Sequence Modeling

in Unsupervised Single-channel Overlapped Speech Recognition

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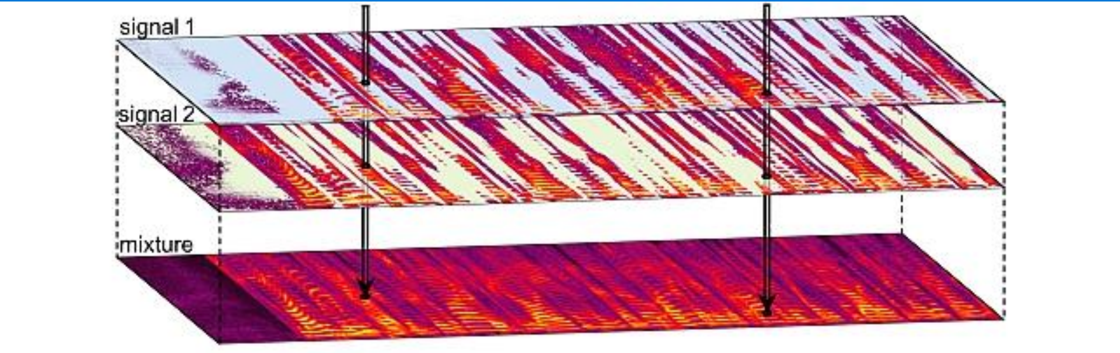

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Outline

- Introduction
  - Cocktail party problem
  - PIT-TS framework and discriminative training
- Proposed methods
  - Temporal Correlation Modeling
  - Integrating Language Model
- Experiments
- Conclusion

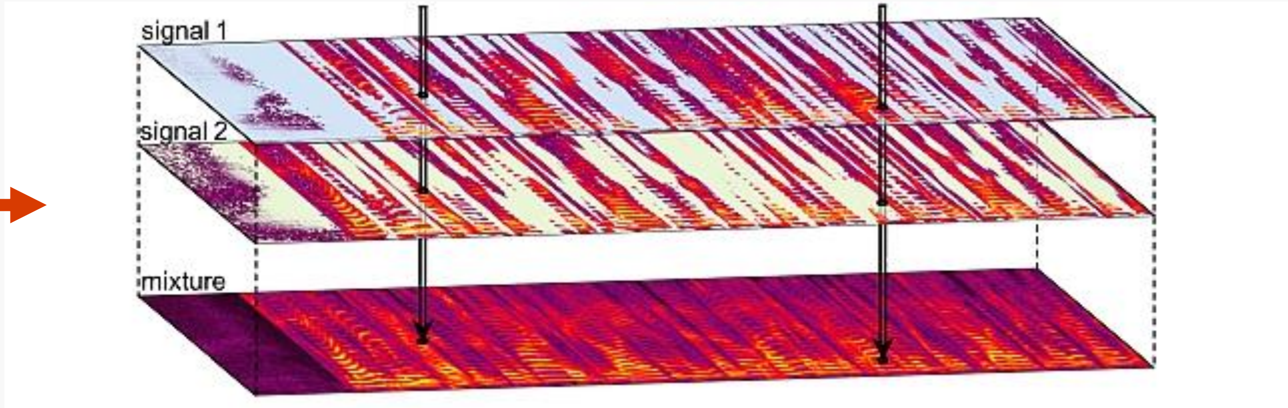
Introduction

- Cocktail-party problem

N=2

$$P(\mathbf{L}_{u1}, ..., \mathbf{L}_{uN} | \mathbf{O}_u^{(m)})$$

$$\mathbf{O}_u^{(m)} = \sum_{n=1}^{N} \mathbf{O}_{un}^{(r)}$$



Assignment error:

e.g. ch-a: how oh you

ch-b: are no

Cross talk error:

e.g. ch-a: how are you

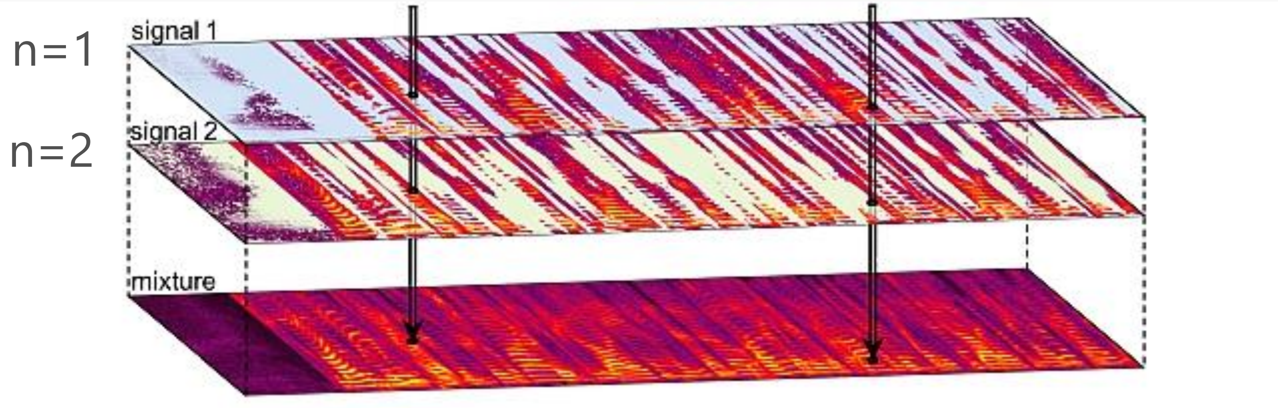
ch-b: oh are no

Label assignment problem

$$P(\mathbf{L}_{u1}, \ldots, \mathbf{L}_{uN} | \mathbf{O}_u^{(m)}) \approx \prod_{n=1}^{N} P(\mathbf{L}_{un}^{(r)} | \mathbf{O}_u^{(m)}) \quad (2)$$

