Carnegie Mellon University

Towards Optimal Heterogeneous Client Sampling in Multi-Model Federated Learning

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Outline

- Introduction
  - Federated learning (FL)
  - Multi-model federated learning (MMFL)
- Variance-reduced client sampling in a simple MMFL system
- Modeling computational heterogeneity in MMFL
- Experiments

Federated Learning

Distributed learning with unshared local data

Server:

1 Receive updates from clients

2 Aggregate local updates for a better global model

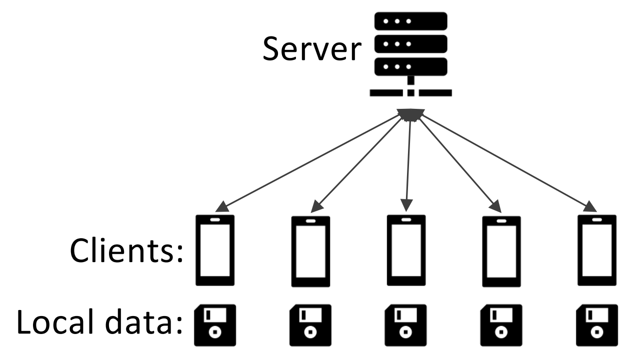
3 Broadcast new model parameters to clients

Local client (device):

1 Get global model parameters

2 Train model parameters with local data

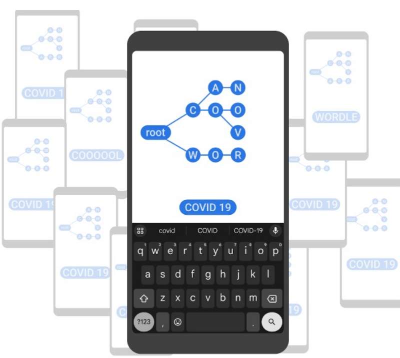
3 Send updated parameters to the server



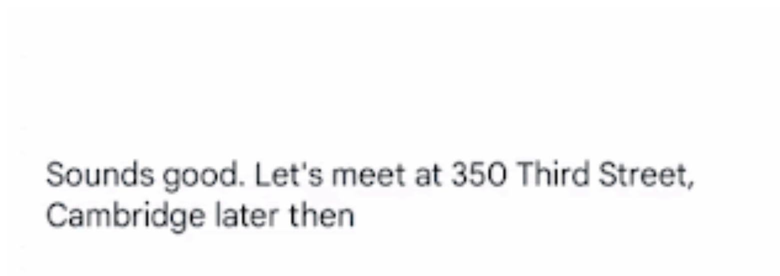
Multi-Model Federated Learning

Examples: Multiple FL applications on one device.

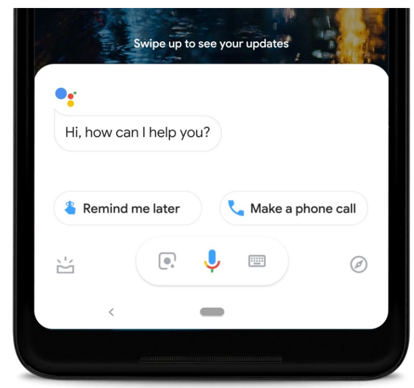
Keyboard prediction



Predicting text selection



Speech model



Source: federated.withgoogle.com

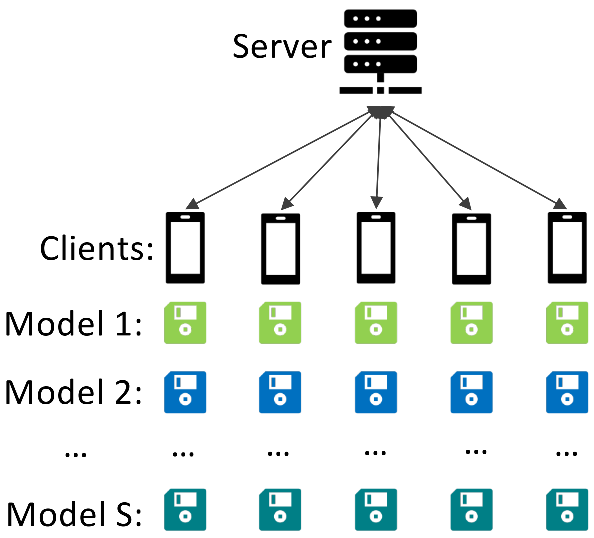
Multi-Model Federated Learning

Key assumptions from previous work [1]

In each round, the server only allows partial participation, and each active client can only train one model.

1) Partial Participation: reduce communication cost

2) Only train one model: computational constraints



Multi-model federated learning

[1] Bhuyan, Neelkamal, Sharayu Moharir, and Gauri Joshi. "Multi-model federated learning with provable guarantees." *EAI International Conference on Performance Evaluation Methodologies and Tools*. Cham: Springer Nature Switzerland, 2022.

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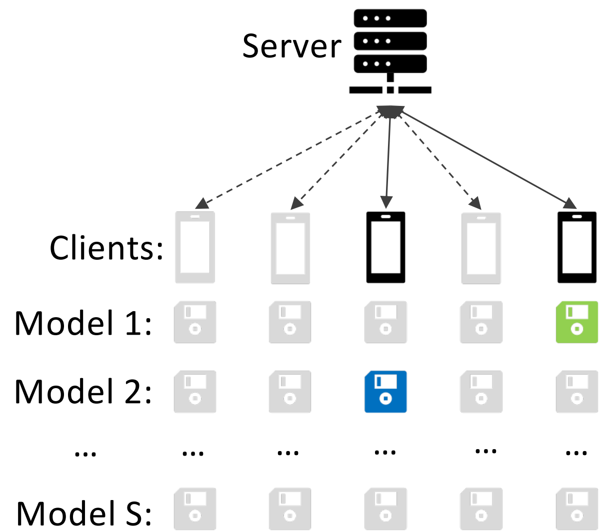

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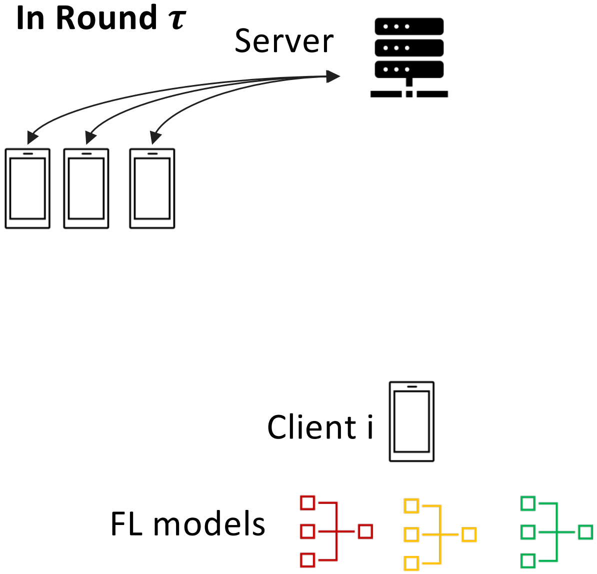
MMFL Optimal Variance-Reduced Sampling

Idea: the server prefers selecting more "important" clients.

