 convolutional layers + 2 fully connected layers)
- **Fault Injection:** Crash faults introduced via input file configuration



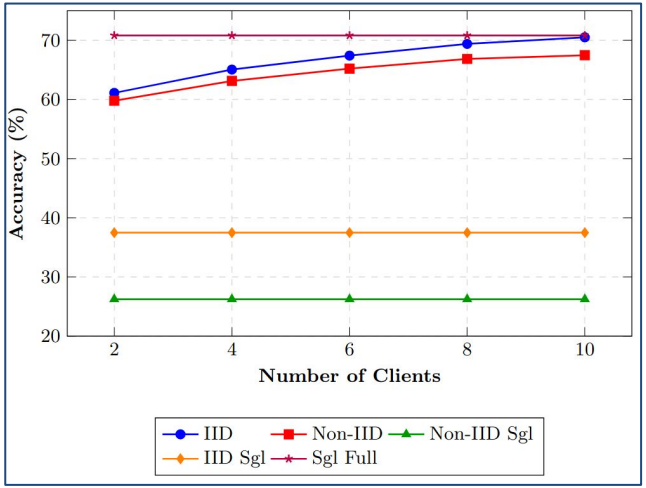
Results

Data Distribution Cases:

- IID (Independent & Identically Distributed): Data evenly distributed across clients.
- Non-IID: Clients have heterogeneous data (more realistic).
- IID Sgl / Non-IID Sgl: Training with a single client only.
- Sgl Full: Centralized training on the entire dataset.

Key Insights:

- Accuracy improves with more clients in both IID and Non-IID cases.
- IID achieves slightly higher accuracy than Non-IID.
- Single-client training (Sgl) lags far behind.
- Centralized Single Machine training (Sgl Full) gives the best performance but loses decentralization benefits.

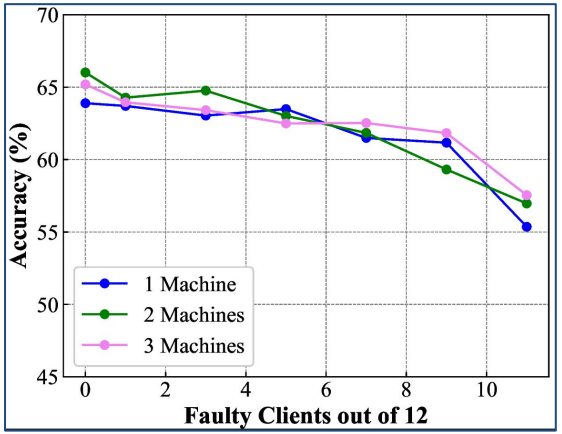


Scenario	Accuracy (%)
Non-IID Single Client (Fixed data chunk)	26.23
IID Single Client (Fixed data chunk)	37.48
Single Client (Full dataset)	70.82

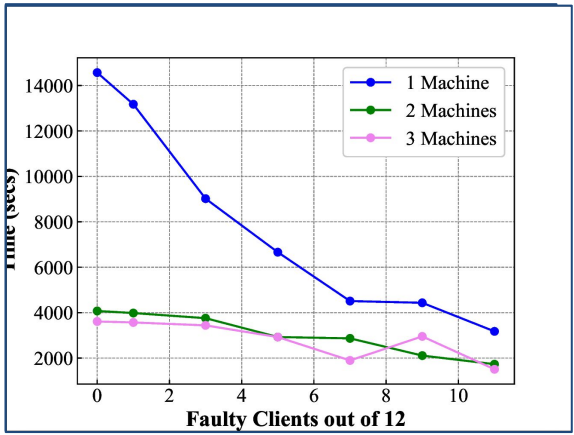
Results

Experiment 1: Variable number of faulty clients with 12 Clients

- Even as the number of failed clients rose from 0 to 11, the system maintained reasonable accuracy and convergence time, particularly when deployed in a multi-machine setup.
- This highlighted the effectiveness of distributing clients across machines to reduce contention and better reflect real-world asynchronous behaviour.