Label Independence

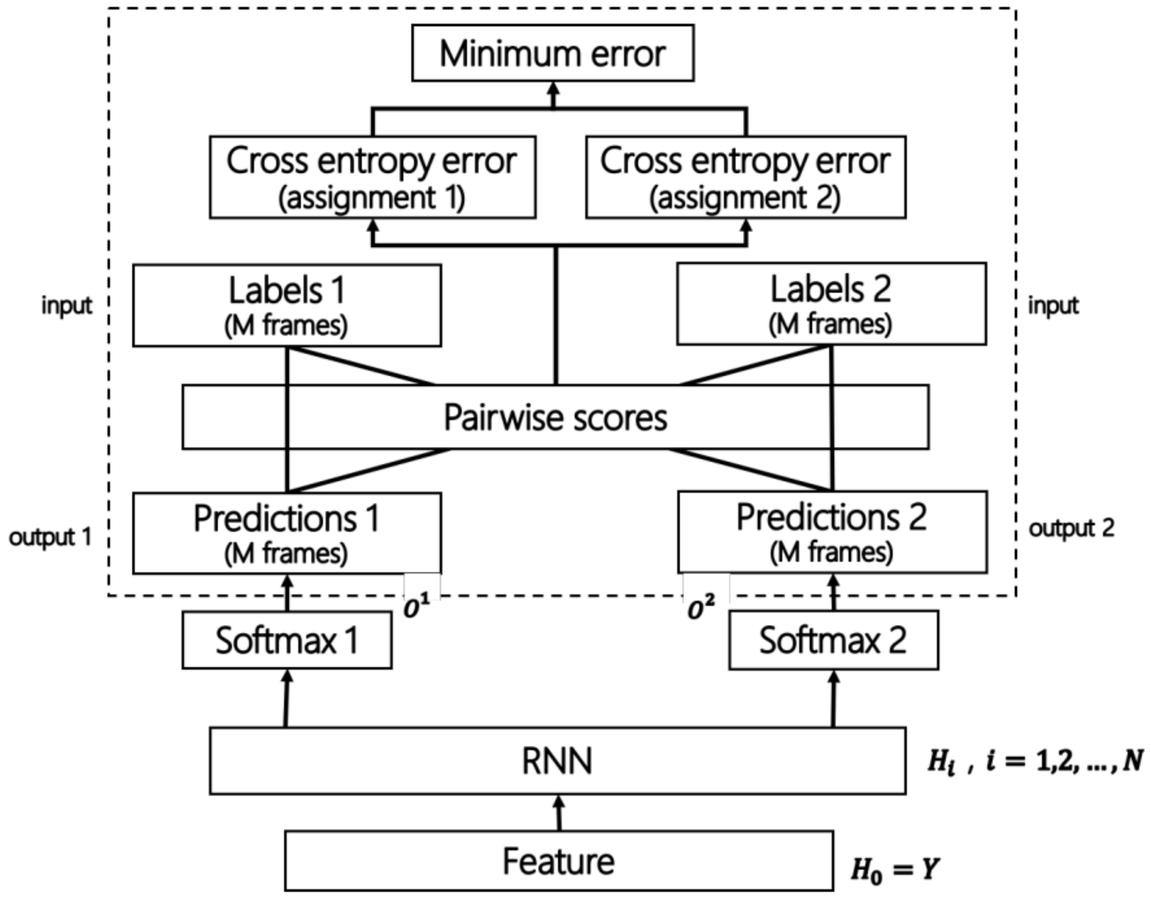
$$\mathbf{O}_u^{(m)} = \sum_{n=1}^{N} \mathbf{O}_{un}^{(r)}$$



Permutation Invariant Training for ASR

$$P(\mathbf{L}_{u1}, ..., \mathbf{L}_{uN}|\mathbf{O}_u^{(m)}) \approx \prod_{n=1}^{N} P(\mathbf{L}_{un}^{(r)}|\mathbf{O}_u^{(m)}) \qquad (2)$$

$$\mathcal{J}_{\text{CE-PIT}} = \sum_u \boxed{\min_{s' \in \mathbf{S}}} \sum_t \frac{1}{N} \sum_{n \in [1,N]} CE(l_{utn}^{(s')}, l_{utn}^{(r)}) \qquad (4)$$



- Disadvantage
  - Model Complexity (3 hardest problems)
  - Frame CE → Utt. Problem
  - No Linguistics

PIT + Transfer Learning (TS)

