Omni-Fedge

Federated Algorithm With Bayesian Approach

Paper ID: 4632, IEEE ICASSP 2021

Sai Anuroop Kesanapalli
Dept. of Computer Science & Engineering

B. N. Bharath
Dept. of Electrical Engineering

॥ सा विद्या या विमुक्तये ॥
भारतीय प्रौद्योगिकी संस्थान धारवाड
Indian Institute of Technology Dharwad

Indian Institute of Technology Dharwad

What is Federated Learning?

- Distributed machine learning architecture where edge-devices learn shared predictive model collaboratively

Figure: FL Architecture *

*https://blog.ml.cmu.edu/2019/11/12/federated-learning-challenges-methods-and-future-directions/

Where is FL being used?

Figure: GBoard: Query prediction using FL †

† https://blog.google/products/search/gboard-now-on-android/

Where can FL be used?

Figure: Private learning among hospitals [‡]

[‡] https://www.nature.com/articles/s41746-020-00323-1

Where can FL be used?

Figure: Self-driving cars in an autonomous vehicle network [§]

[§] https://ieeexplore.ieee.org/abstract/document/9141214

What are the fundamental challenges in FL?

- Implementing FL in practice imposes several challenges

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How is FL formulated?

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- **Example:** f can be a $0-1$ loss in query prediction

How is FL formulated?

$$\theta_1^{t+1} = \theta_1^t - \eta_1 \nabla_{\theta_1} f_1(\theta_1, z_1) \qquad \theta_2^{t+1} = \theta_2^t - \eta_2 \nabla_{\theta_2} f_2(\theta_2, z_2) \qquad \theta_3^{t+1} = \theta_3^t - \eta_3 \nabla_{\theta_3} f_3(\theta_3, z_3)$$

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How is FL formulated?

- FedAvg*: $g(\theta_1^*, \theta_2^*, \theta_3^*) = \dfrac{\theta_1^* + \theta_2^* + \theta_3^*}{3}$

*http://proceedings.mlr.press/v54/mcmahan17a/mcmahan17a.pdf

Our Work: Problem Setting

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$$\min_{\theta} \mathbb{E}_{z_1 \sim D_1}\{L_1(z_1, \theta)\}$$

$$\min_{\theta} \mathbb{E}_{z_3 \sim D_3}\{L_3(z_3, \theta)\}$$

$$\min_{\theta} \mathbb{E}_{z_2 \sim D_2}\{L_2(z_2, \theta)\}$$

Our Work: Problem Setting

$$\min_{\theta} \mathbb{E}_{z_1 \sim D_1}\{L_1(z_1, \theta)\}$$

$$\min_{\theta} \mathbb{E}_{z_3 \sim D_3}\{L_3(z_3, \theta)\}$$

$$\min_{\theta} \mathbb{E}_{z_2 \sim D_2}\{L_2(z_2, \theta)\}$$

Our Work: Problem Setting

$$\min_{\theta} \hat{\mathbb{E}} L_1(z_1, \theta) \qquad \min_{\theta} \hat{\mathbb{E}} L_2(z_2, \theta) \qquad \min_{\theta} \hat{\mathbb{E}} L_3(z_3, \theta)$$

Our Work: Problem Setting

$$\min_{\theta} \hat{\mathbb{E}} L_1(z_1, \theta) \qquad \min_{\theta} \hat{\mathbb{E}} L_2(z_2, \theta) \qquad \min_{\theta} \hat{\mathbb{E}} L_3(z_3, \theta)$$

Our Work: Problem Setting

$$\min_{\theta^{(1)},\theta^{(sh)}} \hat{\mathbb{E}} L_1(z_1, \theta^{(1)}, \theta^{(sh)})$$

$$\min_{\theta^{(3)},\theta^{(sh)}} \hat{\mathbb{E}} L_3(z_3, \theta^{(3)}, \theta^{(sh)})$$

$$\min_{\theta^{(2)},\theta^{(sh)}} \hat{\mathbb{E}} L_2(z_2, \theta^{(2)}, \theta^{(sh)})$$

Our Work: Neural Network

Figure: Shared and task-specific layers of the neural network.