Graph 1: Variable No. of Faults with 12 clients

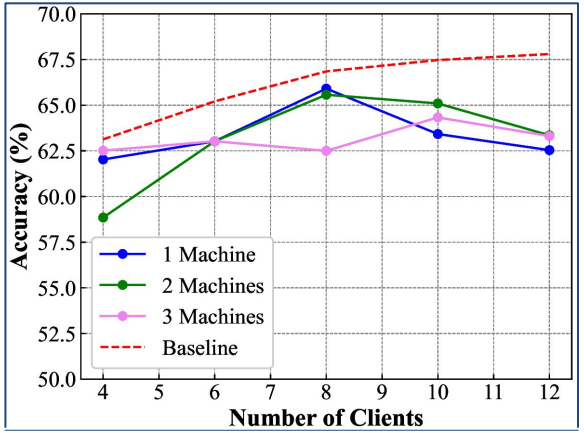


Graph 2: Variable No. of Faults with 12 clients

Results

Experiment 2: n/3 faulty clients with variable number of clients

- The results showed that despite substantial asynchronous and partial failures, the proposed approach performed comparably to a fault-free baseline.
- As the number of clients increases from 4 to 12, the system maintains relatively stable accuracy, suggesting that federated learning can scale under fault-tolerant settings.

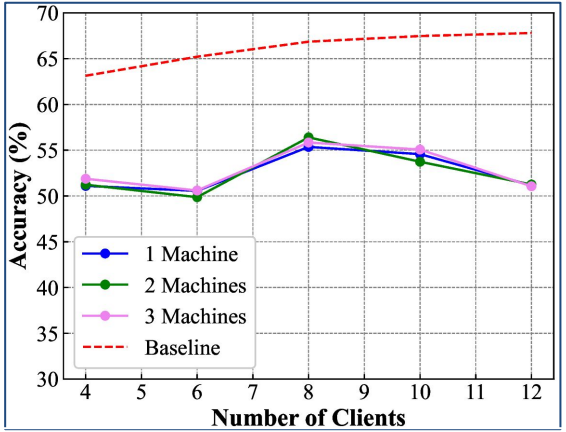


Graph 2: n/3 Faults

Results

Experiment 3: n-1 faulty clients with variable number of clients

- While the accuracy dropped significantly when compared with the synchronized no-fault system as baseline, it still outperformed the Non-IID single-client (Table in previous slide), underlining the benefit of initial collaborative updates and the residual value of even limited federation.



Graph 3: n-1 Faults

Conclusion

- We present a **fully asynchronous, fault-tolerant federated learning framework** designed to operate effectively under realistic deployment conditions
- Addressed client heterogeneity, instability in the absence of centralized control
- Proposed **Client-Confident Convergence** and **Client-Responsive Termination** mechanisms address a long-standing challenge in decentralized asynchronous FL
- We demonstrated the framework's **robustness** to crash faults, its **ability to scale** under partial failures, and its **resilience** even in extreme scenarios with minimal active clients.