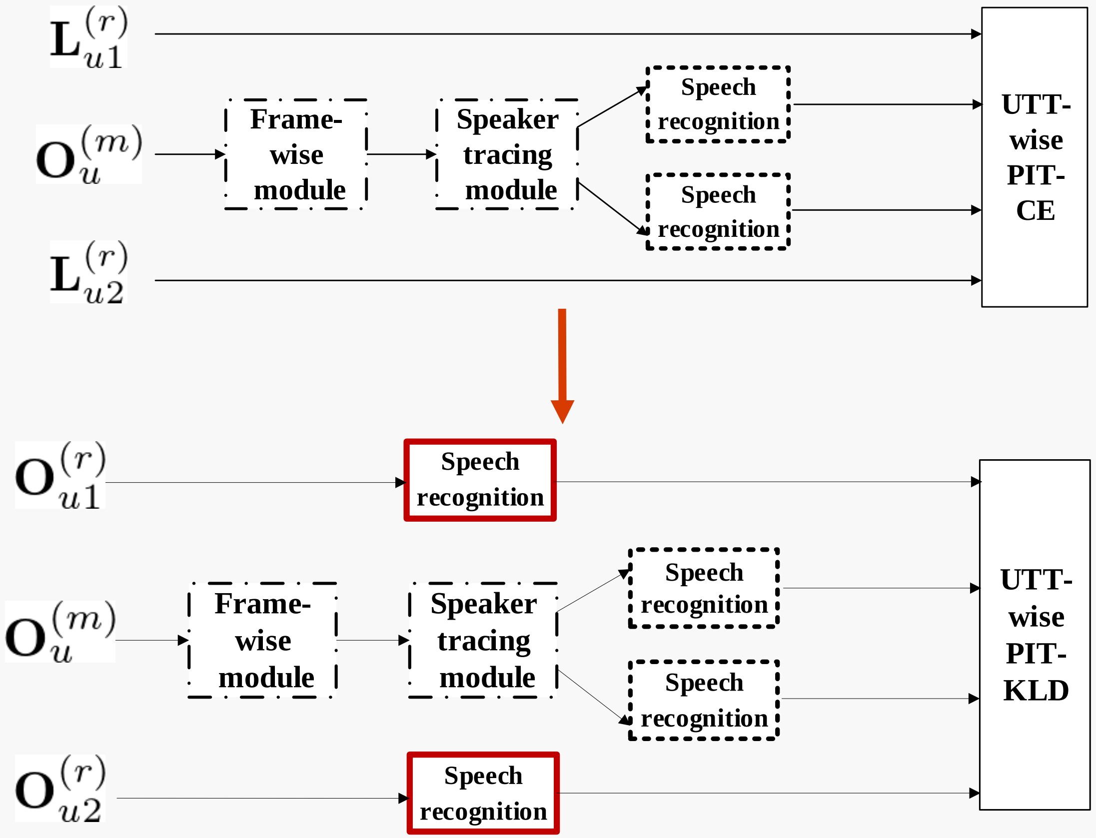
$$\mathcal{J}_{\text{CE-PIT}} = \sum_{u} \min_{s' \in \mathbf{S}} \sum_{t} \frac{1}{N} \sum_{n \in [1,N]} \boxed{CE}(l_{utn}^{(s')}, l_{utn}^{(r)}) \quad (4)$$

$$\mathcal{J}_{\text{KLD-PIT}} = \sum_{u} \min_{s' \in \mathbf{S}} \sum_{t} \frac{1}{N} \sum_{n \in [1,N]} \boxed{KLD}(P(l_{utn}^{(c)} | \mathbf{O}_{un}^{(r)}), P(l_{utn}^{(s')} | \mathbf{O}_{u}^{(m)})) \quad (8)$$

Clean infer.

PIT model infer.

- Better model convergence
  - Domain adaptation v.s. from scratch



[1] Zhehuai Chen, Jasha Droppo, Jinyu Li, Wayne Xiong, Progressive Joint Modeling in Unsupervised Single-channel Overlapped Speech Recognition. IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 26, no. 1, pp. 184-196, Jan. 2018. doi: 10.1109/TASLP.2017.2765834.

Linguistics - Multi-outputs Seq. Disc. Training

- Motivation:
  - Both ASR & speaker tracing → sequential
  - Implicit integrating language model
- Formulation:

$$\mathcal{J}_{\text{CE-PIT}} = \sum_{u} \min_{s' \in \mathbf{S}} \sum_{t} \frac{1}{N} \sum_{n \in [1,N]} \boxed{CE}(l_{utn}^{(s')}, l_{utn}^{(r)}) \quad (4)$$

$$\mathcal{J}_{\text{SEQ-PIT}} = \sum_{u} \min_{s' \in \mathbf{S}} \frac{1}{N} \sum_{n \in [1,N]} -\boxed{\mathcal{J}_{\text{SEQ}}}(\mathbf{L}_{un}^{(s')}, \mathbf{L}_{un}^{(r)}) \quad (12)$$

- Key challenges:
  - Design the multi-output search space
  - Integrate with label assignment

[1] Zhehuai Chen, Jasha Droppo, Jinyu Li, Wayne Xiong, Progressive Joint Modeling in Unsupervised Single-channel Overlapped Speech Recognition. IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 26, no. 1, pp. 184-196, Jan. 2018. doi: 10.1109/TASLP.2017.2765834.

Proposed methods

- Follow PIT-TS diagram

- Motivation
  - improve sequence modeling & language model

- Method
  - Implicit correlation modeling → explicit
  - Integrate linguistic information