In Round τ



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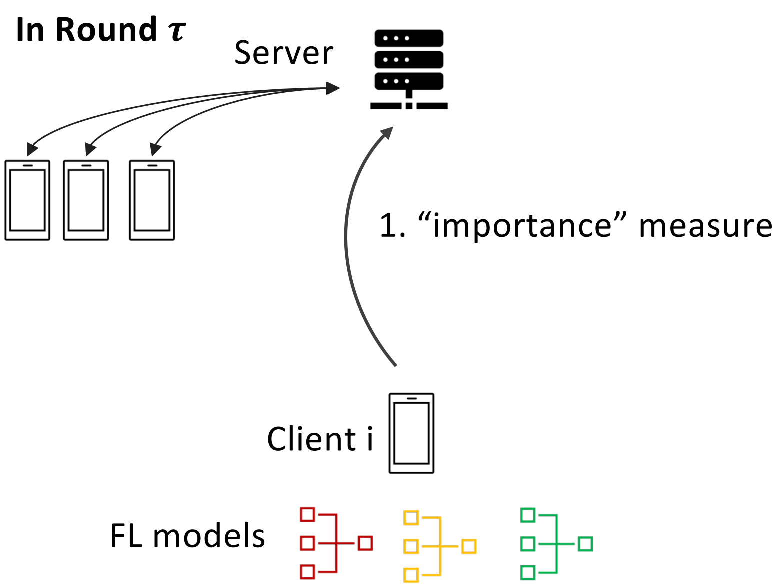

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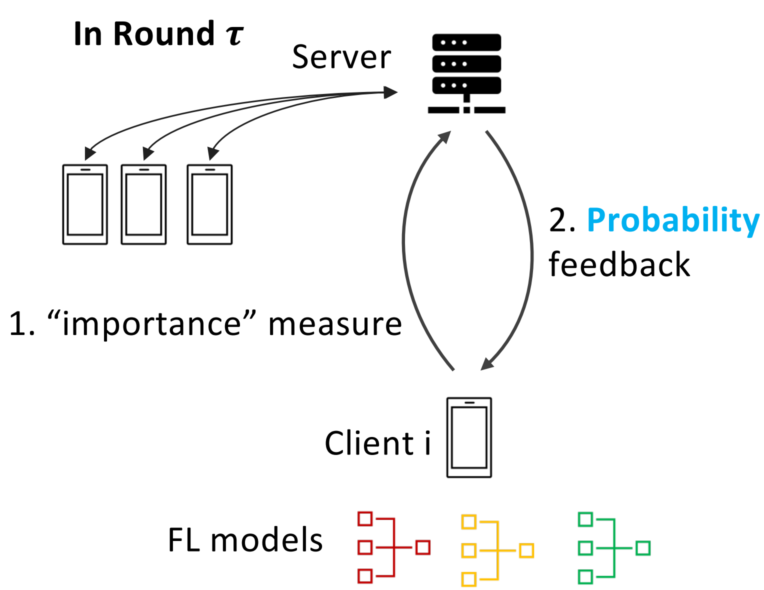

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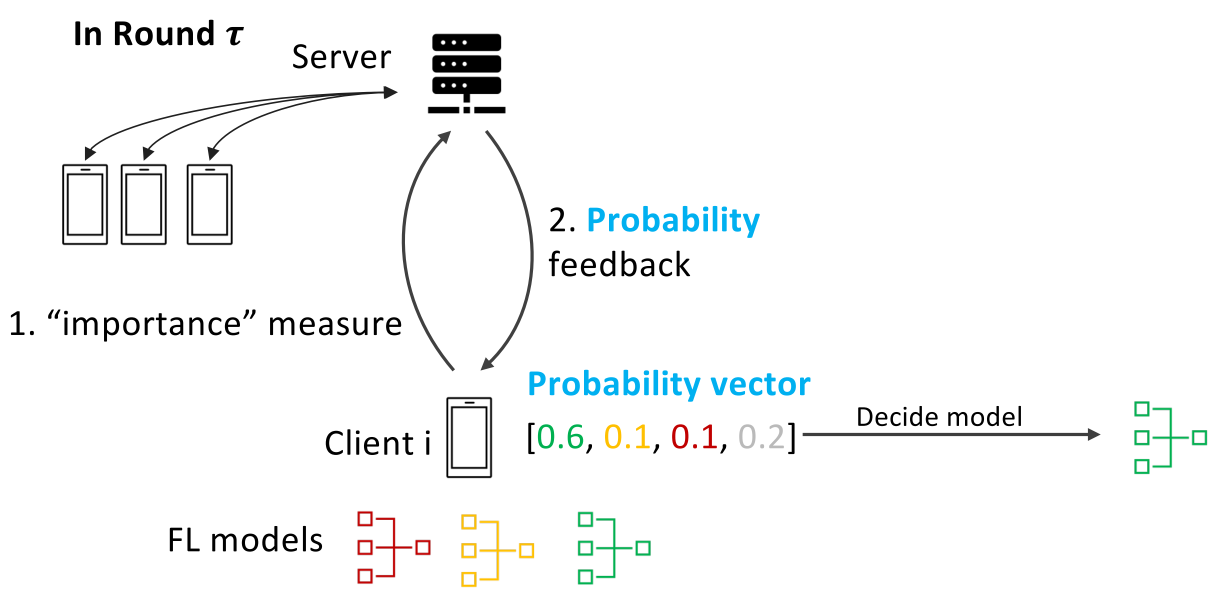

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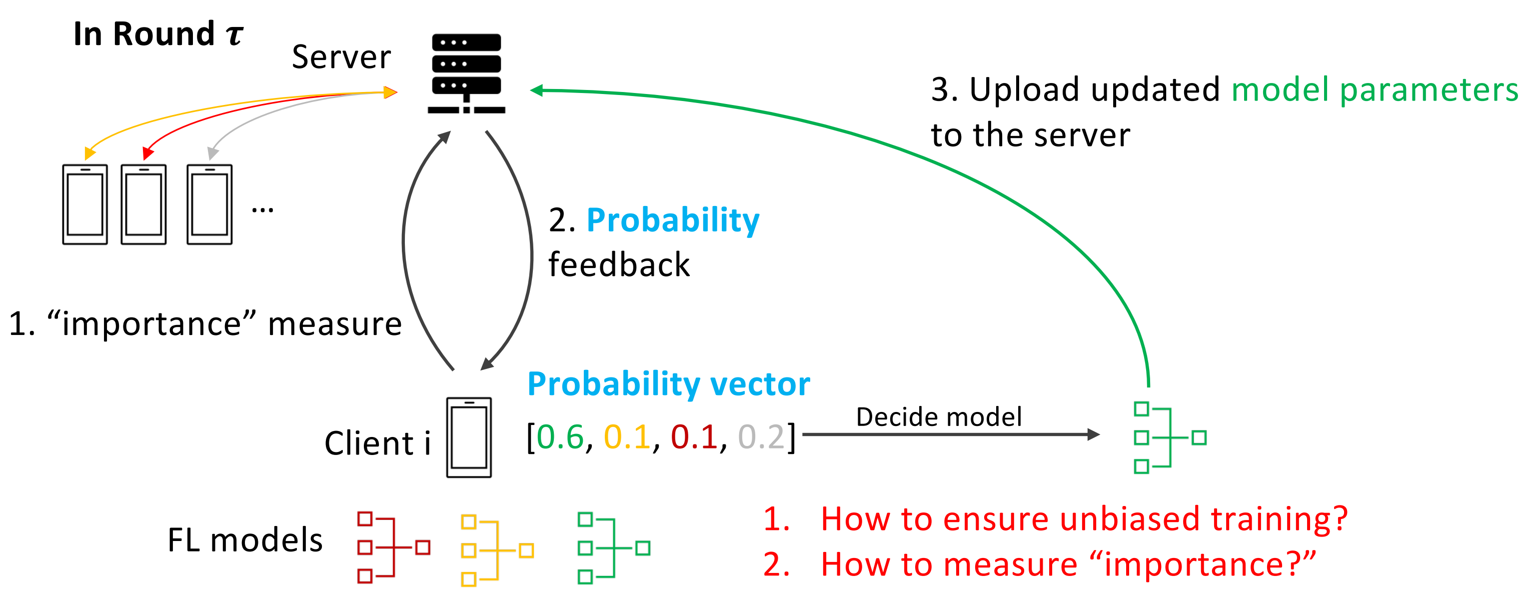
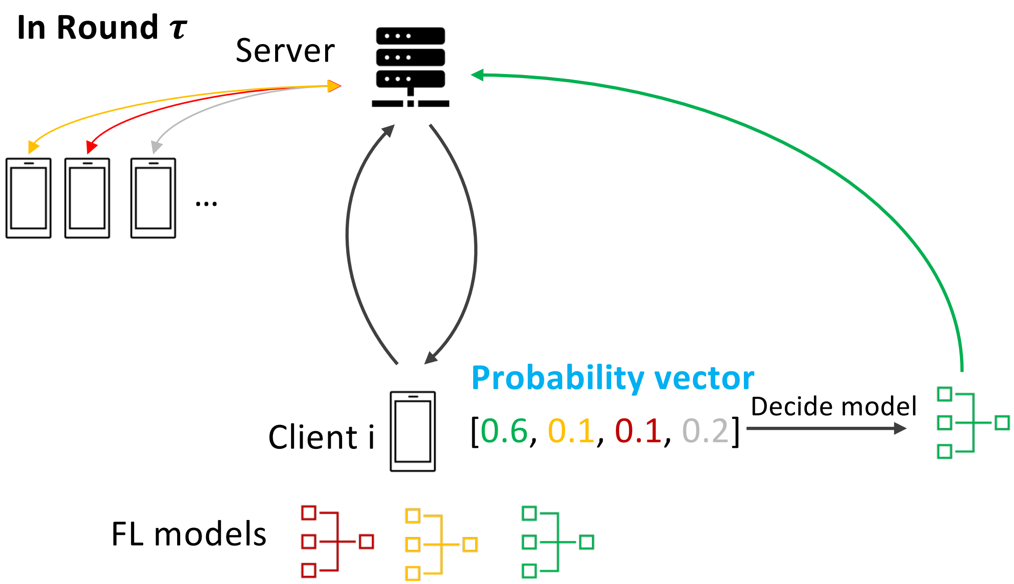