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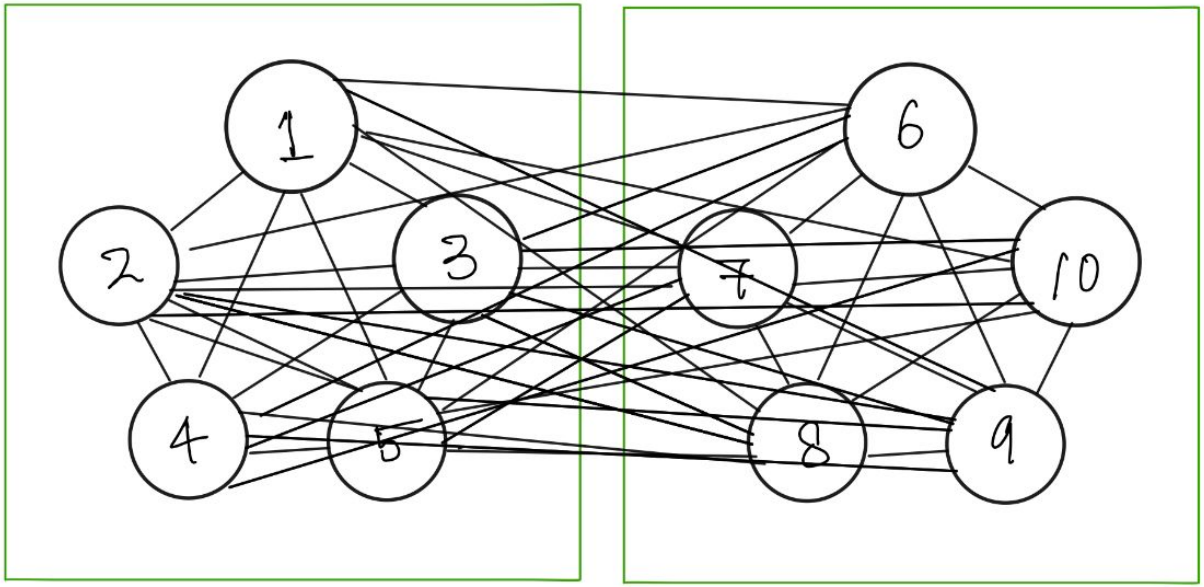
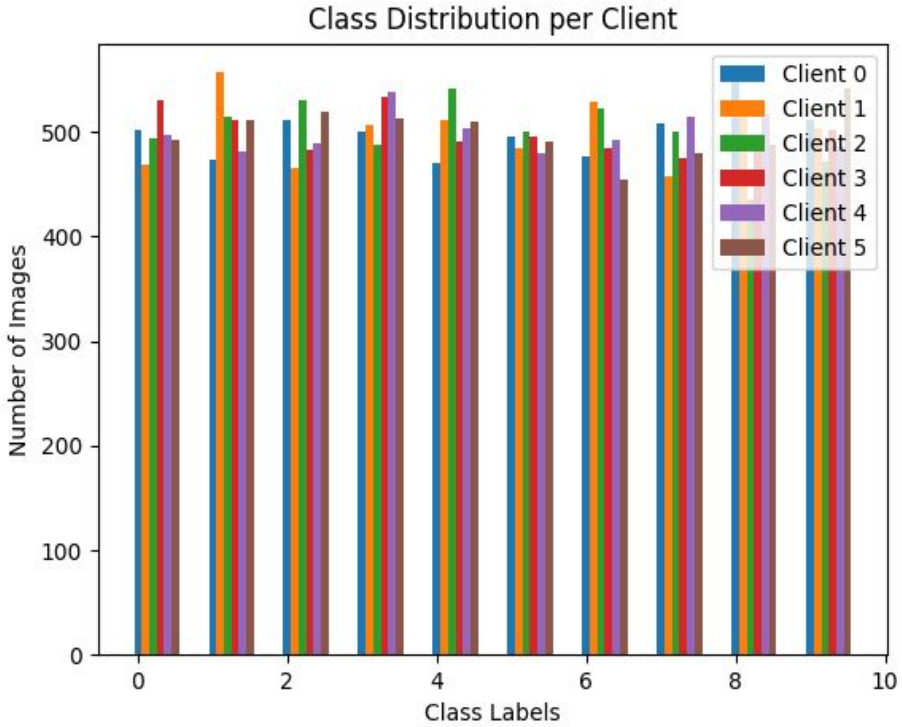
Thank You!

Appendix

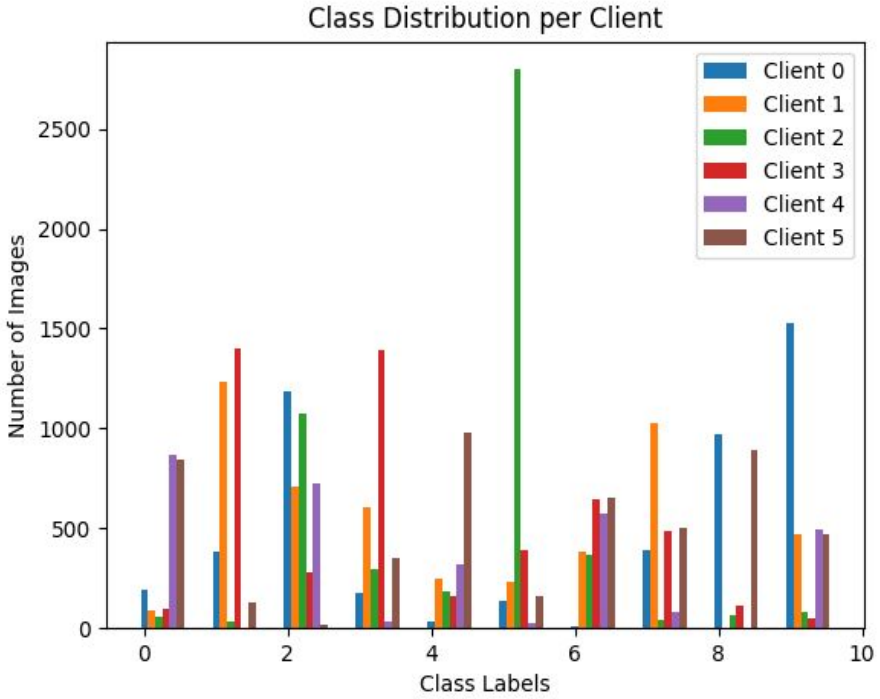
Multi_machine - Multi_client System



IID data Class Distribution per Client



Non-IID data Class Distribution per Client



IID data 5,000 pr client distinct data points (CIFAR10)