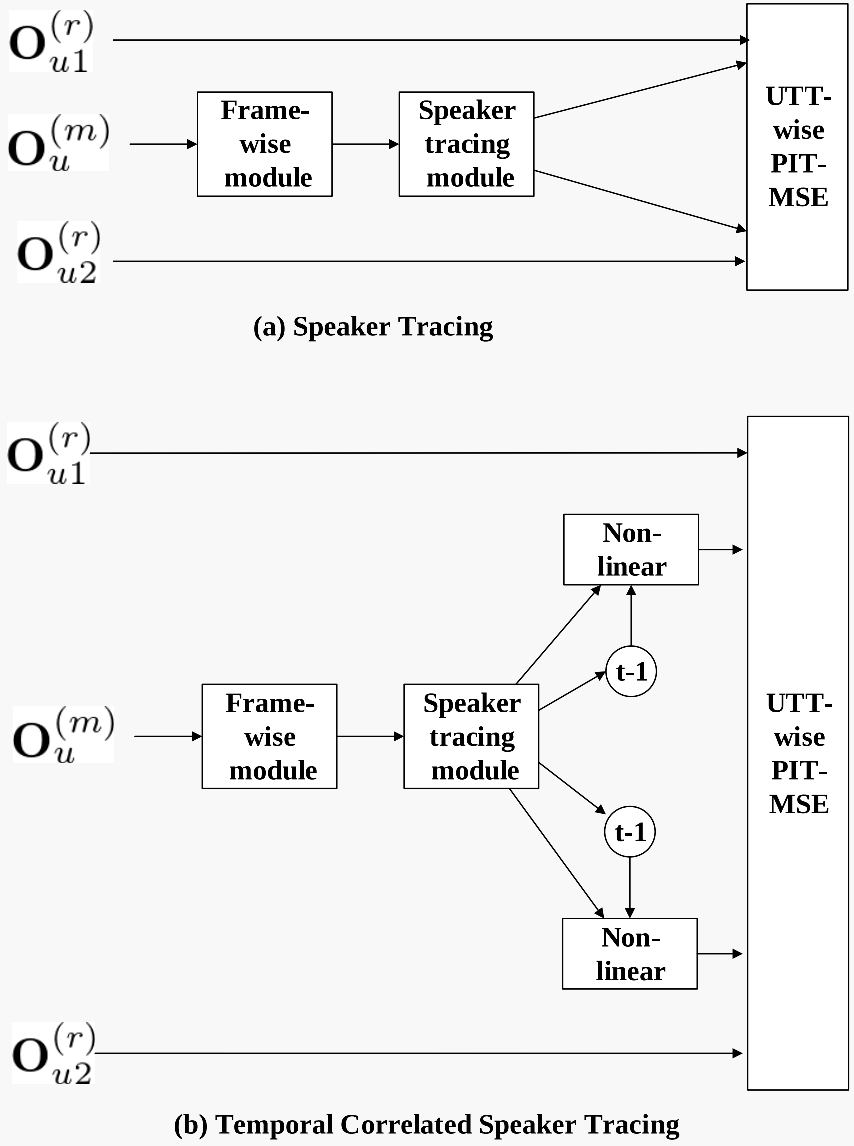
Acoustics – Temporal Correlation Modeling

- Motivation
  - Sequential correlation v.s. stream de-correlation
    - the frequency bins between adjacent frames of the same speaker are correlated
  - Last inference can improve current inference

Assignment error:

e.g. ch-a: how oh you

ch-b: are no

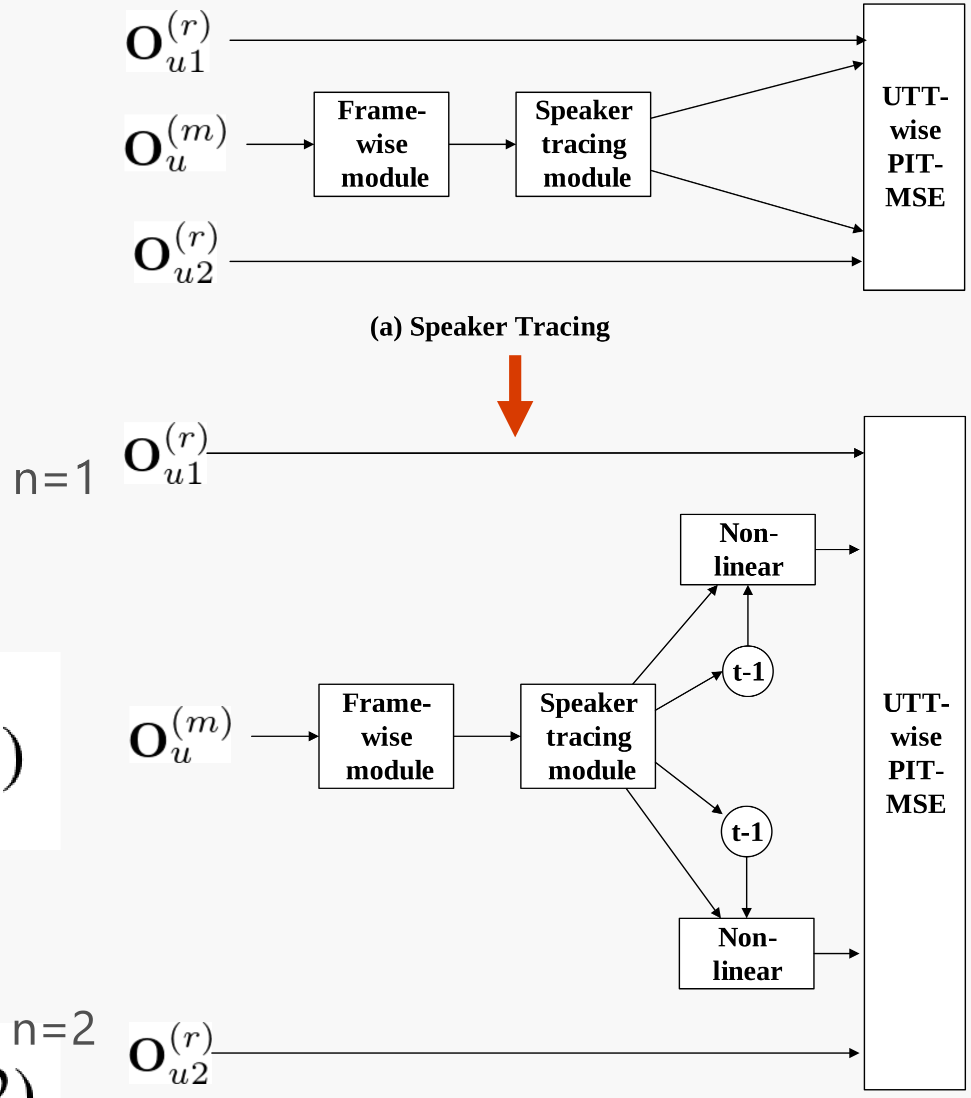


Acoustics – Temporal Correlation Modeling

- Motivation
  - **Sequential correlation** v.s. stream de-correlation
  - Last inference can improve current inference
- Sequential labels correlation