1. How to ensure unbiased training?
2. How to measure “importance?”

MMFL Optimal Variance-Reduced Sampling



In each global round (Aggregation):

$$w_s^{\tau+1} = w_s^{\tau} - \sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p_{s|i}^{\tau}} U_{i,s}^{\tau}$$

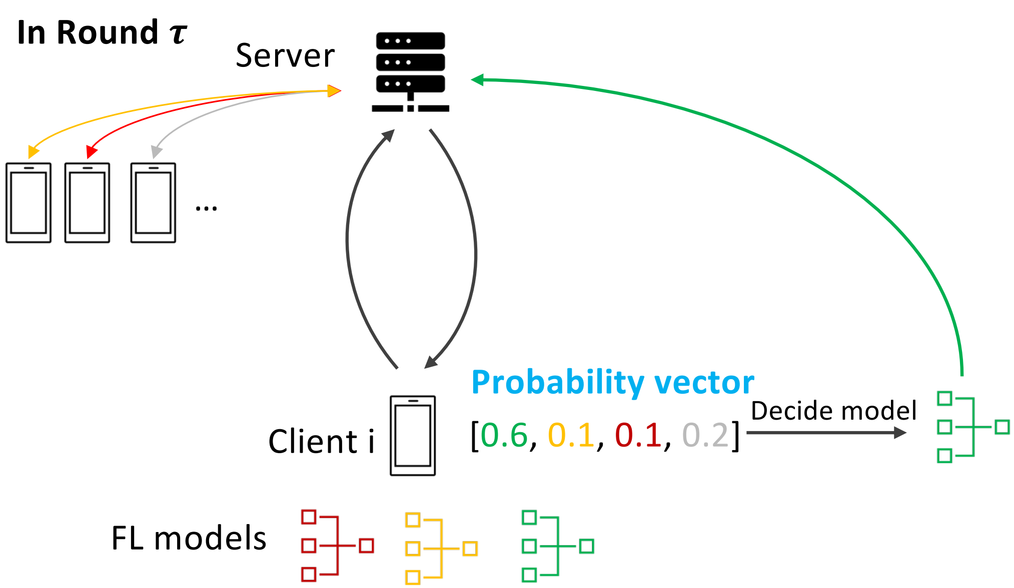
$d_{i,s} = \frac{n_{i,s}}{\sum_{j=1}^{N} n_{j,s}}$: dataset size ratio.

$U_{i,s}^{\tau} = \eta_{\tau} \sum_{t=1}^{K} \nabla f_{i,s}^{t,\tau}$: local update.

$p_{s|i}^{\tau}$: probability of assigning client i to model s.

$\mathcal{A}_{\tau,s}$: set of assigned clients for model s.

MMFL Optimal Variance-Reduced Sampling



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Unbiased Training:

$$\mathbb{E}\left[\sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p_{s|i}^{\tau}} U_{i,s}^{\tau}\right]$$

$$= \mathbb{E}\left[\sum_{i=1}^{N} \frac{d_{i,s}}{p_{s|i}^{\tau}} U_{i,s}^{\tau} 1_{i \in \mathcal{A}_{\tau,s}}\right]$$

$$= \sum_{i=1}^{N} d_{i,s} U_{i,s}^{\tau}$$

MMFL optimal variance-reduced sampling

Aggregation:

$$w_s^{\tau+1} = w_s^{\tau} - \boxed{\sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p_{s|i}^{\tau}} U_{i,s}^{\tau}}$$

Random Variable X

$\mathbb{E}[X]$ is given.

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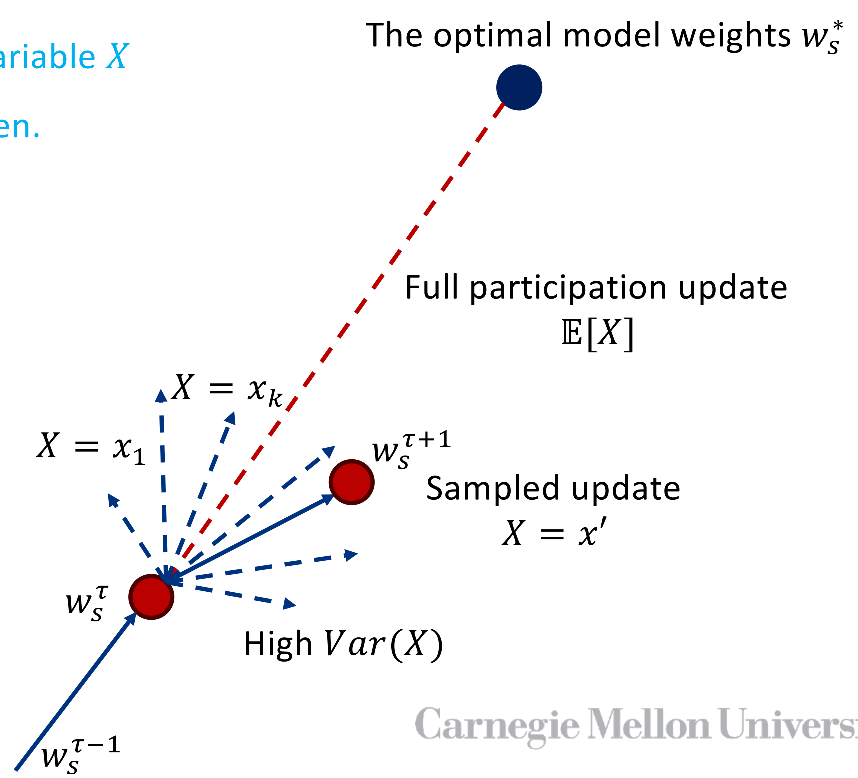
Random Variable X

$\mathbb{E}[X]$ is given.

High variance of X can make the training unstable…
Therefore, define our objective:

$$\min_{\{p_{s|i}^{\tau}\}} \sum_{s=1}^{S} \mathbb{E}_{\mathcal{A}_{\tau,s}} \left[\| \sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p_{s|i}^{\tau}} U_{i,s}^{\tau} - \sum_{i=1}^{N} d_{i,s} U_{i,s}^{\tau} \|^2 \right]$$



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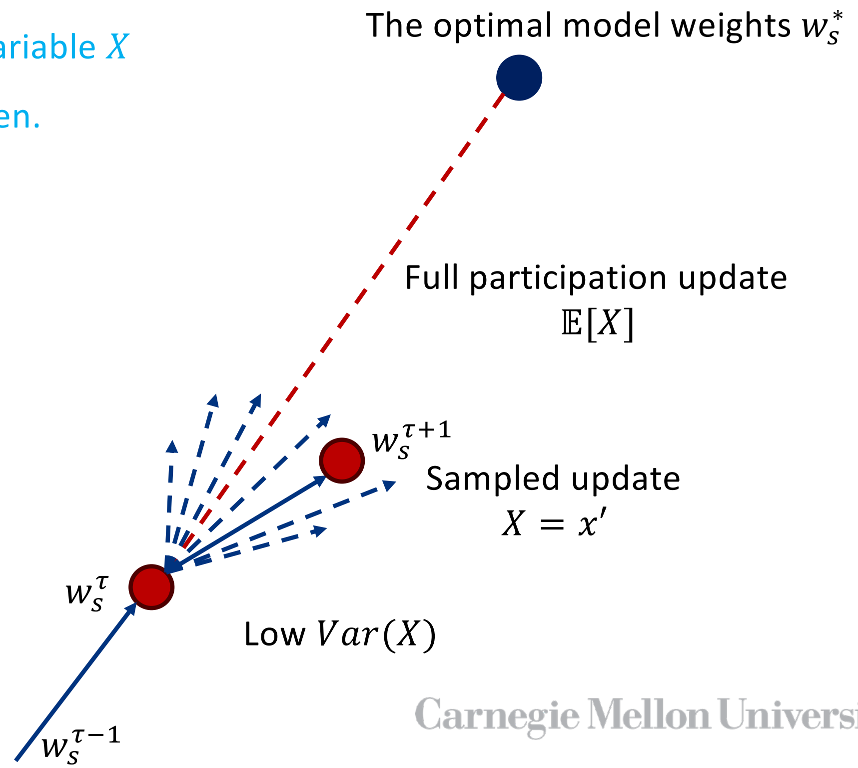
Notice: variance is an ideal objective to stabilize the training, but there could be other factors… (will further discuss later)