Our Work: Bayesian Approach

Our Work: Bayesian Approach

$$\omega_{11} e^{-\omega_{11} \hat{\mathbb{E}} L_1(z_1, \theta^{(1)}, \theta^{(sh)})}$$

$$\omega_{13} e^{-\omega_{13} \hat{\mathbb{E}} L_3(z_3, \theta^{(1)}, \theta^{(sh)})}$$

$$\omega_{12} e^{-\omega_{12} \hat{\mathbb{E}} L_2(z_2, \theta^{(1)}, \theta^{(sh)})}$$

Our Work: Bayesian Approach

$$\omega_{11}\omega_{12}\omega_{13}e^{-(\omega_{11}\hat{\mathbb{E}}L_1(z_1,\theta^{(1)},\theta^{(sh)})+\omega_{12}\hat{\mathbb{E}}L_2(z_2,\theta^{(1)},\theta^{(sh)})+\omega_{13}\hat{\mathbb{E}}L_3(z_3,\theta^{(1)},\theta^{(sh)}))}$$

- We refer to the above distribution as $Q(\theta^{(1)}, \theta^{(sh)})$ and the true joint distribution as $P(\theta^{(1)}, \theta^{(sh)})$. Note that $Q(\theta^{(1)}, \theta^{(sh)}) \neq P(\theta^{(1)}, \theta^{(sh)})$

Our Work: Bayesian Approach

$$\omega_{21}\omega_{22}\omega_{23}e^{-(\omega_{21}\hat{\mathbb{E}}L_1(z_1,\theta^{(2)},\theta^{(sh)})+\omega_{22}\hat{\mathbb{E}}L_2(z_2,\theta^{(2)},\theta^{(sh)})+\omega_{23}\hat{\mathbb{E}}L_3(z_3,\theta^{(2)},\theta^{(sh)}))}$$

- We refer to the above distribution as $Q(\theta^{(2)}, \theta^{(sh)})$ and the true joint distribution as $P(\theta^{(2)}, \theta^{(sh)})$. Note that $Q(\theta^{(2)}, \theta^{(sh)}) \neq P(\theta^{(2)}, \theta^{(sh)})$

Our Work: Bayesian Approach

$$\omega_{31}\omega_{32}\omega_{33}e^{-(\omega_{31}\hat{\mathbb{E}}L_1(z_1,\theta^{(3)},\theta^{(sh)})+\omega_{32}\hat{\mathbb{E}}L_2(z_2,\theta^{(3)},\theta^{(sh)})+\omega_{33}\hat{\mathbb{E}}L_3(z_3,\theta^{(3)},\theta^{(sh)}))}$$

- We refer to the above distribution as $Q(\theta^{(3)}, \theta^{(sh)})$ and the true joint distribution as $P(\theta^{(3)}, \theta^{(sh)})$. Note that $Q(\theta^{(3)}, \theta^{(sh)}) \neq P(\theta^{(3)}, \theta^{(sh)})$

Our Work: Maximum Likelihood Estimate

- We define our objective as minimizing the negative log of $Q(\theta^{(i)}, \theta^{(sh)})$:

$$\min_{\boldsymbol{\omega}_i} \sum_{j=1}^{N} \omega_{ij} \hat{\mathbb{E}} L_j(z_j, \boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)}) - \sum_{j=1}^{N} \log \omega_{ij} \tag{1}$$

- So our algorithm roughly is:
  1. Given $\boldsymbol{\theta}^{(sh)}$, each edge-device solves $\min_{\boldsymbol{\theta}^{(i)}} \hat{\mathbb{E}} L_i(z_i, \boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)})$ to obtain updated $\boldsymbol{\theta}^{(i)}$
  2. Using updated $\boldsymbol{\theta}^{(i)}$, the next step is to solve the optimization problem in (1) to find $\boldsymbol{\omega}_i^*$
  3. Using $\boldsymbol{\omega}_i^*$, the final step is to minimize $\sum_{i=1}^{N} \sum_{j=1}^{N} \omega_{ij}^* \hat{\mathbb{E}} L_j(z_j, \boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)})$ over $\boldsymbol{\theta}^{(sh)}$ to obtain updated $\boldsymbol{\theta}^{(sh)}$
- Performance of the neural network obtained by solving the problem in (1) in comparison to the true optimization problem needs to be investigated