$$o_{utn} = \mathcal{F}_{utn}(\mathbf{O}_u^{(m)}) \quad (1)$$

$$o_{utn} = \mathcal{F}'_{utn}(\mathbf{O}_u^{(m)}, o_{u(t-1)n}) \quad (2)$$



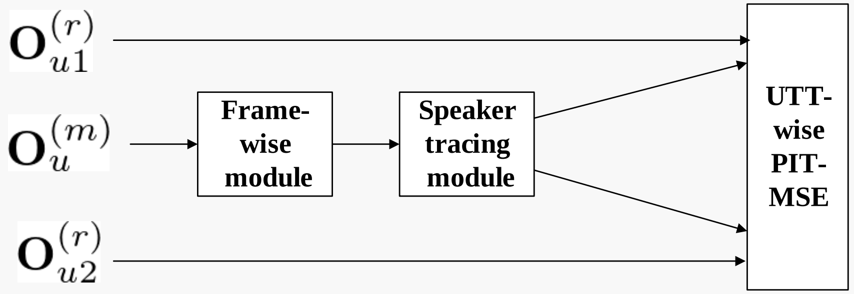
(a) Speaker Tracing

(b) Temporal Correlated Speaker Tracing

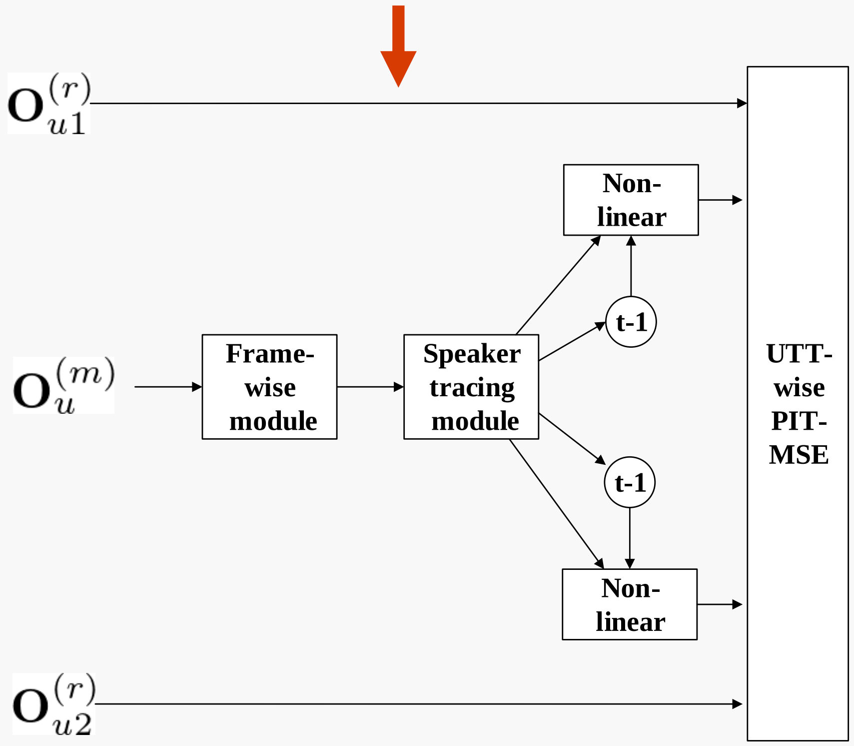
Acoustics – Temporal Correlation Modeling

- Motivation
  - Sequential correlation v.s. **stream de-correlation**
  - last inference can improve current inference
- Sequential labels correlation
- alleviates the assignment & cross talk errors

Assignment error:
e.g. ch-a: how oh you
ch-b: are no



(a) Speaker Tracing



(b) Temporal Correlated Speaker Tracing

Linguistics – Language Model Integration

- Motivation:
  - Improve **assignment decision** by **combining LM** in training stage
  - Still train a **pure** acoustic model and integrate it with more powerful word level language model in evaluation stage
- Original PIT-CE

$$\mathcal{J}_{\text{U-PIT-CE}} = \sum_{u} \min_{s' \in \mathbf{S}} \sum_{t} \frac{1}{N} \sum_{n \in [1,N]} CE(l_{utn}^{(s')}, l_{utn}^{(r)}) \qquad (3)$$

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- PIT-MAP:

$$MAP(l_{utn}^{(s')}, l_{utn}^{(r)}) = \frac{P(l_{utn}^{(r)} | \mathbf{O}_u^{(m)}) / P(l) \cdot P(l_{utn}^{(r)} | \mathbf{L}_{u(t-1)n}^{(s')})}{\boxed{P(\mathbf{O}_u^{(m)})}}$$

Discriminative training

$$\approx \frac{P(l_{utn}^{(r)} | \mathbf{O}_u^{(m)})}{P(l)} \cdot (\, P(l_{utn}^{(r)} | \mathbf{L}_{u(t-1)n}^{(s')})\,)^{\lambda}$$

Proposed method

Linguistics – Language Model Integration

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- Original PIT-CE

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$$CE(\cdot) \longrightarrow MAP(\cdot)$$

PIT-trained AM

- Proposed:

$$MAP(l_{utn}^{(s')}, l_{utn}^{(r)}) = \frac{\boxed{P(l_{utn}^{(r)} | \mathbf{O}_u^{(m)})}}{P(l)} \cdot \left(P(l_{utn}^{(r)} | \mathbf{L}_{u(t-1)n}^{(s')}) \right)^{\lambda} \quad (4)$$