MMFL Optimal Variance-Reduced Sampling

Minimizing the variance of update

$$\min_{\{p_{s|i}^{\tau}\}} \sum_{s=1}^{S} \mathbb{E}_{\mathcal{A}_{\tau,s}} \left[\| \sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p_{s|i}^{\tau}} U_{i,s}^{\tau} - \sum_{i=1}^{N} d_{i,s} U_{i,s}^{\tau} \|^2 \right]$$

$$\text{s.t. } p_{s|i}^{\tau} \geq 0, \ \sum_{s=1}^{S} p_{s|i}^{\tau} \leq 1, \ \sum_{s=1}^{S} \sum_{i=1}^{N} p_{s|i}^{\tau} = m \quad \forall i, s$$

τ: global round number
i: client index
s: model index
m: expected number of active clients
$d_{i,s}$: dataset size ratio
t: local epoch number
$\mathcal{A}_{\tau,s}$: set of active clients

MMFL Optimal Variance-Reduced Sampling

Closed-form solution of the problem

$$p^{\tau}_{s|i} = \begin{cases} (m - N + k)\frac{\|\tilde{U}^{\tau}_{i,s}\|}{\sum_{j=1}^{k} M^{\tau}_{j}} & \text{if } i = 1, 2, \cdots, k, \\ \frac{\|\tilde{U}^{\tau}_{i,s}\|}{M^{\tau}_{i}} & \text{if } i = k+1, \cdots, N. \end{cases} \quad (5)$$

where $\|\tilde{U}^{\tau}_{i,s}\| = \|d_{i,s}U^{\tau}_{i,s}\|$ and $M^{\tau}_{i} = \sum_{s=1}^{S}\|\tilde{U}^{\tau}_{i,s}\|$. We reorder clients such that $M^{\tau}_{i} \leq M^{\tau}_{i+1}$ for all i, and k is the largest integer for which $0 < (m - N + k) \leq \frac{\sum_{j=1}^{k} M^{\tau}_{j}}{M^{\tau}_{k}}$.

τ: global round number
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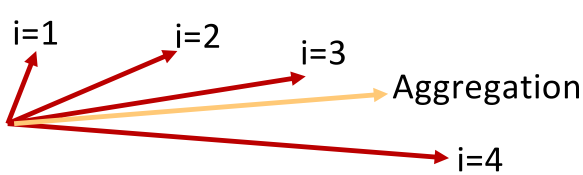
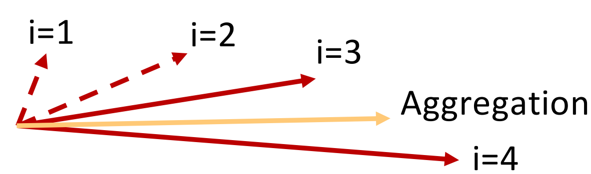
Full participation (N=4)



Partial participation (active=2)



Proof: https://tinyurl.com/mmflos

MMFL Optimal Variance-Reduced Sampling

Closed-form solution of the problem

$$p_{s|i}^{\tau} = \begin{cases} (m - N + k)\frac{\|\tilde{U}_{i,s}^{\tau}\|}{\sum_{j=1}^{k} M_j^{\tau}} & \text{if } i = 1, 2, \cdots, k, \\ \frac{\|\tilde{U}_{i,s}^{\tau}\|}{M_i^{\tau}} & \text{if } i = k+1, \cdots, N. \end{cases} \quad (5)$$

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Gradient-based Variance-Reduce Sampling (GVR)

Computing the gradient norm is too expensive on the client side!

τ: global round number
i: client index
s: model index
m: expected number of active clients
$d_{i,s}$: dataset size ratio
t: local epoch number
$\mathcal{A}_{\tau,s}$: set of active clients

 Proof: https://tinyurl.com/mmflos

Reduce computational cost

Computing the gradient norm is too expensive on the client side.

Client i loss value

$$\min_{\{p^{\tau}_{s|i}\}} \sum_{s=1}^{S} \mathbb{E}_{\mathcal{A}_{\tau,s}} \left[\| \sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p^{\tau}_{s|i}} U^{\tau}_{i,s} - \sum_{i=1}^{N} d_{i,s} U^{\tau}_{i,s} \|^2 \right]$$

$$\text{s.t. } p^{\tau}_{s|i} \geq 0, \ \sum_{s=1}^{S} p^{\tau}_{s|i} \leq 1, \ \sum_{s=1}^{S} \sum_{i=1}^{N} p^{\tau}_{s|i} = m \quad \forall i, s$$

Loss-based **V**ariance-**R**educed Sampling **(LVR)**

τ: global round number
i: client index
s: model index
m: expected number of active clients
$d_{i,s}$: dataset size ratio
t: local epoch number
$\mathcal{A}_{\tau,s}$: set of active clients

Reduce computational cost

Computing the gradient norm is too expensive on the client side.

τ: global round number
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Client i loss value

$$\min_{\{p^{\tau}_{s|i}\}} \sum_{s=1}^{S} \mathbb{E}_{\mathcal{A}_{\tau,s}} \left[\| \sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p^{\tau}_{s|i}} U^{\tau}_{i,s} - \sum_{i=1}^{N} d_{i,s} U^{\tau}_{i,s} \|^2 \right]$$

$$\text{s.t. } p^{\tau}_{s|i} \geq 0, \ \sum_{s=1}^{S} p^{\tau}_{s|i} \leq 1, \ \sum_{s=1}^{S} \sum_{i=1}^{N} p^{\tau}_{s|i} = m \quad \forall i, s$$

Now we have two methods to optimize the sampling distribution.
Can we analyze their influence on convergence speed?

Convergence proof

Based on some common assumptions (L-smoothness, mu-strongly convex, etc.)
We modified and adapted the proof from [2].

Theorem 4 (Convergence). *Let w_s^* denote the optimal weights of model s. If the learning rate $\eta_\tau = \frac{16}{\mu}\frac{1}{(\tau+1)K+\gamma}$, then*

$$\mathbb{E}\left(\|w_s^\tau - w_s^*\|^2\right) \le \frac{V_\tau}{(\tau K + \gamma_\tau)^2} \tag{413}$$

Here we define $\gamma_\tau = \max\{\frac{32L}{\mu}, 4K\sum_{i\in\mathcal{N}_s} \mathbb{1}_i^{s,\tau} P_{i,s}^\tau\}$

$V_\tau = \max\{\gamma_\tau^2 \mathbb{E}(\|w_s^0 - w_s^*\|^2), (\frac{16}{\mu})^2 \sum_{\tau'=0}^{\tau-1} z_{\tau'}\}$,

$z_{\tau'} = \mathbb{E}[Z_g^{\tau'} + Z_l^{\tau'} + Z_p^{\tau'}]$,

$\mathbb{E}[Z_g^\tau] = K\sum_{i\in\mathcal{N}_s} \frac{(d_{i,s}\sigma_{i,s})^2}{p_{s|i}^\tau} + 4LK\sum_{i\in\mathcal{N}_s} d_{i,s}\Gamma_{i,s} + \max(\frac{1}{d_{i,s}})\mathbb{E}[\sum_{i\in\mathcal{N}_s} \frac{(d_{i,s})^2\sum_{t=1}^K \|\nabla f_{i,s}(w_{i,s}^{t,\tau})\|^2}{p_{s|i}^\tau}]$,

$\mathbb{E}[Z_l^\tau] = R\mathbb{E}[|\mathcal{N}_s|\sum_{i\in\mathcal{N}_s}(\mathbb{1}_i^{s,\tau} P_{i,s}^\tau f_{i,s}(w_s^\tau) - d_{i,s} f_{i,s}(w_s^\tau))^2]$, *where* $R = \frac{2K^3\bar{\sigma}^2}{e_w^2 e_f^2 \theta}$,

$\mathbb{E}[Z_p^\tau] = (\frac{2}{\theta} + K(2 + \frac{\mu}{2L}))K^2\bar{\sigma}^2 + \frac{2K^3\bar{\sigma}^2}{\theta}\mathbb{E}[(\sum_{i\in\mathcal{N}_s} \mathbb{1}_i^{s,\tau} P_{i,s}^\tau - 1)^2]$.

