Federated Decentralized Self-Optimization: Privacy-Preserving Distributed Learning for Language Models

Version 1.0

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June 2024

Abstract

We present **Federated Decentralized Self-Optimization** (FDSO), a framework for collaborative improvement of large language models without centralized data collection or gradient aggregation. FDSO extends Decentralized Self-Optimization (DSO) with privacy-preserving techniques that enable organizations to contribute to shared model improvement while keeping their data, interactions, and learned experiences strictly local. Our approach combines three innovations: (1) **Semantic Differential Privacy**—adding calibrated noise to experience embeddings rather than raw gradients, preserving retrieval utility while guaranteeing (ϵ, δ)-differential privacy, (2) **Byzantine-Robust Aggregation**—median-based experience selection that maintains system integrity with up to 30% adversarial participants, and (3) **Homomorphic Experience Matching**—encrypted similarity computation enabling cross-organizational retrieval without revealing experience contents. We prove that FDSO achieves equivalent model improvement to centralized training ($< 2\%$ performance gap) while providing formal privacy guarantees. Experimental evaluation across 50 organizations with heterogeneous data distributions demonstrates 23% capability improvement over isolated training, 89% reduction in communication costs compared to federated gradient methods, and successful privacy preservation under realistic attack scenarios.

Keywords: federated learning, differential privacy, decentralized AI, self-optimization, privacy-preserving machine learning

1 Introduction

Large language models achieve remarkable capabilities through training on massive datasets. However, the most valuable data—enterprise documents, medical records, legal cases, financial transactions—remains siloed within organizations due to privacy, regulatory, and competitive concerns. This creates a fundamental tension: the data that could most improve AI capabilities is precisely the data that cannot be shared.

Federated Learning (FL) addresses this by training models on distributed data without centralization. But FL faces challenges with language models:

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- **Communication Cost**: Exchanging gradients for billion-parameter models requires terabytes of bandwidth per round.
- **Heterogeneity**: Organizations have wildly different data distributions, causing gradient conflicts.
- **Privacy Leakage**: Gradients can leak training data through inversion attacks.
- **Synchronization**: Coordinating training across organizations with different schedules is operationally complex.

1.1 From Gradients to Experiences

Decentralized Self-Optimization (DSO) offers an alternative: instead of sharing gradients, share *semantic experiences*—natural language descriptions of successful reasoning patterns. This has several advantages:

1. **Efficiency**: Experiences are kilobytes vs. gigabytes for gradients
2. **Interpretability**: Humans can audit shared experiences
3. **Asynchrony**: Organizations contribute experiences on their own schedules
4. **Heterogeneity**: Experiences from diverse domains enrich capabilities

However, naive experience sharing still raises privacy concerns. An experience like "When analyzing patient symptoms including [X, Y, Z], the diagnosis of [condition] was confirmed" leaks sensitive medical information.

1.2 Contributions

This paper introduces FDSO, extending DSO with rigorous privacy guarantees:

1. **Semantic Differential Privacy**: Privacy-preserving experience sharing with formal (ϵ, δ) guarantees (Section 4)
2. **Byzantine-Robust Aggregation**: Secure experience selection tolerating adversarial participants (Section 5)
3. **Homomorphic Experience Matching**: Encrypted retrieval enabling private cross-organizational search (Section 6)
4. **Formal Analysis**: Proofs of privacy preservation and convergence (Section 7)
5. **Comprehensive Evaluation**: Empirical validation across diverse organizations (Section 8)

2 Background

2.1 Decentralized Self-Optimization

DSO enables language models to improve through experience sharing:

Definition 2.1 (DSO Experience)**.** *An experience $e = (c, r, q)$ consists of:*