Our Work: Theoretical Guarantees

Theorem

For a given neural network $\boldsymbol{\theta}$, and the $\log-\exp$ complexity, the following bound holds with a probability of at least $1-\delta$, $(\delta > 0)$

$$\inf_{\boldsymbol{\theta}} \mathbb{E}_{z_i \sim \mathcal{D}_i}\{L_i(z_i, \boldsymbol{\theta})\} \leq \inf_{\boldsymbol{\theta}^{(sh)}} \Big[\mathtt{Obj}_i(\boldsymbol{\theta}^{(sh)}) + \mathcal{R}_i(\boldsymbol{\theta})$$

$$+ \sup_{\boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)}, \boldsymbol{\omega}_i} \mathtt{KL}(Q||P) + l_{max}\sqrt{\sum_{j=1}^{N} \frac{\omega_{ij}^2}{2n_j^2} \log\left(\frac{1}{\delta}\right)} - N\Big],$$

where $\mathtt{KL}(Q||P)$ is the KL-divergence between the distributions Q and P,

$\mathtt{Obj}_i(\boldsymbol{\theta}^{(sh)}) := \inf_{\boldsymbol{\omega}_i} \sum_{j=1}^{N} \Big[\omega_{ij} \inf_{\boldsymbol{\theta}^{(i)}} \hat{\mathbb{E}} L_j(z_j, \boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)}) - \log \omega_{ij}\Big]$,

and $\log-\exp$ complexity of the neural network is given by

$$\mathcal{R}_i(\boldsymbol{\theta}) := \log \mathbb{E}_Q \sup_{\boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)}} \frac{\exp\left\{\mathbb{E}_{z \sim \mathcal{D}_i} L_i(z, \boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)})\right\}}{\Pi_{j=1}^{N} \hat{\mathbb{E}} L_j(z_j, \boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)})}, \; i = \{1, \cdots, N\}$$

Our Work: Theoretical Guarantees

Corollary

Equivalently[a], the following bound holds with a probability of at least $1-\delta$,

$$\inf_{\boldsymbol{\theta}} \sum_{i=1}^{N} \mathbb{E}_{z_i \sim \mathcal{D}_i}\{L_i(z_i, \boldsymbol{\theta})\} \leq \inf_{\boldsymbol{\theta}^{(sh)}} \Bigg[\sum_{i=1}^{N} \texttt{Obj}_i(\boldsymbol{\theta}^{(sh)}) + \sum_{i=1}^{N} \mathcal{R}_i(\boldsymbol{\theta})$$

$$+ \sum_{i=1}^{N} \sup_{\boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)}, \boldsymbol{\omega}_i} \texttt{KL}(Q||P) + \sum_{i=1}^{N} l_{max} \sqrt{\sum_{j=1}^{N} \frac{\omega_{ij}^2}{2n_j^2} \log\left(\frac{1}{\delta}\right)} - N^2 \Bigg],$$

where $\texttt{KL}(Q||P)$, $\texttt{Obj}_i(\boldsymbol{\theta}^{(sh)})$ and $\mathcal{R}_i(\boldsymbol{\theta})$ are as defined earlier.

[a] This corollary is not presented in the paper

Our Work: Algorithm

Algorithm 1: Omni-Fedge

1 `Omni-Fedge():`
2 INITIALIZE $\boldsymbol{\theta}^{sh}$ and BROADCAST (BC) to all nodes
3 **for** $t \in \{1, 2, \ldots\ldots\}$ **do**
4 **for** $i = 1, 2, \ldots, N$ **do**
5 $\boldsymbol{\theta}_t^{(i)} = \arg\min_{\boldsymbol{\theta}^{(i)}} \hat{\mathbb{E}} L_i(z_i, \boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)})$
6 Each device i BCs $\boldsymbol{\theta}_t^{(i)}$ to all other nodes $l = 1, 2, \ldots, N$ through FS.
7 COMPUTE AND SEND $\hat{\mathbb{E}} L_i(z_i, \boldsymbol{\theta}^{(j)}, \boldsymbol{\theta}^{(sh)})$ to all nodes.
8 `Minimize-Objective()`
9 to get $\boldsymbol{\omega}_i$ for all i.
10 At each node, COMPUTE $\sum_{j=1}^{N} \omega_{ji}^* \nabla_{\boldsymbol{\theta}_t^{(sh)}} \hat{\mathbb{E}} L_i(z_i, \boldsymbol{\theta}^{(j)}, \boldsymbol{\theta}^{(sh)})$ and BC it to all nodes through FS.
11 Perform GRADIENT UPDATE $\boldsymbol{\theta}_{t+1}^{(sh)} := \boldsymbol{\theta}_t^{(sh)} - \eta^{com} \gamma_t^{(i)}$, where $\gamma_t^{(i)} := \frac{1}{N}\Big(\sum_{l=1}^{N} \sum_{j=1}^{N} \omega_{jl}^* \nabla_{\boldsymbol{\theta}_t^{(sh)}} \hat{\mathbb{E}} L_l(z_l, \boldsymbol{\theta}^{(j)}, \boldsymbol{\theta}^{(sh)})\Big)$
12 GO TO step 3.
13 `Minimize-Objective():`
14 COMPUTE $\boldsymbol{\omega}_i^* = \arg\min_{\boldsymbol{\omega}_i} \Big(\sum_{j=1}^{N} \omega_{ij} \hat{\mathbb{E}} L_j(z_j, \boldsymbol{\theta}^{(i)}, \boldsymbol{\theta}^{(sh)}) - \log \prod_{j=1}^{N} \omega_{ij}\Big)$