[2] Ruan, Yichen, et al. "Towards flexible device participation in federated learning." *International Conference on Artificial Intelligence and Statistics*. PMLR, 2021.

Convergence proof

Based on some common assumptions (L-smoothness, mu-strongly convex, etc.)
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$$\mathbb{E}[Z_l^\tau] = R\mathbb{E}[|\mathcal{N}_s| \sum_{i \in \mathcal{N}_s} (\mathbb{1}_i^{s,\tau} P_{i,s}^\tau f_{i,s}(w_s^\tau) - d_{i,s} f_{i,s}(w_s^\tau))^2], \ \textit{where}\ R = \frac{2K^3\bar{\sigma}^2}{e_w^2 e_f^2 \theta},$$

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$\mathbb{E}[Z_g^\tau]$ -> Sampled update variance (GVR)

In the proof: https://tinyurl.com/mmflos

From the upper bound to variance term:
$\left\|\sum_{t=1}^K \nabla f_{i,s}\right\|^2 \leq K \sum_{t=1}^K \left\|\nabla f_{i,s}\right\|^2$ (GM-HM inequality)

$$= \boxed{\sum_{s=1}^S \left[\mathbb{E}\left[\left\|\sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p_{s|i}^\tau} U_{i,s}^\tau\right\|^2\right] - \left\|\sum_{i=1}^N d_{i,s} U_{i,s}^\tau\right\|^2\right]} \tag{9}$$

$$= \sum_{s=1}^S \left[\mathbb{E}\left[\sum_{i,j} \frac{d_{i,s}(U_{i,s}^\tau)^\top}{p_{s|i}^\tau} \frac{d_{j,s} U_{j,s}^\tau}{p_{s|j}^\tau} \mathbb{1}_{i,j \in \mathcal{A}_{\tau,s}}\right] - \sum_{i,j} d_{i,s} d_{j,s} (U_{i,s}^\tau)^\top U_{j,s}^\tau\right] \tag{10}$$

$$= \sum_{s=1}^S \left[\sum_{i \neq j} d_{i,s}(U_{i,s}^\tau)^\top d_{j,s} U_{j,s}^\tau + \sum_{i=1}^N \frac{d_{i,s}^2 (U_{i,s}^\tau)^\top U_{i,s}^\tau}{p_{s|i}^\tau} - \sum_{i,j} d_{i,s} d_{j,s} (U_{i,s}^\tau)^\top U_{j,s}^\tau\right] \tag{11}$$

$$= \sum_{s=1}^S \left(\sum_{i=1}^N \left(\frac{\|d_{i,s} U_{i,s}^\tau\|^2}{p_{s|i}^\tau} - \|d_{i,s} U_{i,s}^\tau\|^2\right)\right) \tag{12}$$

$$= \sum_{s=1}^S \boxed{\sum_{i=1}^N \frac{\|d_{i,s} U_{i,s}^\tau\|^2}{p_{s|i}^\tau}} - \sum_{s=1}^S \sum_{i=1}^N \|d_{i,s} U_{i,s}^\tau\|^2 \tag{13}$$

Convergence proof

Based on some common assumptions (L-smoothness, mu-strongly convex, etc.)
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$$\mathbb{E}[Z_g^\tau] = K \sum_{i\in\mathcal{N}_s} \frac{(d_{i,s}\sigma_{i,s})^2}{p_{s|i}^\tau} + 4LK \sum_{i\in\mathcal{N}_s} d_{i,s}\Gamma_{i,s} + \max(\frac{1}{d_{i,s}})\mathbb{E}[\sum_{i\in\mathcal{N}_s} \frac{(d_{i,s})^2 \sum_{t=1}^{K} \|\nabla f_{i,s}(w_{i,s}^{t,\tau})\|^2}{p_{s|i}^\tau}],$$

$$\mathbb{E}[Z_l^\tau] = R\mathbb{E}[|\mathcal{N}_s| \boxed{\sum_{i\in\mathcal{N}_s} (\mathbb{1}_i^{s,\tau} P_{i,s}^\tau f_{i,s}(w_s^\tau) - d_{i,s} f_{i,s}(w_s^\tau))^2}], \ where\ R = \frac{2K^3\bar{\sigma}^2}{e_w^2 e_f^2 \theta},$$

$$\mathbb{E}[Z_p^\tau] = (\frac{2}{\theta} + K(2 + \frac{\mu}{2L}))K^2\bar{\sigma}^2 + \frac{2K^3\bar{\sigma}^2}{\theta}\mathbb{E}[(\sum_{i\in\mathcal{N}_s} \mathbb{1}_i^{s,\tau} P_{i,s}^\tau - 1)^2].$$

$\mathbb{E}[Z_l^\tau]$ -> Sampled loss variance (LVR), with similar GM-HM inequality.

Client i loss value

$$\min_{\{p_{s|i}^\tau\}} \sum_{s=1}^{S} \mathbb{E}_{\mathcal{A}_{\tau,s}} \left[\| \sum_{i\in\mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p_{s|i}^\tau} U_{i,s}^\tau - \sum_{i=1}^{N} d_{i,s} U_{i,s}^\tau \|^2 \right]$$

$$\text{s.t. } p_{s|i}^\tau \geq 0, \ \sum_{s=1}^{S} p_{s|i}^\tau \leq 1, \ \sum_{s=1}^{S}\sum_{i=1}^{N} p_{s|i}^\tau = m \quad \forall i, s$$

Convergence proof

Based on some common assumptions (L-smoothness, mu-strongly convex, etc.)
We modified and adapted the proof from [2].

$$\mathbb{E}[Z_g^\tau] = K \sum_{i\in\mathcal{N}_s} \frac{(d_{i,s}\sigma_{i,s})^2}{p_{s|i}^\tau} + 4LK \sum_{i\in\mathcal{N}_s} d_{i,s}\Gamma_{i,s} + \max(\frac{1}{d_{i,s}})\mathbb{E}[\sum_{i\in\mathcal{N}_s} \frac{(d_{i,s})^2 \sum_{t=1}^K \|\nabla f_{i,s}(w_{i,s}^{t,\tau})\|^2}{p_{s|i}^\tau}],$$

$$\mathbb{E}[Z_l^\tau] = R\mathbb{E}[|\mathcal{N}_s| \sum_{i\in\mathcal{N}_s} (\mathbb{1}_i^{s,\tau} P_{i,s}^\tau f_{i,s}(w_s^\tau) - d_{i,s} f_{i,s}(w_s^\tau))^2], \ \textit{where}\ R = \frac{2K^3\bar{\sigma}^2}{e_w^2 e_f^2 \theta},$$

$$\mathbb{E}[Z_p^\tau] = (\frac{2}{\theta} + K(2 + \frac{\mu}{2L}))K^2\bar{\sigma}^2 + \frac{2K^3\bar{\sigma}^2}{\theta}\boxed{\mathbb{E}[(\sum_{i\in\mathcal{N}_s} \mathbb{1}_i^{s,\tau} P_{i,s}^\tau - 1)^2]}.$$

$$P_{i,s}^\tau = \frac{d_{i,s}}{p_{s|i}^\tau}$$

$\mathbb{E}[Z_p^\tau]$ -> Participation heterogeneity (or variance).

The red term is only related to dataset distribution and sampling distribution.

What is the meaning of this term?