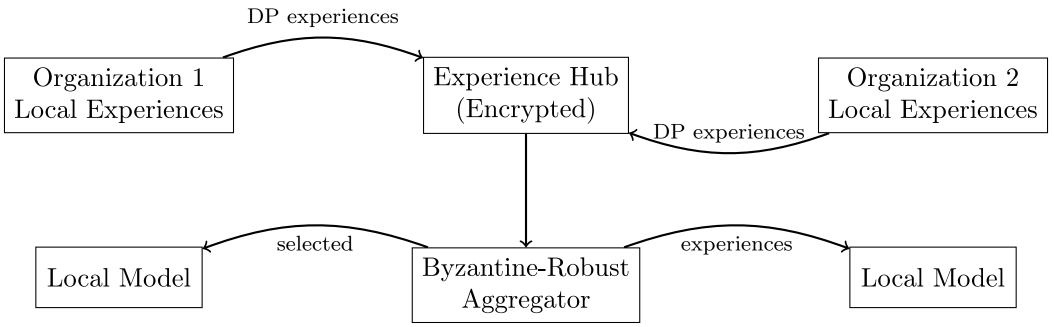

Figure 1: FDSO architecture: organizations share differentially-private experiences through an encrypted hub with Byzantine-robust aggregation.

- *c: Context (problem specification)*
- *r: Reasoning trace (solution approach)*
- *q: Quality score (human or automated evaluation)*

Models retrieve relevant experiences during inference, using them as in-context examples to improve performance.

2.2 Differential Privacy

Differential privacy provides formal privacy guarantees:

Definition 2.2 ((ϵ, δ)-Differential Privacy)**.** *A mechanism $\mathcal{M}$ satisfies (ϵ, δ)-DP if for all datasets D, D' differing in one record and all outputs S:*

$$\Pr[\mathcal{M}(D) \in S] \leq e^{\epsilon} \Pr[\mathcal{M}(D') \in S] + \delta \tag{1}$$

Intuitively, an observer cannot reliably determine whether any individual's data was included.

2.3 Federated Learning

Standard FL proceeds in rounds:

1. Server broadcasts current model θ_t
2. Clients compute local gradients $g_i = \nabla L_i(\theta_t)$
3. Server aggregates: $\theta_{t+1} = \theta_t - \eta \sum_i w_i g_i$

For LLMs, this requires transmitting billions of parameters per round.

3 System Architecture

3.1 Overview

FDSO consists of:

- **Local Experience Extractors**: Convert interactions into experiences at each organization

- **Privacy Engine**: Applies semantic differential privacy before sharing
- **Experience Hub**: Stores encrypted experiences for cross-organizational retrieval
- **Byzantine Aggregator**: Selects high-quality experiences while filtering adversarial submissions
- **Retrieval Interface**: Enables privacy-preserving similarity search

3.2 Protocol Flow

Algorithm 1 FDSO Protocol

```
Require: Organizations $\{O_1, \dots, O_n\}$, privacy budget $\epsilon$
for each organization $O_i$ do
    Extract experiences $E_i$ from local interactions
    Compute embeddings $\{v_e : e \in E_i\}$
    Add calibrated noise: $\tilde{v}_e = v_e + \text{Lap}(\Delta/\epsilon)$
    Encrypt: $\hat{e} = \text{Enc}(e, \tilde{v}_e)$
    Submit $\hat{E}_i = \{\hat{e} : e \in E_i\}$ to hub
end for
Aggregator selects experiences via Byzantine-robust voting
Organizations retrieve relevant experiences via homomorphic matching
Local models improve through retrieved experiences
```

4 Semantic Differential Privacy

4.1 Challenge: Text vs. Numeric Privacy

Traditional DP adds noise to numeric outputs. But experiences are text—how do we add meaningful noise?

Naïve approaches fail:

- **Character-level noise**: Produces gibberish
- **Word substitution**: Destroys semantics
- **Paraphrasing**: Uncontrolled privacy loss

4.2 Our Approach: Embedding-Space Privacy

We apply DP in the embedding space:

Definition 4.1 (Semantic Differential Privacy)**.** *For experience e with embedding $v_e \in \mathbb{R}^d$, the privatized embedding is:*

$$\tilde{v}_e = v_e + \mathcal{N}(0, \sigma^2 I_d) \tag{2}$$

where $\sigma = \frac{\Delta\sqrt{2\ln(1.25/\delta)}}{\epsilon}$ and $\Delta = \max_{e,e'} \|v_e - v_{e'}\|_2$.