Linguistics – Language Model Integration

- Motivation:
  - Improve assignment decision by combining LM in training stage
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- Original PIT-CE

$$\mathcal{J}_{\text{U-PIT-CE}} = \sum_u \min_{s' \in \mathbf{S}} \sum_t \frac{1}{N} \sum_{n \in [1,N]} CE(l_{utn}^{(s')}, l_{utn}^{(r)}) \quad (3)$$

$$CE(\cdot) \longrightarrow MAP(\cdot)$$

- Proposed:

Senone level NNLM

$$MAP(l_{utn}^{(s')}, l_{utn}^{(r)}) = \frac{P(l_{utn}^{(r)} | \mathbf{O}_u^{(m)})}{P(l)} \cdot \boxed{(P(l_{ut\underline{n}}^{(r)} | \mathbf{L}_{u(t-1)\underline{n}}^{(s')})})^{\lambda} \quad (4)$$

Linguistics – Language Model Integration

- Motivation:
  - Improve assignment decision by combining LM in training stage
  - Still train a pure acoustic model and integrate it with more powerful word level language model in evaluation stage
- Original PIT-CE

$$\mathcal{J}_{\text{U-PIT-CE}} = \sum_u \min_{s' \in \mathbf{S}} \sum_t \frac{1}{N} \sum_{n \in [1,N]} CE(l_{utn}^{(s')}, l_{utn}^{(r)})$$

system	Ass.	Opt.
PIT	CE	CE
Proposed	**MAP**	**CE**
Disc. Train	MAP	MAP

- Proposed:

$$MAP(l_{utn}^{(s')}, l_{utn}^{(r)}) = \frac{P(l_{utn}^{(r)} | \mathbf{O}_u^{(m)}) / P(l) \cdot P(l_{utn}^{(r)} | \mathbf{L}_{u(t-1)n}^{(s')})}{\boxed{P(\mathbf{O}_u^{(m)})}}$$

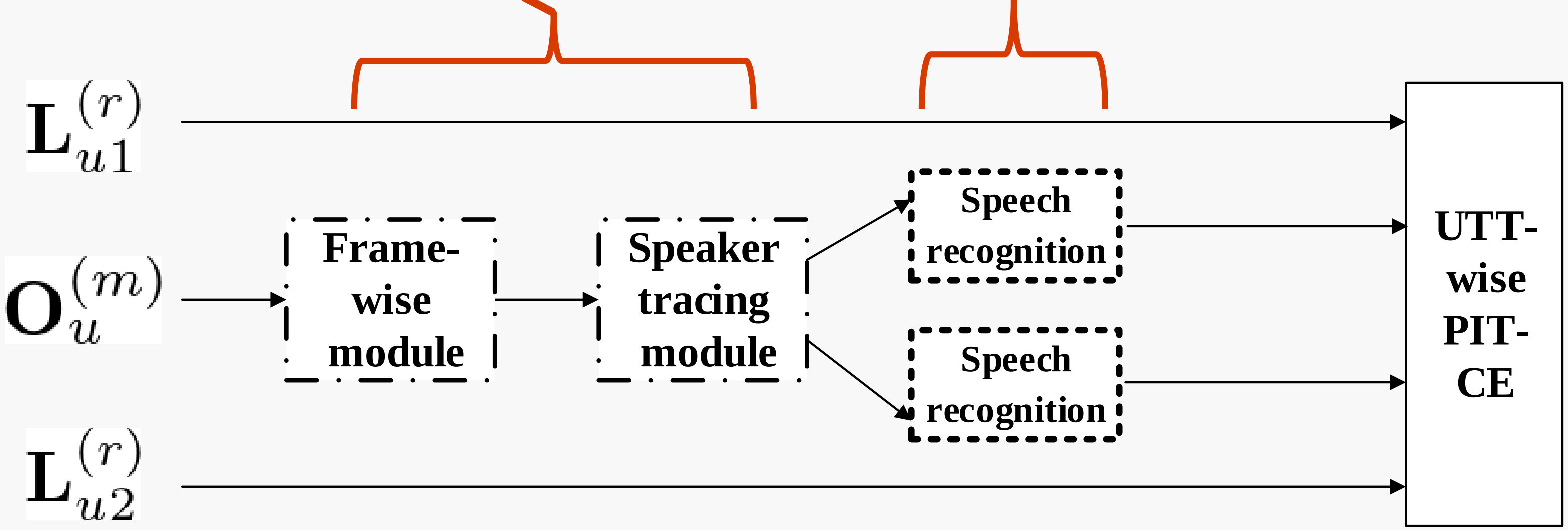
Discriminative training

$$\approx \frac{P(l_{utn}^{(r)} | \mathbf{O}_u^{(m)})}{P(l)} \cdot (\, P(l_{utn}^{(r)} | \mathbf{L}_{u(t-1)n}^{(s')}) \,)^{\lambda}$$

Proposed method

Experiments

- Setup and baselines:
  - Artificial overlapped SWBD 300→150 (→50); hub5e-swb 1831 → 915 utts
  - 9000 senones; clean speech alignment;
  - Baseline 1: 6L 768 cells BLSTM PIT-SS + 4L 768 cells BLSTM ASR