Convergence proof

Based on some common assumptions (L-smoothness, mu-strongly convex, etc.)
We modified and adapted the proof from [2].

$$\mathbb{E}[Z_p^\tau] = \left(\frac{2}{\theta} + K\left(2 + \frac{\mu}{2L}\right)\right)K^2\bar{\sigma}^2 + \frac{2K^3\bar{\sigma}^2}{\theta}\boxed{\mathbb{E}\left[\left(\sum_{i\in\mathcal{N}_s} \mathbb{1}_i^{s,\tau} P_{i,s}^\tau - 1\right)^2\right]}.$$

$$P_{i,s}^\tau = \frac{d_{i,s}}{p_{s|i}^\tau}$$

$\mathbb{E}\left[Z_p^\tau\right]$ -> Participation heterogeneity (or variance)

Recall our global aggregation rule:

$$w_s^{\tau+1} = w_s^\tau - \sum_{i\in\mathcal{A}_{\tau,s}} \frac{d_{i,s}}{p_{s|i}^\tau} U_{i,s}^\tau$$

Can be rewritten as:

$$w_s^{\tau+1} = w_s^\tau - (H_s^\tau)^\top U_s^\tau$$

$$H_s^\tau = \left[\cdots, 1_i^{s,\tau} P_{i,s}^\tau, \cdots\right]^\top, U_s^\tau = \left[\cdots, U_{i,s}^\tau, \cdots\right]$$

Convergence proof

Based on some common assumptions (L-smoothness, mu-strongly convex, etc.)
We modified and adapted the proof from [2].

$$\mathbb{E}[Z_p^\tau] = (\tfrac{2}{\theta} + K(2 + \tfrac{\mu}{2L}))K^2\bar{\sigma}^2 + \tfrac{2K^3\bar{\sigma}^2}{\theta}\boxed{\mathbb{E}[(\textstyle\sum_{i\in\mathcal{N}_s} \mathbb{1}_i^{s,\tau} P_{i,s}^\tau - 1)^2]}.$$

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$$H_s^\tau = \left[\cdots, 1_i^{s,\tau} P_{i,s}^\tau, \cdots\right]^\top, U_s^\tau = \left[\cdots, U_{i,s}^\tau, \cdots\right]$$

$$|H_s^\tau|_1 = \sum_{i=1}^N 1_i^{s,\tau} P_{i,s}^\tau = \sum_{i=1}^N 1_i^{s,\tau} \frac{d_{i,s}}{p_{s|i}^\tau}$$

Notice $\mathbb{E}[|H_s^\tau|_1] = 1$, therefore

$$\boxed{\text{red term}} = \mathbb{E}[(|H_s^\tau|_1 - 1)^2]$$

This is also a variance!

How does this variance influence the training?

The influence of participation heterogeneity

$$|H_s^\tau|_1 = \sum_{i=1}^{N} 1_i^{s,\tau} P_{i,s}^\tau = \sum_{i=1}^{N} 1_i^{s,\tau} \frac{d_{i,s}}{p_{s|i}^\tau}$$

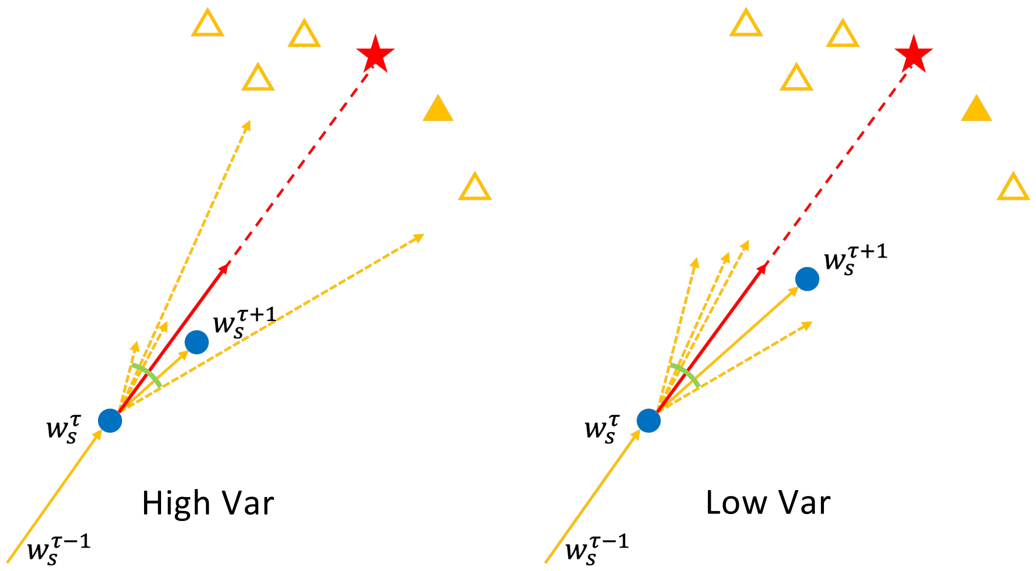
$$Var_H = \mathbb{E}[(|H_s^\tau|_1 - 1)^2]$$

High Var_H: $|H_s^\tau|_1$ may change a lot across rounds.

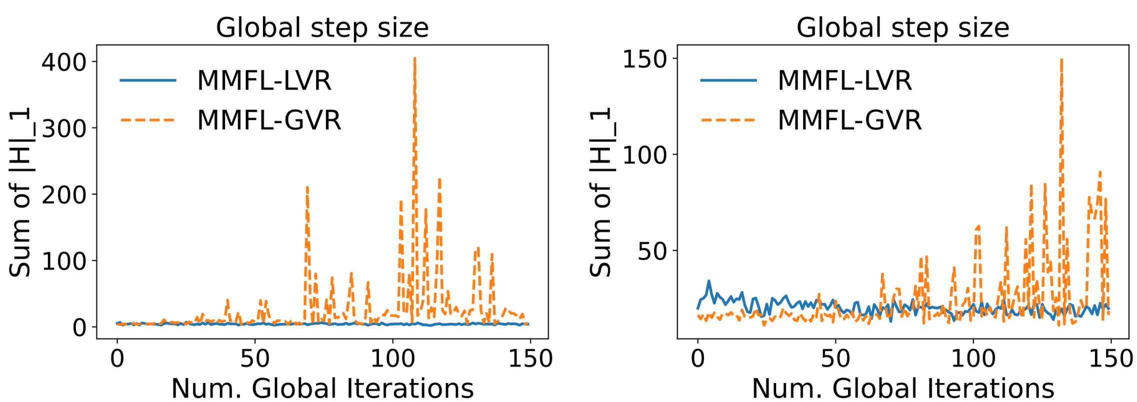
Lead to unstable "global step."

$$w_s^{\tau+1} = w_s^\tau - (H_s^\tau)^\top U_s^\tau$$

Impact the training especially at the end stage of the training.



Compare GVR and LVR



3 models | 5 models

$$w_s^{\tau+1} = w_s^{\tau} - (H_s^{\tau})^\top U_s^{\tau}$$

How to mitigate the impact of unstable “global step?”

Mitigate the impact of participation heterogeneity

Previous Aggregation Rule:

$$|H_s^\tau|_1 = \sum_{i=1}^{N} 1_i^{s,\tau} P_{i,s}^\tau = \sum_{i=1}^{N} 1_i^{s,\tau} \frac{d_{i,s}}{p_{s|i}^\tau}$$

$$w_s^{\tau+1} = w_s^\tau - (H_s^\tau)^\top U_s^\tau$$

New Aggregation Rule [3]:

$$w_s^{\tau+1} = w_s^\tau - (\sum_{i=1}^{N} d_{i,s} h_{i,s}^\tau + \sum_{i \in \mathcal{A}_{\tau,s}} \frac{d_{i,s}\left(U_{i,s}^\tau - h_{i,s}^\tau\right)}{p_{s|i}^\tau})$$

$$h_{i,s}^\tau = \begin{cases} U_{i,s}^{\tau-1}, if\ i \in \mathcal{A}_{\tau-1,s} \\ h_{i,s}^{\tau-1}, if\ i \in \mathcal{A}_{\tau-1,s} \end{cases}$$

$U_{i,s}^\tau - h_{i,s}^\tau$ should be small. Even though $|H_s^\tau|_1$ has a high variance, the impact is small.

Server stores stale updates from clients, and use stale updates to stabilize the training. **GVR***

[3] Jhunjhunwala, Divyansh, et al. "Fedvarp: Tackling the variance due to partial client participation in federated learning." *Uncertainty in Artificial Intelligence*. PMLR, 2022.