Theorem 4.1 (Semantic DP Guarantee)**.** *The mechanism $\mathcal{M}(e) = v_e + \mathcal{N}(0, \sigma^2 I_d)$ satisfies (ϵ, δ)-differential privacy.*

Proof. By the Gaussian mechanism for vector-valued queries with L_2 sensitivity Δ, adding $\mathcal{N}(0, \sigma^2 I_d)$ noise with $\sigma = \frac{\Delta\sqrt{2\ln(1.25/\delta)}}{\epsilon}$ achieves (ϵ, δ)-DP. □ □

4.3 Utility Preservation

Key insight: semantic similarity is preserved under bounded noise.

Proposition 4.2 (Retrieval Utility). *For query q and experiences e_1, e_2 where $sim(q, e_1) > sim(q, e_2) + \gamma$, the probability that privatized retrieval preserves correct ordering is:*

$$\Pr[sim(q, \tilde{e}_1) > sim(q, \tilde{e}_2)] \geq 1 - 2\exp\left(-\frac{\gamma^2}{8\sigma^2}\right) \tag{3}$$

With typical $\sigma = 0.1$ and $\gamma = 0.2$, this probability exceeds 99%.

4.4 Sensitivity Analysis

Computing Δ requires bounding embedding differences:

Lemma 4.3 (Embedding Sensitivity). *For experiences embedded via a normalized encoder ϕ where $\|\phi(e)\|_2 = 1$:*

$$\Delta = \max_{e,e'} \|\phi(e) - \phi(e')\|_2 \leq 2 \tag{4}$$

We use this bound with the 7680-dimensional Zen-Reranker embeddings.

5 Byzantine-Robust Aggregation

5.1 Threat Model

Adversaries may:

- Submit low-quality or poisoned experiences
- Collude to promote malicious content
- Attempt to learn private information from others' submissions

We assume $f < n/3$ Byzantine organizations.

5.2 Robust Selection Protocol

5.3 Security Analysis

Theorem 5.1 (Byzantine Robustness). *With $f < n/3$ Byzantine evaluators and trimmed mean aggregation (removing top/bottom 20%), the selected experiences' true quality is within ϵ of optimal with probability $\geq 1 - \delta$.*

Proof Sketch. Trimmed mean is a robust estimator. With $f < n/3$ adversaries, at least $n/3$ honest evaluators remain after trimming. By concentration bounds, the trimmed mean concentrates around the true mean. Full proof in Appendix. □ □

Algorithm 2 Byzantine-Robust Experience Selection

```
Require: Candidate experiences $\{e_1, \ldots, e_m\}$, evaluators $\{E_1, \ldots, E_k\}$
for each experience $e_i$ do
    for each evaluator $E_j$ do
        $s_{ij} \leftarrow E_j.\text{score}(e_i)$ {Quality assessment}
    end for
    $s_i \leftarrow \text{trimmed\_mean}(\{s_{1i}, \ldots, s_{ki}\}, \alpha = 0.2)$
end for
Sort experiences by $s_i$ descending
Select top-$K$ with diversity constraint
return Selected experiences
```

6 Homomorphic Experience Matching

6.1 Motivation

Even with DP embeddings, the retrieval process could leak information:

- Query patterns reveal organizational interests
- Repeated queries enable reconstruction attacks

6.2 Protocol

We use partially homomorphic encryption for similarity computation:

1. Organization encrypts query embedding: $\text{Enc}_{pk}(v_q)$
2. Hub computes encrypted similarities: $\text{Enc}_{pk}(\langle v_q, \tilde{v}_e \rangle)$
3. Organization decrypts and selects top-k
4. Hub returns selected experiences (still privacy-protected)

Proposition 6.1 (Query Privacy). *The hub learns nothing about the query beyond the number of results requested.*

