Efficient Beamforming for Over-the-Air Federated Learning Model Aggregation

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Abstract

In this paper, we propose low algorithms to minimize MSE for over-the-air computation (AirComp) federated learning (FL), improving aggregation accuracy, convergence, and robustness.

Ⅰ. Introduction

Centralized aggregation in Internet of Things (IoT) networks suffers from prohibitive latency, bandwidth, and privacy issues. Although AirComp-based FL reduces uplink load, it incurs aggregation MSE from channel noise and misalignment. This paper presents low complexity joint beamforming algorithms to minimize MSE.

Ⅱ. System Model and Beamforming Vector Design

We consider a wireless FL framework where K devices each perform E local updates and send a unit-power signal x_k over channel $\boldsymbol{h}_k \in \mathbb{C}^N$ to a Base station (BS) with N antennas using AirComp. The BS receives $y = \sum_{k=1}^{K} \mathbf{h}_k b_k x_k + \mathbf{n}$, with $|b_k|^2 \leq P_{\max}$ and $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2 I)$. Applying beamformer $\mathbf{a} \in \mathbb{C}^N$, it estimates the average update via $\frac{1}{K}\mathbf{a}^H\mathbf{y} = \frac{1}{K}\sum_{k=1}^{K} \mathbf{a}^H \mathbf{h}_k b_k x_k + \frac{1}{K}\mathbf{a}^H\mathbf{n}$. The MSE is defined as $\mathbb{E}\left[\left|\frac{1}{K}\mathbf{a}^H\mathbf{y} - \frac{1}{K}\sum_{k=1}^{K} x_k\right|^2\right]$. Minimizing MSE under $|b_k|^2 \leq P_{\max}$, yields

$$\text{(P1)} \min_{\mathbf{a},\mathbf{b}} \sum_{k=1}^{K} |\mathbf{a}^H\mathbf{h}_k b_k - 1|^2 + \sigma^2 \|\mathbf{a}\|^2 \quad \text{s.t.} \quad |b_k|^2 \leq P_{\max},\ \forall k. \tag{1}$$

Using the misalignment allowed optimization (Miso) approach and, since the constraint is not convex, we employ a majorization minimization (MM) algorithm to derive a series of convex subproblems

$$\text{(P2)} \left(\mathbf{a}^{(l+1)}, \mathbf{t}^{(l+1)}\right) = \underset{\mathbf{a},\mathbf{t}}{\operatorname{argmin}} \sum_{k=1}^{K} (t_k - 1)^2 + \sigma^2 \|\mathbf{a}\|^2 \quad \text{s.t.} \quad t_k^2 \leq P_{\max}\psi_k\left(\mathbf{a}, \mathbf{a}^{(l)}\right),\ \forall k. \tag{2}$$

where $\psi_k(\mathbf{a}, \mathbf{a}^{(l)}) \equiv 2\mathrm{Re}\{(\mathbf{a}^{(l)})^H \mathbf{h}_k \mathbf{h}_k^H \mathbf{a}\} - |\mathbf{h}_k^H \mathbf{a}^{(l)}|^2$.

Since (P2) is a convex problem, we solve it with the interior point method using the CVX toolbox, which is called Miso-CVX. Since its complexity is $O(N^3)$, we propose a low-complexity algorithm based on the projected subgradient method, called Miso-Subgradient

Repeat

$$a \leftarrow \frac{P_{\max}}{\sigma^2}\mathbf{H}\mathrm{diag}(\boldsymbol{\lambda})\mathbf{H}^H\mathbf{a}^{(l)}$$

$$t_k \leftarrow \frac{1}{1+\lambda_k}, \forall k$$

$$\lambda_k \leftarrow \max\left(\lambda_k - \xi\left(P_{\max}\psi_k\left(\mathbf{a}, \mathbf{a}^{(l)}\right) - t_k^2\right), 0\right), \forall k$$

$$j \leftarrow j+1$$

Until convergence (3)

where we define $\mathbf{H} = [\mathbf{h}_1 \cdots \mathbf{h}_K] \in \mathbb{C}^{N\times K}$ and λ_k is the dual variable associated with the k-th inequality

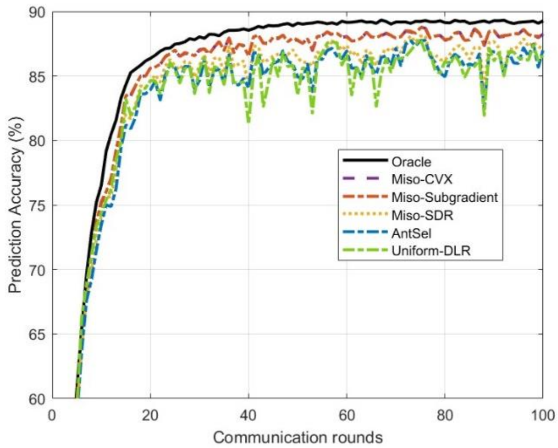

Fig. 1. The prediction accuracy of CNN with SVHN datasets (K = 10, N = 20, SNR = -15dB).

We compare our proposed algorithm with Oracle-AirComp, without aggregation error, Miso-SDR[1], AntSel[2], and Uniform-DLR[3]. Fig. 1 shows that the proposed algorithm exhibits at most a 2% point deviation from the Oracle algorithm, but the other algorithms deviate up to 5% point.

Ⅲ. Conclusion

In this paper we proposed efficient beamforming vector design algorithm for AirComp federated learning. The proposed algorithm shows superior robustness and learning performance than existing algorithms.

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