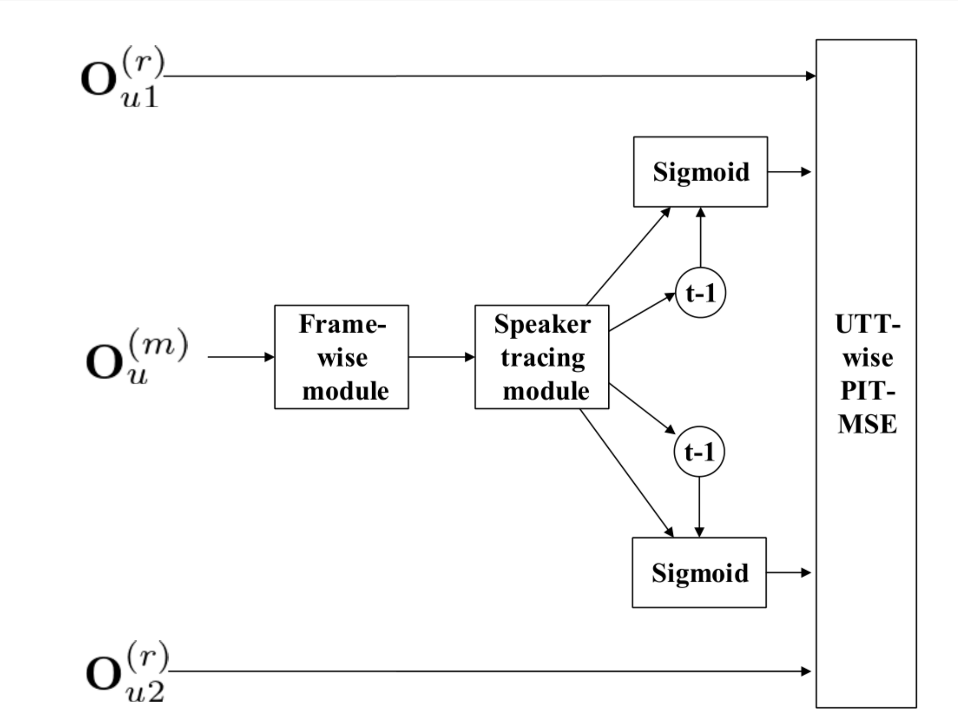
Experiments

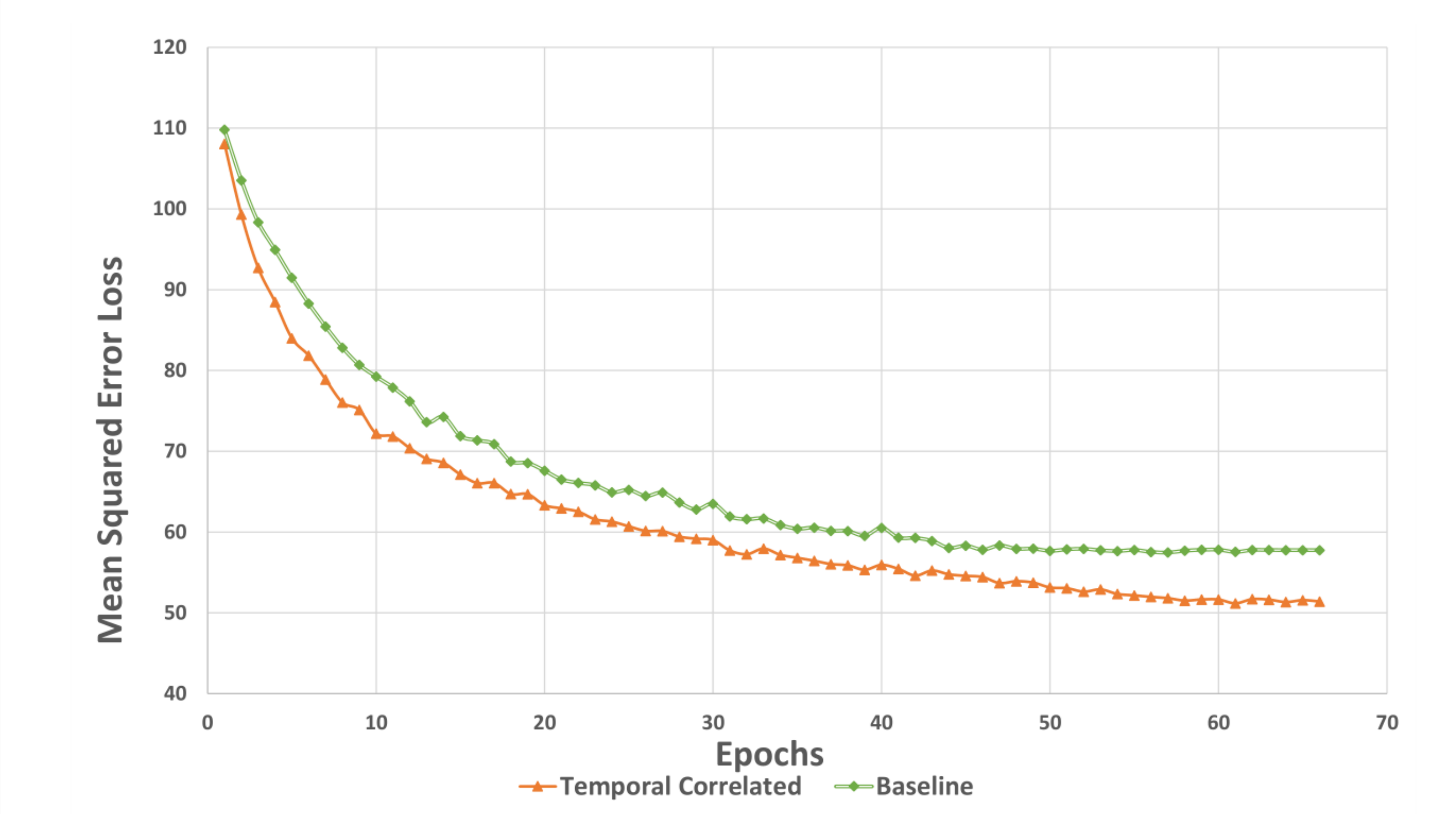
- Setup and baselines:
  - Artificial overlapped SWBD 300→150 (→50); hub5e-swb 1831 → 915 utts
  - 9000 senones; clean speech alignment;
  - Baseline 1: 6L 768 cells BLSTM PIT-SS + 4L 768 cells BLSTM ASR
  - Baseline 2: + transfer learning (TS, taught by clean teacher)