No of Clients	No. of messages	Convergence Round	Accuracy	Time (secs)
2	60	28	61.62%	251.90
4	552	44	65.74%	862.22
6	1650	53	68.30%	3077.55
8	3751	65	70.50%	3240.10
10	7018	76	70.95%	4792.88

Non-IID data 5,000 pr client distinct data points (CIFAR10)

No of Clients	No. of messages	Convergence Round	Accuracy	Time (secs)
2	72	34	58.63%	348.34
4	660	53	60.05%	1021.03
6	1980	64	65.45%	2164.95
8	616	9	50.80%	429.97
10	360	2	10.14%	120.86

Non-IID data 5,000 pr client distinct data points (CIFAR10)

Clients	No of Model messages		No of Termination messages		Rounds	Accuracy	Total Time Taken(secs)	
	Machine 1	machine 2	Machine 1	machine 2			machine 1	machine 2
2	29	29	1	1	29	61.1	157.31	154.75
4	234	234	6	6	39	65.05	454.91	454.28
6	675	675	15	15	45	67.41	1740.54	1740.54
8	1624	1624	28	28	58	69.39	2000.24	2000.95
10	2925	2925	45	45	65	70.5	3195.24	3204.25

Clients	No of Model messages		No of Termination messages		Rounds	Accuracy	Total Time Taken(secs)	
	Machine 1	machine 2	Machine 1	machine 2			machine 1	machine 2
2	31	31	1	1	31	59.78	172.19	170.81
4	294	294	6	6	49	63.13	563.66	562.28
6	930	930	15	15	62	65.21	2309.49	2309.52
8	1960	1960	28	28	70+	66.85	3720.45	3718.78
10	270	270	45	45	80+	67.23	4000+	4000+

Model Architecture (CNN)

- **Conv1:** 3×32 filters, kernel 3×3 → Output: 32 feature maps
- **MaxPool1:** 2×2 → Downsample
- **Conv2:** 32×64 filters, kernel 3×3 → Output: 64 feature maps
- **MaxPool2:** 2×2 → Downsample
- **Flatten:** → 64×6×6 = 2304 features
- **FC1:** 2304 → 128 units (ReLU)
- **FC2:** 128 → 10 units (classes)

Total Parameters:

1. Conv1: (3×3×3×32) + 32 = **896**
2. Conv2: (3×3×32×64) + 64 = **18,496**
3. FC1: (2304×128) + 128 = **295,040**
4. FC2: (128×10) + 10 = **1,290**

Total = 896 + 18,496 + 295,040 + 1,290 = ***315,722 Parameters***

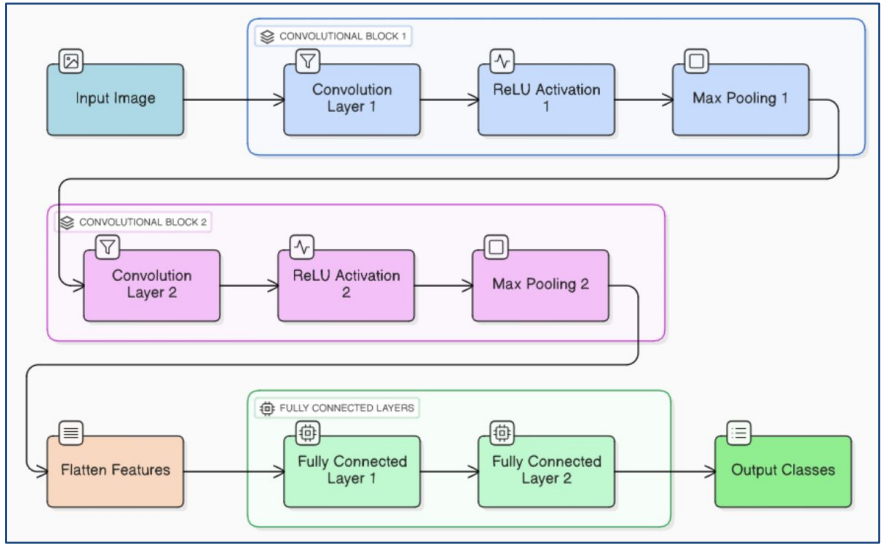


Fig. 7: CNN Model Architecture

Results: 12 Clients with variable number of faults (1 Machine)

