NOMA-Based Federated Learning under Imperfect SIC

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불완전한 SIC 환경에서의 NOMA 기반 연합학습

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Abstract

Non-orthogonal multiple access (NOMA)-based federated learning (FL) suffers from residual-interference accumulation under imperfect successive interference cancellation (SIC), which distorts uplink aggregation. We derive a convergence upper bound for non-independent and identically distributed (non-IID) FL that jointly accounts for data heterogeneity and uplink bit errors, and formulate an optimal client selection problem that minimizes the bound each round. Simulations on non-IID MNIST show faster convergence and higher accuracy than a Benchmark threshold-based selection scheme.

Ⅰ. Introduction

As data-privacy regulations tighten, federated learning (FL) enables collaborative learning without sharing raw data but suffers from a severe uplink bottleneck when many clients participate [1]. Non-orthogonal multiple access (NOMA)-based FL mitigates this by allowing simultaneous transmissions over the same time-frequency resources. In practice, however, imperfect successive interference cancellation (SIC) leaves residual interference that accumulates across decoding stages, causing error propagation and distorting the aggregated update. As a result, increasing participation does not necessarily improve learning performance, especially in non-independent and identically distributed (non-IID) settings.

Existing studies[1,2] often overlook this by assuming perfect SIC or excluding users solely based on channel quality [3]. In this paper, we derive a convergence upper bound for NOMA-based FL under imperfect SIC that jointly captures data heterogeneity and communication-induced aggregation distortion and formulate an optimal client selection problem based on the derived bound.

Ⅱ. System Model

We consider a NOMA-based FL system consisting of a central server and N clients, where each client i holds a local dataset D_i following a non-IID distribution. In each communication round t, the server selects K clients to transmit their local model update Δw_t^i simultaneously over the same time-frequency resources. The received signal y_t at the server is the superposition of transmitted signals from the K clients, expressed as $y_t = \sum_{i=1}^{K} h_i \sqrt{P_i} x_i + n_t$,where h_i and P_i denote the channel coefficient and transmit power, respectively.

The server employs a successive interference cancellation receiver to decode signals in descending order of signal power. However, in practical scenarios with imperfect SIC, decoding errors from previous stages $\left(\hat{x}_j^t \neq x_j^t\right)$ lead to residual interference accumulation. Consequently, the SINR for the i-th decoded client is modeled as:

$$SINR_i = \frac{P_i |h_i|^2}{\sum_{j=1}^{i-1} P_j \left|h_j\right|^2 \left|x_j - \hat{x}_j\right|^2 + \sum_{m=i+1}^{K} 2P_m |h_m|^2 + N_0} \quad (1)$$

where the denominator explicitly captures the accumulated error propagation from previously decoded users $(j < i)$and the inter-user interference from undecoded users $(m > i)$

III. Convergence of NOMA-based FL under Imperfect SIC

To optimize client selection, we derive a convergence upper bound of the global loss function that jointly captures learning-related effects under non-IID data heterogeneity Γ and communication-induced distortion due to uplink bit errors. Under standard assumptions, the bound provides an explicit objective for participant selection.

Theorem 1. Let P_b^i denote the bit error rate of client i. The expected loss at round $t+1$ is bounded as:

$$
[f(w_{t+1})] \leq \mathbb{E}[f(w_t)] - \frac{\eta}{2}\sum_{e=0}^{E-1}\mathbb{E}\left|\left|\nabla \mathrm{f}(\overline{\mathrm{w}}_{t,e})\right|\right|^2
$$
$$
+2\eta L\sum_{e=0}^{E-1}\mathbb{E}[f(\overline{w}_{t,e} - f^* + \Gamma]
$$
$$
-\frac{\eta}{2K}(1 - L\eta - 8\eta^2 L^2 E(\mathrm{E}-1))\sum_{e=0}^{E-1}\sum_{i=1}^{K}\mathbb{E}\left|\left|\nabla \mathrm{f_i}(w_{t,e}^i)\right|\right|^2
$$
$$
+\left(\frac{\eta^3 L^2}{K}(1+K)E(E-1) + \frac{L\eta^2}{2K}E\right)\sigma^2
$$
$$
+\left(\frac{L}{2}+\frac{1}{2\eta}\right)\frac{d\delta^2}{K}\frac{4^Q-1}{3}Q\sum_{i=1}^{K}P_b^i \qquad (2)
$$

This bound shows that the expected loss depends on both the participant composition and the uplink error characteristics under imperfect SIC. In particular, test performance is not necessarily monotonic in the number of participating clients because interference accumulation can increase aggregation distortion as participation grows. Therefore, rather than maximizing the number of clients, we select the participating client set by minimizing the derived upper bound.

IV. Optimal Client Selection

To minimize the convergence upper bound derived in Theorem 1, we define a simplified objective function $G(K)$ with a weighting factor $\lambda \in [0,1]$:

$$
G(K) = \lambda g_{gain} + (1-\lambda) g_{error} \qquad (3)
$$

Here, g_{gain} represent the learning gain term that accelerates convergence, while g_{error} denotes the communication cost term that impedes it. The optimal number of clients is determined by $S_t = argmin\, G(K)$, effectively balancing data diversity against error propagation. we obtain S_t by a brute-force search over all feasible client subsets, selecting the set that minimizes $G(K)$.

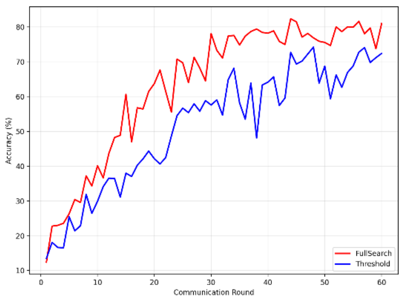

Figure 1. Test accuracy versus communication round

V. Experimental Results

We evaluate the proposed optimal client selection method in a NOMA-based FL system with imperfect SIC. Experiments are conducted on non-IID MNIST with $N = 10$ clients, where each client holds samples from only a subset of labels, and the wireless channel follows Rayleigh fading. We compare the proposed method against a benchmark threshold-based selection scheme (Benchmark) that excludes clients whose BER exceeds 0.3[4]. Results show that the proposed method converges faster and achieves over 90% final accuracy, while Benchmark saturates around 80%, demonstrating the benefit of bound-minimizing participant selection under imperfect SIC.

VI. Conclusion

This paper proposed an optimal client selection method for NOMA-based FL in non-IID environments under imperfect SIC. We derived a convergence upper bound that jointly captures data heterogeneity and uplink-induced aggregation distortion, and formulated a bound-minimizing selection problem to determine the participant set each round. Simulations show faster convergence and higher final accuracy than Benchmark, even when the average uplink SINR is lower, highlighting the need for learning-aware selection beyond physical-layer metrics. Future work will develop low-complexity approximations to the exact selection and further characterize the weighting parameter under varying heterogeneity and channel conditions.

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