Our Work: Algorithm (Example)

$$\hat{\theta}^{(1)} = arg \min_{\theta^{(1)}} \hat{\mathbb{E}} L_1(z_1, \theta^{(1)}, \theta^{(sh)})$$

$$\hat{\theta}^{(2)} = arg \min_{\theta^{(2)}} \hat{\mathbb{E}} L_2(z_2, \theta^{(2)}, \theta^{(sh)})$$

$$\hat{\theta}^{(3)} = arg \min_{\theta^{(3)}} \hat{\mathbb{E}} L_3(z_3, \theta^{(3)}, \theta^{(sh)})$$

Our Work: Algorithm (Example)

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Our Work: Algorithm (Example)

$$\omega_1^* = arg \min_{\omega_{11},\omega_{12},\omega_{13}} \left(\omega_{11}\hat{\mathbb{E}}L_1(z_1,\hat{\theta}^{(1)},\theta^{(sh)}) + \omega_{12}\hat{\mathbb{E}}L_2(z_2,\hat{\theta}^{(1)},\theta^{(sh)}) + \omega_{13}\hat{\mathbb{E}}L_3(z_3,\hat{\theta}^{(1)},\theta^{(sh)}) - \log \omega_{11}\omega_{12}\omega_{13}\right)$$

$$\omega_2^* = arg \min_{\omega_{21},\omega_{22},\omega_{23}} \left(\omega_{21}\hat{\mathbb{E}}L_1(z_1,\hat{\theta}^{(2)},\theta^{(sh)}) + \omega_{22}\hat{\mathbb{E}}L_2(z_2,\hat{\theta}^{(2)},\theta^{(sh)}) + \omega_{23}\hat{\mathbb{E}}L_3(z_3,\hat{\theta}^{(2)},\theta^{(sh)}) - \log \omega_{21}\omega_{22}\omega_{23}\right)$$

$$\omega_3^* = arg \min_{\omega_{31},\omega_{32},\omega_{33}} \left(\omega_{31}\hat{\mathbb{E}}L_1(z_1,\hat{\theta}^{(3)},\theta^{(sh)}) + \omega_{32}\hat{\mathbb{E}}L_2(z_2,\hat{\theta}^{(3)},\theta^{(sh)}) + \omega_{33}\hat{\mathbb{E}}L_3(z_3,\hat{\theta}^{(3)},\theta^{(sh)}) - \log \omega_{31}\omega_{32}\omega_{33}\right)$$

Our Work: Algorithm (Example)

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Our Work: Algorithm (Example)

$$\alpha_1 = \omega_{11}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_1(z_1, \hat{\theta}^{(1)}, \theta^{(sh)}) + \omega_{21}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_1(z_1, \hat{\theta}^{(2)}, \theta^{(sh)}) + \omega_{31}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_1(z_1, \hat{\theta}^{(3)}, \theta^{(sh)})$$

$$\alpha_2 = \omega_{12}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_2(z_2, \hat{\theta}^{(1)}, \theta^{(sh)}) + \omega_{22}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_2(z_2, \hat{\theta}^{(2)}, \theta^{(sh)}) + \omega_{32}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_2(z_2, \hat{\theta}^{(3)}, \theta^{(sh)})$$

$$\alpha_3 = \omega_{13}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_3(z_3, \hat{\theta}^{(1)}, \theta^{(sh)}) + \omega_{23}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_3(z_3, \hat{\theta}^{(2)}, \theta^{(sh)}) + \omega_{33}^* \nabla_{\theta^{(sh)}} \hat{\mathbb{E}} L_3(z_3, \hat{\theta}^{(3)}, \theta^{(sh)})$$

