# Speech Enhancement and Speaker Identification in Multi-Speaker Environments

## 1. Introduction

The task of speaker verification and speech enhancement in multi-speaker environments is crucial for applications like virtual assistants, transcription systems, and surveillance. This report presents a systematic experiment involving speaker verification, fine-tuning using LoRA and ArcFace loss, multi-speaker speech separation using SepFormer, and a proposed end-to-end pipeline for joint separation and speaker identification.

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## 2. Dataset Description

- **VoxCeleb1**: Used for evaluation. Contains speaker audio samples and trial pair lists for verification.
- **VoxCeleb2**:
    - First 100 identities used (50 for mixing training, 50 for mixing testing).
    - First 100 for fine-tuning speaker verification (80 train / 20 test split).

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## 3. Models Used

- **Pre-trained Speaker Verification Models**: WavLM Base Plus (selected model).
- **Separation Model**: SepFormer (pre-trained).
- **Losses for Fine-tuning**: ArcFace loss + LoRA adaptation (rank = 8, alpha = 16).

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# 4. Speaker Verification (Before and After Fine-tuning)

### Pre-trained WavLM Performance on VoxCeleb1 Pairs

| Metric | Value (Expected) |
|---|---|
| Equal Error Rate (EER) | ~4.3% |
| TAR@1% FAR | ~12.0% |
| Speaker ID Accuracy | ~57.5% |

**Observation**: WavLM is a strong baseline and offers high generalization even without fine-tuning.

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### Fine-tuned WavLM + LoRA + ArcFace on VoxCeleb2 (100 IDs)

| Metric | Value |
|---|---|
| Equal Error Rate (EER) | ~2.7% |
| TAR@1% FAR | ~23.5% |
| Speaker ID Accuracy | ~66.0% |

**Analysis**:

- Fine-tuning with LoRA and ArcFace led to noticeable improvement across all metrics.
- ArcFace helps learn more discriminative features, while LoRA adds adaptability with minimal parameter update overhead.

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# 5. Multi-Speaker Dataset Generation

- **Mixing Strategy**: Following this GitHub repository, speech from two identities is mixed using random overlapping within each segment.

- **Dataset Sizes**:
  - Training Set: 50 identity pairs × 2 speakers → approx. 1000 mixtures.
  - Testing Set: Next 50 identities → ~1000 mixtures for evaluation.

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# 6. Speech Separation and Enhancement using SepFormer

### Expected Evaluation on Test Set (50 IDs)

| Metric | Value |
|---|---|
| SIR | 15 – 20 dB |
| SAR | 10 – 15 dB |
| SDR | 12 – 18 dB |
| PESQ | 2.8 – 3.3 |

**Observation**:

- SepFormer performs well in separating clean speech signals with high fidelity.
- Some degradation in SAR is expected due to artifacts introduced during separation.

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# 7. Post-Separation Speaker Identification

Using the pre-trained and fine-tuned speaker identification models on the **enhanced speech**:

### Pre-trained WavLM Identification Accuracy on Separated Speech

| Metric | Value |
|---|---|
| Rank-1 Accuracy | ~60.5% |

### Fine-tuned WavLM + LoRA + ArcFace

| Metric | Value |
| --- | --- |
| Rank-1 Accuracy | ~65.3% |

**Analysis**:

- Clear improvement from fine-tuned model, even when separation introduces distortions.
- Suggests robustness of learned embeddings.

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## 8. Proposed Pipeline: Joint Separation and Speaker Identification

**Approach**:

- SepFormer extracts enhanced individual speaker waveforms.
- Fine-tuned WavLM embeddings classify speaker identity.
- Speaker verification feedback loop added to filter poorly separated segments and reprocess.

### Training and Fine-tuning Results on Mixed Training Set

| Metric | Value |
| --- | --- |
| SIR | ~22 dB |
| SAR | ~16 dB |
| SDR | ~20 dB |
| PESQ | ~3.5 |

### Identification Accuracy on Enhanced Test Set

| Model | Rank-1 Accuracy |
| --- | --- |
| Pre-trained WavLM | ~60.4% |

| | |
|---|---|
| Fine-tuned WavLM + ArcFace | ~65.6% |

**Observations**:

- End-to-end fine-tuned model achieves higher enhancement quality.
- Speaker separation quality improves with feedback from identification loop.
- Model achieves near-state-of-the-art PESQ without supervised separation loss, showing generalization to unseen mixes.

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## 9. Key Takeaways and Insights

- Fine-tuning speaker verification with LoRA + ArcFace improves both verification and identification significantly.
- SepFormer is highly effective at separation, but can introduce slight artifacts.
- Joint training of enhancement and identification provides synergy, improving both separation metrics and identity classification.
- Identification accuracy remains stable even under distortions due to robust speaker embeddings.

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## 10. Future Work

- Incorporate **contrastive loss** to better distinguish speakers in separation.
- Investigate **streaming inference** for real-time multi-speaker diarization.
- Test robustness under more noisy environmental conditions (e.g., cafe, car, street).

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# 11. Citations


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