Outline

- Introduction
  - Federated learning (FL) ✓
  - Multi-model federated learning (MMFL) ✓
- Variance-reduced client sampling in a simple MMFL system ✓
- Modeling computational heterogeneity in MMFL
- Experiments

Recall

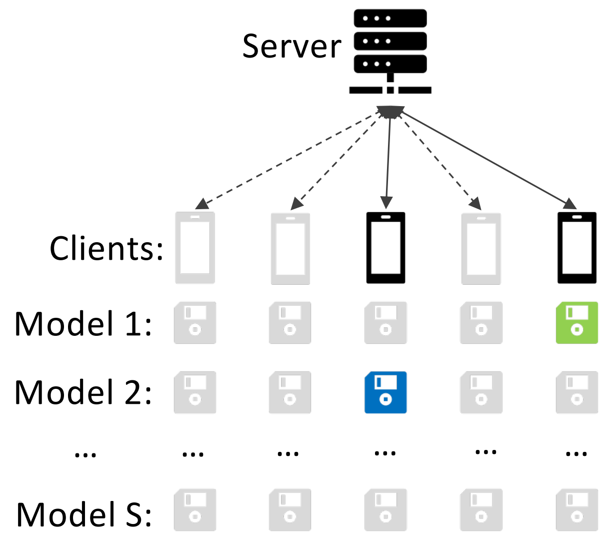
Key assumptions from previous work [1]

In each round, the server only allows partial participation, and each active client can only train one model.

1) Partial Participation: reduce communication cost

2) Only train one model: computational constraints

"Only train one model" is too ideal, without considering heterogeneity of computational abilities.



Multi-model federated learning

[1] Bhuyan, Neelkamal, Sharayu Moharir, and Gauri Joshi. "Multi-model federated learning with provable guarantees." *EAI International Conference on Performance Evaluation Methodologies and Tools*. Cham: Springer Nature Switzerland, 2022.

Multi-Model Federated Learning

Make more realistic assumptions

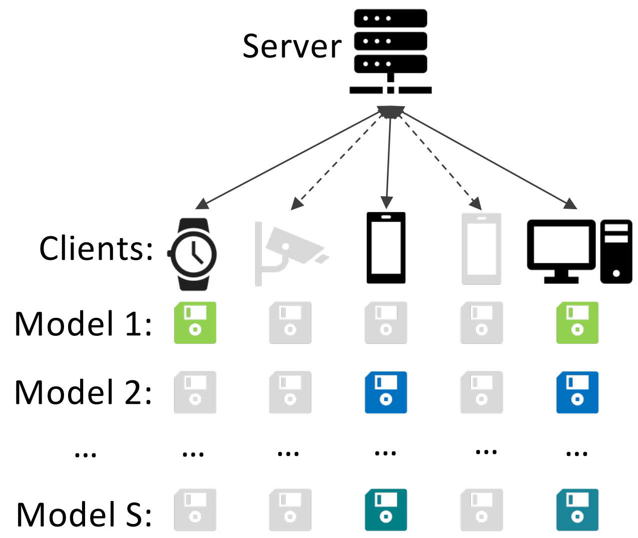
In each round, the server only allows partial participation, and each active client $\boldsymbol{i}$ can train $\boldsymbol{B_i}$ models in parallel.

1) Partial Participation: reduce communication cost

2) Client $\boldsymbol{i}$ can train $\boldsymbol{B_i}$ models ($\boldsymbol{B_i} \le \boldsymbol{S}$):

Computational constraint & heterogeneity

"Powerful" clients train more models, leading to biased convergence. How to achieve unbiased training?



Multi-model federated learning

System model for heterogeneous MMFL

For ease of description, assume client i has B_i processors, each processor (i,b) can train one model independently.

1) Adjust the aggregation rule to ensure unbiased training

$$w_s^{\tau+1} = w_s^{\tau} - \sum_{(i,b)\in\mathcal{A}_{\tau,s}} P_{(i,b),s}^{\tau} G_{(i,b),s}^{\tau}$$

$$P_{(i,b),s}^{\tau} = \frac{d_{i,s}}{B_i p_{s|(i,b)}^{\tau}}, \qquad G_{(i,b),s}^{\tau} = \eta_\tau \sum_{t=1}^{K} \nabla f_{i,s}^{t,\tau}$$

Notations:
w_s^{τ}: global model parameters
$\mathcal{A}_{\tau,s}$: set of active "processors"
$d_{i,s}$: dataset size ratio
$p_{s|(i,b)}^{\tau}$: the probability of having processor (i,b) to train model s
τ: global round index
t: local epoch index

System model for heterogeneous MMFL

For ease of description, <u>assume client i has B_i processors</u>, each processor (i,b) can train one model independently.

1) Adjust the aggregation rule to ensure unbiased training

$$w_s^{\tau+1} = w_s^{\tau} - \sum_{(i,b)\in\mathcal{A}_{\tau,s}} P_{(i,b),s}^{\tau} G_{(i,b),s}^{\tau}$$

$$\mathbb{E}\left[\sum_{i=1}^{N}\sum_{b=1}^{B_i} 1_{(i,b),s}^{\tau} \frac{d_{i,s}}{B_i p_{s|(i,b)}} G_{(i,b),s}^{\tau}\right] = \sum_{i=1}^{N} d_{i,s}\mathbb{E}\left[G_{(i,b),s}^{\tau}\right]$$

Sampling at the "processor-level"

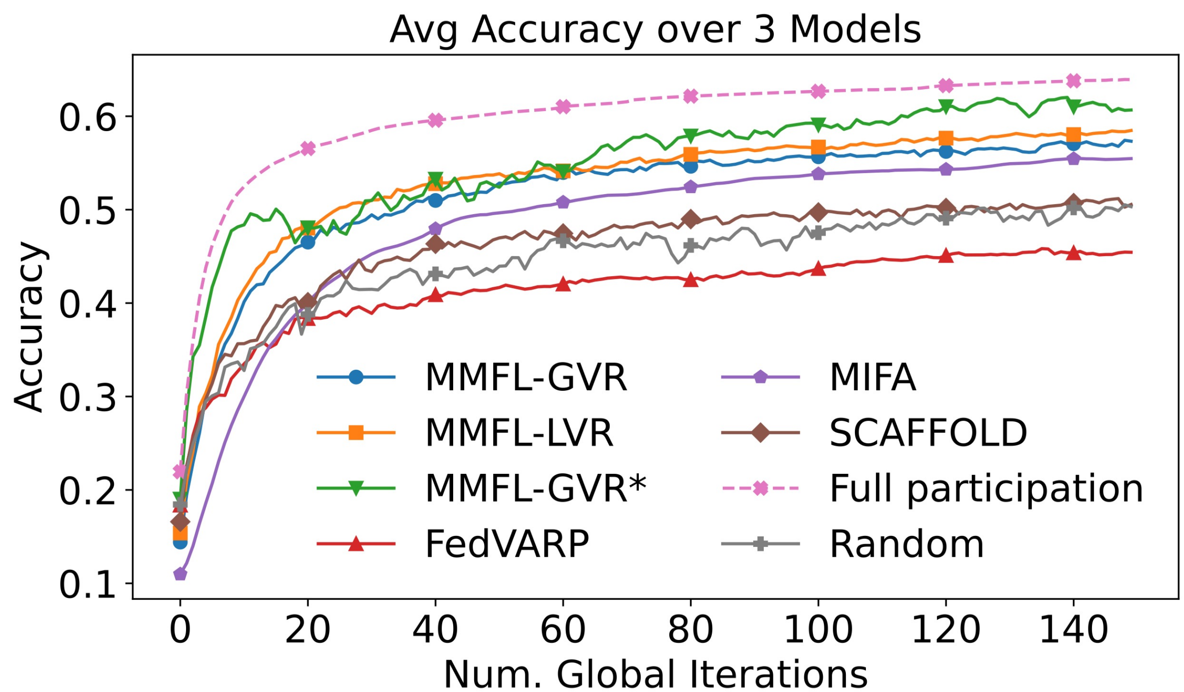
Notations:
w_s^{τ}: global model parameters
$\mathcal{A}_{\tau,s}$: set of active "processors"
$d_{i,s}$: dataset size ratio
$p_{s|(i,b)}^{\tau}$: the probability of having processor (i,b) to train model s
τ: global round index
t: local epoch index