S. No.	Crashes	Max Rounds	Accuracies(%)	Range	Time (secs)
1	0	100	64.90, 62.72, 64.90, 64.20, 63.71, 63.29, 64.73, 64.73, 64.35, 64.71, 61.43, 63.05	61 - 65	14569
2	1	100	63.44, 63.42, 63.37, 64.72, 64.00, 65.32, -, 62.06, 63.38, 65.04, 63.63, 62.37	62 - 66	13176
3	3	88	63.69, -, 64.18, 60.89, 62.66, 64.91, -, 63.08, 64.58, -, 62.75, 60.58	60 - 65	9020
4	5	86	63.91, -, 64.60, -, 63.67, 62.15, -, 63.91, -, -, 63.78, 62.40	62 - 65	6663
5	7	68	62.46, -, 62.10, -, -, 62.63, -, 57.74, -, -, 62.54, -	57 - 63	4511
6	9	70	61.79, -, -, -, -, 59.92, -, 61.79, -, -, -, -	59 - 62	4435
7	11	45	55.36, -, -, -, -, -, -, -, -, -, -, -	-	3177

Results: Variable No. of Clients with n/3 Faults (1 Machine)

S. No.	No. of Clients	Crashes	Max Rounds	Accuracies (%)	Range	Time (secs)
1	4	1	89	61.51, 62.29, -, 62.29	61 - 63	3214
2	6	2	93	63.28, 63.28, 62.63, -, -, 62.91	62 - 64	3544
3	8	2	99	65.98, 66.05, 65.98, -, 66.27, 65.58, -, 65.58	65 - 67	4514
4	10	3	94	63.73, 62.65, -, 64.43, -, 64.23, 64.23, -, 64.23, 63.11	62 - 65	5868
6	12	4	81	62.27, 62.53, -, 61.95, 62.53, -, 61.70, 62.98, -, 62.92, 63.43, -	61 - 64	6812

Results: Variable No. of Clients with n-1 Faults (1 Machine)

S. No.	No. of Clients	Crashes	Max Rounds	Accuracies (%)	Time (secs)
1	4	3	46	52.49, -, -, -	1639
2	6	5	45	-, 48.38, -, -, -, -	1791
3	8	7	45	-, -, -, -, -, -, -, 54.73	2028
4	10	9	45	-, -, -, -, -, -, -, -, -, 52.20	2692
5	12	11	45	55.66, -, -, -, -, -, -, -, -, -, -, -	3176

Results: 12 Clients with variable number of faults (2 Machines)

S. No.	No. of Clients	Crashes	M1 Rounds	M2 Rounds	M1 Accuracies (%)	M2 Accuracies (%)	Range	M1 Time (secs)	M2 Time (secs)
1	12	0	98	100	65.16, 67.02, 65.16, 66.38, 66.71, 66.38	66.71, 66.57, 65.16, 66.38, 66.38, 65.16	65 - 67	4070	4075
2	12	1	100	94	63.21, 65.34, -, 65.12, 64.94, 63.21	65.34, 65.12, 63.21, 64.57, 61.81, 65.17	62 - 66	3984	3984
3	12	3	91	100	65.41, 63.35, -, 64.66, 65.40, 65.67	65.41, -, 64.94, 63.35, -, 64.66	63 - 66	3758	3739
4	12	5	72	82	60.48, -, 63.91, 63.63, -, 63.25	-, 63.77, -, 63.73, 62.33, -	60 - 64	2928	2907
5	12	7	74	77	-, 62.37, -, -, -, -	-, 61.05, 62.37, 62.37, 61.05, -	61 - 63	2844	2869
6	12	9	55	57	-, 60.43, -, -, -, -	-, -, -, 57.09, 60.43, -	57 - 61	2111	2111
7	12	11	45	36	56.97, -, -, -, -, -	-, -, -, -, -, -	-	1732	1431

Results: Variable No. of Clients with n/3 Faults (2 Machines)

S. No.	No. of Clients	Crashes	M1 Rounds	M2 Rounds	M1 Accuracies(%)	M2 Accuracies(%)	Range	Time Taken M1 (secs)	Time Taken M2 (secs)
1	4	1	88	92	60.31, 55.93	60.31, -	56 - 62	2833	2831
2	6	2	95	95	-, 61.03, 60.44	61.03, -, 60.44	60 - 62	3071	3069
3	8	3	99	95	65.53, -, 65.17, -	65.81, 65.81, -, 65.53	65 - 66	3241	3241
4	10	3	71	75	65.27, 64.24, -, 56.73, 62.44	-, 63.79, -, 63.49, 64.92	57 - 66	2693	2682
5	12	4	84	86	64.39, 64.33, -, 59.65, 64.35, -	-, -, 64.39, 64.33, 62.68, 62.68	59 - 65	3355	3346