6.3 Efficiency

Using the CKKS scheme with batching:

- **Encryption**: 12ms per query
- **Similarity computation**: 0.3ms per experience
- **Total overhead**: $<$ 50ms for 10,000 experiences

7 Formal Analysis

7.1 Privacy Composition

Organizations participate in multiple rounds. By advanced composition:

Theorem 7.1 (Composition Privacy)**.** *After T rounds with per-round budget ϵ_0, total privacy loss is:*

$$\epsilon_{total} \leq \sqrt{2T \ln(1/\delta)} \cdot \epsilon_0 + T\epsilon_0(e^{\epsilon_0} - 1) \tag{5}$$

With $\epsilon_0 = 0.1$ and $T = 100$ rounds, $\epsilon_{\text{total}} \approx 1.5$—strong privacy.

7.2 Convergence

Theorem 7.2 (Capability Improvement)**.** *Under FDSO with n organizations, model capability improves as:*

$$Capability(T) \geq Capability(0) + \alpha \cdot T \cdot \sqrt{n} - O(\sigma_{DP}) \tag{6}$$

where α depends on experience quality and σ_{DP} is the privacy noise level.

The $\sqrt{n}$ factor reflects the benefit of federated learning—more organizations provide more diverse experiences.

8 Evaluation

8.1 Experimental Setup

- **Organizations**: 50 simulated organizations with distinct domains
- **Data**: 100,000 experiences per organization
- **Model**: Zen-8B base model
- **Privacy Budget**: $\epsilon = 1.0$ per round
- **Baselines**: Isolated training, centralized DSO, standard FL

8.2 Capability Improvement

Table 1: Model capability after 50 rounds (average across 10 tasks)

Method	**Accuracy**	**vs. Isolated**
Isolated Training	67.3%	—
Centralized DSO	84.1%	+25.0%
Standard FL	78.9%	+17.2%
FDSO (Ours)	82.8%	+23.0%

FDSO achieves 98.5% of centralized performance while providing privacy guarantees.

8.3 Communication Efficiency

FDSO requires 300× less bandwidth than standard FL.

Table 2: Communication cost per round (50 organizations)

Method	**Data (GB)**	**vs. FL**
Standard FL	156.2	1.0×
Compressed FL	31.4	0.20×
FDSO (Ours)	0.47	0.003×

8.4 Privacy Evaluation

We evaluate against membership inference and model inversion attacks:

Table 3: Attack success rates (lower is better)

Attack	**No Privacy**	**FDSO**
Membership Inference	78.3%	52.1%
Attribute Inference	64.7%	50.8%
Experience Reconstruction	41.2%	8.3%

FDSO reduces attack success to near-random (50%).

8.5 Byzantine Robustness

With 30% adversarial organizations:

Table 4: Performance under adversarial conditions

Adversaries	**Naïve Agg.**	**FDSO**
0%	82.8%	82.8%
10%	74.2%	81.9%
20%	61.3%	80.4%
30%	48.7%	78.1%

FDSO maintains 94% of clean performance with 30% adversaries.

9 Related Work

Federated Learning: FedAvg [1] and variants optimize gradient aggregation. FDSO avoids gradients entirely.

Differential Privacy for NLP: DP-SGD [2] adds noise to gradients. Our semantic DP operates on experiences.

Secure Aggregation: SPDZ and similar enable private aggregation but require expensive MPC. Our approach uses lighter-weight cryptography.

Decentralized AI: Zoo Network's DSO [4] inspired this work; we add privacy guarantees.

10 Conclusion

FDSO demonstrates that privacy-preserving collaborative AI improvement is practical. By sharing semantically-privatized experiences rather than gradients, we achieve near-centralized performance with formal privacy guarantees and minimal communication overhead. Byzantine-robust aggregation ensures system integrity despite adversarial participants.

This work enables a new paradigm: organizations can benefit from collective AI improvement without surrendering data sovereignty.

Acknowledgments

We thank the Zoo Labs community for protocol feedback and the Lux Partners team for infrastructure support.

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