Experiments

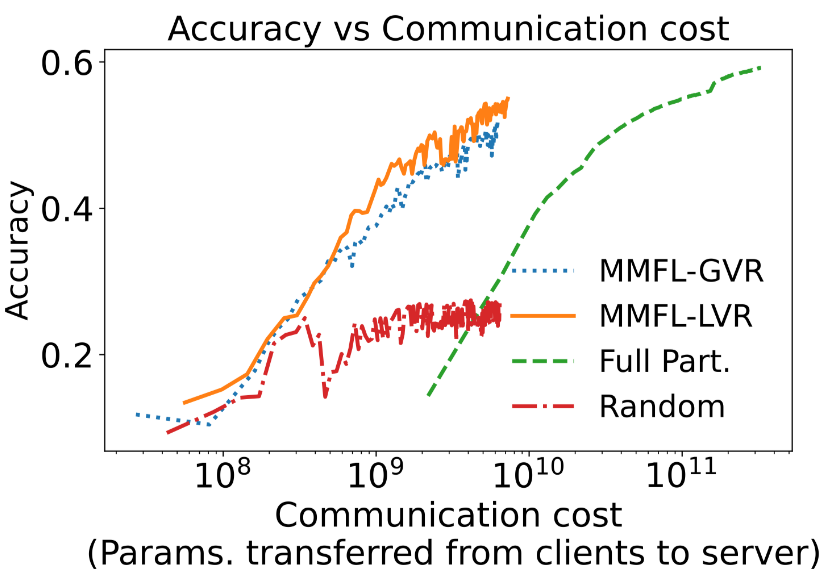
3 Models: all Fashion-MNIST.
N=120 clients
m=12 (active rate=0.1)
Each client: 30% labels.

For each model: 10% high-data clients, 90% low-data clients. 10% clients hold 52.6% data of each task.

25% clients: $B_i = 3$
50% clients: $B_i = 2$
25% clients: $B_i = 1$



Experiments



Experiments

3 Models: all Fashion-MNIST.

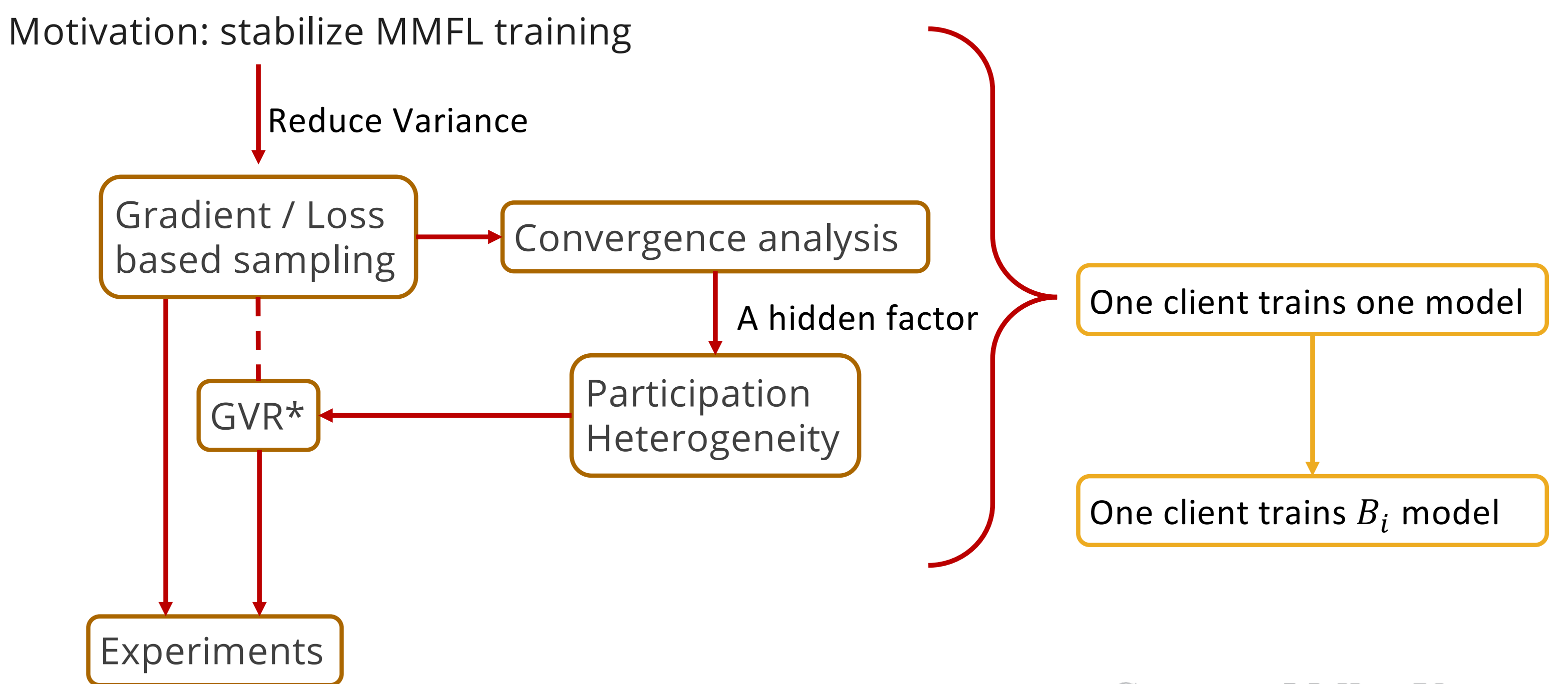
5 Models: two Fashion-MNIST, one CIFAR-10, one EMNIST, one Shakespeare.

10% clients only have data for S-1 models.

TABLE I
FINAL AVERAGE MODEL ACCURACY RELATIVE TO THAT FROM FULL PARTICIPATION (THEORETICALLY THE BEST UNDER THE SAME LOCAL TRAINING SETTINGS).

Methods	3 tasks	5 tasks	Comm. Cost	Comp. Cost	Mem. Cost
FedVARP [30]	0.712±.14	0.690±.19	Low	Low	High
MIFA [31]	0.868±.18	0.835±.18	Low	Low	High
SCAFFOLD [32]	0.794±.14	0.650±.24	Low	Low	Low
Random	0.778±.19	0.749±.23	Low	Low	Low
Full Participation	1.000±.13	1.000±.14	High	High	Low
MMFL-GVR	0.893±.14	0.842±.20	Low	High	Low
MMFL-LVR	0.912±.15	0.849±.16	Low	Low	Low
MMFL-GVR*	**0.960**±.15	**0.869**±.18	Low	High	High

Summary


Motivation: stabilize MMFL training
Reduce Variance
Gradient / Loss based sampling
Convergence analysis
A hidden factor
Participation Heterogeneity
GVR*
Experiments
One client trains one model
One client trains B_i model

Multi-Model Federated Learning

Make more realistic assumptions

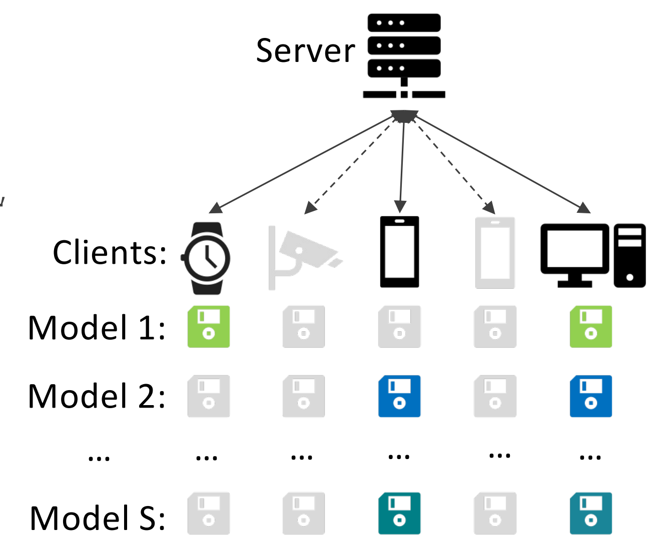
In each round, the server only allows partial participation, and each active client i can train B_i models in parallel.

Other ways to model computational heterogeneity:

1) Asynchronous training [4]

2) Flexible local epochs number [5]

3) Flexible model architectures [6]



Multi-model federated learning

[4] Askin, Baris, et al. "FedAST: Federated Asynchronous Simultaneous Training."
[5] Ruan, Yichen, et al. "Towards flexible device participation in federated learning."
[6] Park, Jong-Ik, and Carlee Joe-Wong. "Federated Learning with Flexible Architectures."