Our Work: Algorithm (Example)

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Our Work: Algorithm (Example)

Our Work: Algorithm (Example)

Our Work: Algorithm (Example)

$$\theta_{t+1}^{(sh)} = \theta_t^{(sh)} - \eta_{com}\frac{(\alpha_1 + \alpha_2 + \alpha_3)}{3}$$

$$\theta_{t+1}^{(sh)} = \theta_t^{(sh)} - \eta_{com}\frac{(\alpha_1 + \alpha_2 + \alpha_3)}{3}$$

$$\theta_{t+1}^{(sh)} = \theta_t^{(sh)} - \eta_{com}\frac{(\alpha_1 + \alpha_2 + \alpha_3)}{3}$$

Our Work: Algorithm (Example)

Our Work: Experimental Setup

Type of Data	Training samples per node	Testing samples per node
MNIST I.I.D.	2488	3112
MNIST non-I.I.D.	667	834
FMNIST I.I.D.	3111	3889
FMNIST non-I.I.D.	745	933

Figure: Sample MNIST and FMNIST images

Our Work: Experimental Results

MNIST non-I.I.D.						
Communication Rounds	Average Training Accuracy %			Average Testing Accuracy %		
	Omni-Fedge	FedSGD	Local	Omni-Fedge	FedSGD	Local
200	87.9460	69.0548	91.4729	86.7679	66.3119	88.2205
400	91.3037	89.4102		89.2289	85.7331	
600	92.6017	92.3645		90.4470	88.0901	
800	93.5092	94.2168		90.7090	89.5451	
1000	94.3296	94.6999		91.0831	89.8870	

MNIST I.I.D.						
Communication Rounds	Average Training Accuracy %			Average Testing Accuracy %		
	Omni-Fedge	FedSGD	Local	Omni-Fedge	FedSGD	Local
200	95.9486	96.6720	93.7714	92.4871	91.4653	91.4139
400	96.0531	96.6077		92.8920	91.4460	
600	96.2138	96.7283		93.4383	91.3882	
800	96.5916	97.0659		93.7596	91.4139	
1000	96.7122	97.1785		93.9846	91.5103	

Figure: Results using MNIST

Our Work: Experimental Results

FMNIST non-I.I.D.						
Communication Rounds	Average Training Accuracy %			Average Testing Accuracy %		
	Omni-Fedge	FedSGD	Local	Omni-Fedge	FedSGD	Local
200	68.9873	55.0306	79.4835	67.7913	53.9147	76.9388
400	75.7603	71.6913		74.0101	68.5354	
600	75.1834	73.4478		73.8718	71.8304	
800	78.7734	77.5678		77.0488	74.7875	
1000	70.2321	77.3219		68.7105	75.2830	

FMNIST I.I.D.						
Communication Rounds	Average Training Accuracy %			Average Testing Accuracy %		
	Omni-Fedge	FedSGD	Local	Omni-Fedge	FedSGD	Local
200	86.5188	86.9174	80.3286	82.9005	82.4479	78.5240
400	87.5731	87.8239		84.4073	83.1525	
600	86.8338	87.6438		84.0679	82.4788	
800	86.4802	87.9781		84.0782	83.0496	
1000	87.3481	88.1903		84.7621	83.0651	

Figure: Results using FMNIST

Our Work: Conclusion

- Considered a specific FL problem under a non-I.I.D. data setting
- Provided a sound theoretical framework for the proposed algorithm based on a Bayesian approach
- Introduced a new complexity measure as a consequence of the PAC bound

Our Work: Current status

- Analysing the following:
  1. Stragglers
  2. log – exp complexity
  3. Convergence
  4. Efficient communication

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Contact

- **Sai Anuroop Kesanapalli**

  Dept. of Computer Science and Engineering, Indian Institute of Technology Dharwad

  - Email ID: ksanu1998@gmail.com, 170030035@iitdh.ac.in

- **Dr. B. N. Bharath**

  Dept. of Electrical Engineering, Indian Institute of Technology Dharwad

  - Email ID: bharathbn@iitdh.ac.in

Thank you!