Results: Variable No. of Clients with n-1 Faults (2 Machines)

S. No.	No. of Clients	Crashes	M1 Rounds	M2 Rounds	M1 Accuracies(%)	M2 Accuracies(%)	Time Taken M1 (secs)	Time Taken M2 (secs)
1	4	3	45	30	53.11, -	-,	1422	997
2	6	5	45	20	56.42, -, -	-, -, -	1496	698
3	8	7	45	29	58.13, -, -, -	-, -, -, -	1631	1006
4	10	9	45	28	57.27, -, -, -, -	-, -, -, -, -	1705	1143
5	12	11	45	36	55.84, -, -, -, -, -	-, -, -, -, -, -	1749	1349

Results: 12 Clients with variable number of faults (3 Machines)

S. No.	Crashes	M1 Rounds	M2 Rounds	M3 Rounds	M1 Accuracies	M2 Accuracies	M3 Accuracies	Range	M1 Time (secs)	M2 Time (secs)	M3 Time (secs)
1	0	98	62	100	65.06, 64.80, 65.47, 65.19	65.38, 64.80, 65.26, 65.58	65.38, 64.80, 65.19, 65.39	64 - 66	3599	3612	3592
2	1	94	62	100	63.90, 64.20, 63.92, 63.82	64.42, -, 64.79, 63.77	64.20, 63.82, 63.61, 63.08	63 - 65	3570	3565	3562
3	3	95	61	100	63.03, -, 58.47, 63.21	64.49, -, 62.91, 63.03	63.21, -, 62.45, 62.91	58 - 65	3421	3420	3407
4	5	88	66	82	62.82, -, -, 63.14	-, 62.67, -, 60.33	62.80, 62.92, 62.80, -	60 - 64	2921	2927	2761
5	7	53	43	56	62.38, 62.74, -, -	-, -, 62.38, 62.74	-, 62.38, -, -	62 - 63	1890	1894	1897
6	9	91	78	84	61.83, -, -, -	61.83, -, -, -	-, -, -, 61.83	61 - 62	2942	2955	2953
7	11	51	28	35	-	-, -, 56.00, -	-, 57.54, 59.27, -	56 - 60	1509	1505	1277

Results: Variable No. of Clients with n/3 Faults (3 Machines)

S. No.	No. of Clients	Crashes	M1 Rounds	M2 Rounds	M3 Rounds	M1 Accuracies	M2 Accuracies	M3 Accuracies	Range	Time Taken (M1)	Time Taken (M2)	Time Taken (M3)
1	4	1	91	10	100	63.22, 59.78	-	63.22	59 - 64	3052	291	3047
2	6	2	74	83	78	63.77, 63.77	-, 64.78	64.78, -	63 - 65	2496	2482	2479
3	8	3	85	72	85	62.69, 62.69, -	62.63, 61.79, -	62.69, -	61 - 63	2701	2711	2699
4	8	2	100	60	97	63.63, 62.04, -	62.87, 63.63, 62.02	62.02, -	62 - 64	3080	3081	3072
5	10	3	79	90	91	65.67, 60.53, 65.92, 59.39	64.82, -, 61.62	-, -, 65.38	59 - 66	2998	2983	2980
6	12	4	92	86	90	63.84, 63.84, 62.98, -	62.98, -, 61.93, -	-, 64.28, 63.30	61 - 65	3170	3168	3159

Results: Variable No. of Clients with n-1 Faults (3 Machines)

S. No.	No. of Clients	Crashes	M1 Rounds	M2 Rounds	M3 Rounds	M1 Accuracies	M2 Accuracies	M3 Accuracies	M1 Time (secs)	M2 Time (secs)	M3 Time (secs)
1	4	3	45	28	15	54.46, -	-	-	1410	805	462
2	6	5	45	28	17	56.34, -	-, -	-, -	1467	855	578
3	8	7	45	17	22	58.52, -, -	-, -, -	-, -	1532	776	773
5	10	9	44	22	24	57.71, -, -, -	-, -, -	-, -, -	1577	975	883
6	12	11	45	28	30	55.40, -, -, -	-, -, -, -	-, -, -, -	1608	1383	1097