Neural network	Model	WER
6 BLSTM + 4 BLSTM	PIT-ASR	57.5
	progressive joint training + clean teacher	**38.9**

Experiments – Temporal Correlated

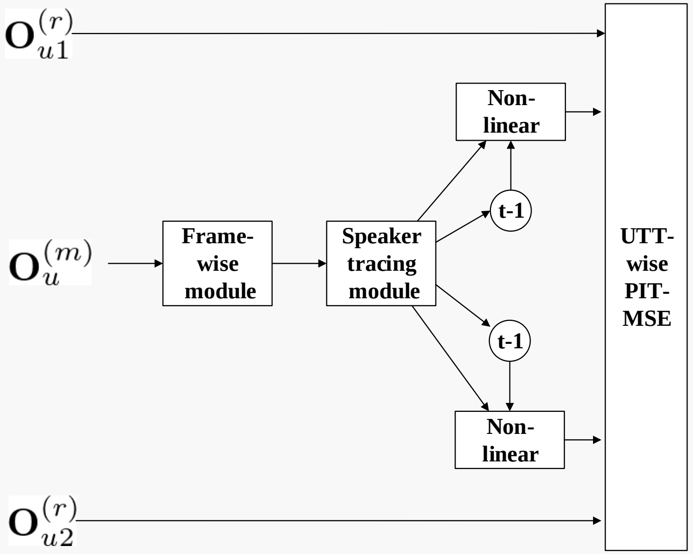
- Baseline: modularization + clean teacher WER=38.9
- Improve in Speaker Tracing:





Experiments – Temporal Correlated

- Baseline: modularization + clean teacher WER=38.9
- Improve in Speaker Tracing
- WER improve after joint training



Temporal Correlated	# of Sigmoid	WER	Rel. (%)
×	0	38.9	0
	0	37.5	-3.6
√	1	**35.8**	**-8.0**
	2	36.7	-5.7

Experiments – LM Integration

- Baseline: modularization + clean teacher WER=38.9

$$\mathcal{J}_{\text{U-PIT-CE}} = \sum_u \min_{s' \in \mathbf{S}} \sum_t \frac{1}{N} \sum_{n \in [1,N]} CE(l_{utn}^{(s')}, l_{utn}^{(r)}) \tag{3}$$

$$CE(\cdot) \longrightarrow MAP(\cdot)$$

$$MAP(l_{utn}^{(s')}, l_{utn}^{(r)}) = \frac{P(l_{utn}^{(r)} | \mathbf{O}_u^{(m)})}{P(l)} \cdot (\ P(l_{utn}^{(r)} | \mathbf{L}_{u(t-1)n}^{(s')})\ )^{\lambda} \tag{4}$$

Assign.	Opt.	50 hours WER	50 hours Rel. (%)	150 hours WER	150 hours Rel. (%)
CE	CE	38.9	0	32.8	0
MAP	CE	37.3	**-4.1**	30.9	**-5.8**

Experiments – LM Integration

- Baseline: modularization + clean teacher WER=32.8

$$MAP(l_{utn}^{(s')}, l_{utn}^{(r)}) = \frac{P(l_{utn}^{(r)} | \mathbf{O}_u^{(m)})}{P(l)} \cdot \left(P(l_{utn}^{(r)} | \mathbf{L}_{u(t-1)n}^{(s')}) \right)^{\lambda} \quad (4)$$

		50 hours		150 hours	
Assign.	Opt.	WER	Rel. (%)	WER	Rel. (%)
CE	CE	38.9	0	32.8	0
MAP	CE	37.3	**-4.1**	30.9	**-5.8**

- with more data, the improvement becomes larger
  - AM becomes stronger
  - Assignment decision is not over-fit to the LM

Experiments – Compare with disc. training

system	Assign.	Opt.	50 hours WER	50 hours Rel. (%)
baseline	CE	CE	38.9	0
LM integration	MAP	CE	37.3	**-4.1**
LF-DC-bMMI	MAP	$\boxed{\text{MAP}}$	35.6	**-8.5**

$$MAP(l_{utn}^{(s')}, l_{utn}^{(r)}) = \frac{P(\mathbf{O}^{(m)}|\mathbf{L}^{(r)}) \cdot P(\mathbf{L}^{(r)})}{P(\mathbf{O}^{(m)})}$$

$$= \frac{P(l_{utn}^{(r)}|\mathbf{O}_u^{(m)})/P(l) \cdot P(l_{utn}^{(r)}|\mathbf{L}_{u(t-1)n}^{(s')})}{\boxed{P(\mathbf{O}_u^{(m)})}}$$

$$\approx \frac{P(l_{utn}^{(r)}|\mathbf{O}_u^{(m)})}{P(l)} \cdot (\ P(l_{utn}^{(r)}|\mathbf{L}_{u(t-1)n}^{(s')})\ )^{\lambda}$$

Discriminative training

Proposed method

- Differences:
  - optimization stage
  - NNLM v.s. N-gram in discriminative training
  - hardness in modeling $P(\mathbf{O}_u^{(m)})$

Experiments – Combination

Method	WER	Rel. (%)
baseline	38.9	0
+ Temporal Correlated	35.8	-8.0
+ LM Integration	34.4	-11.5
+ LF-DC-bMMI	$\boxed{31.6}$	$\boxed{-18.8}$

- Operate in different levels → can be combined

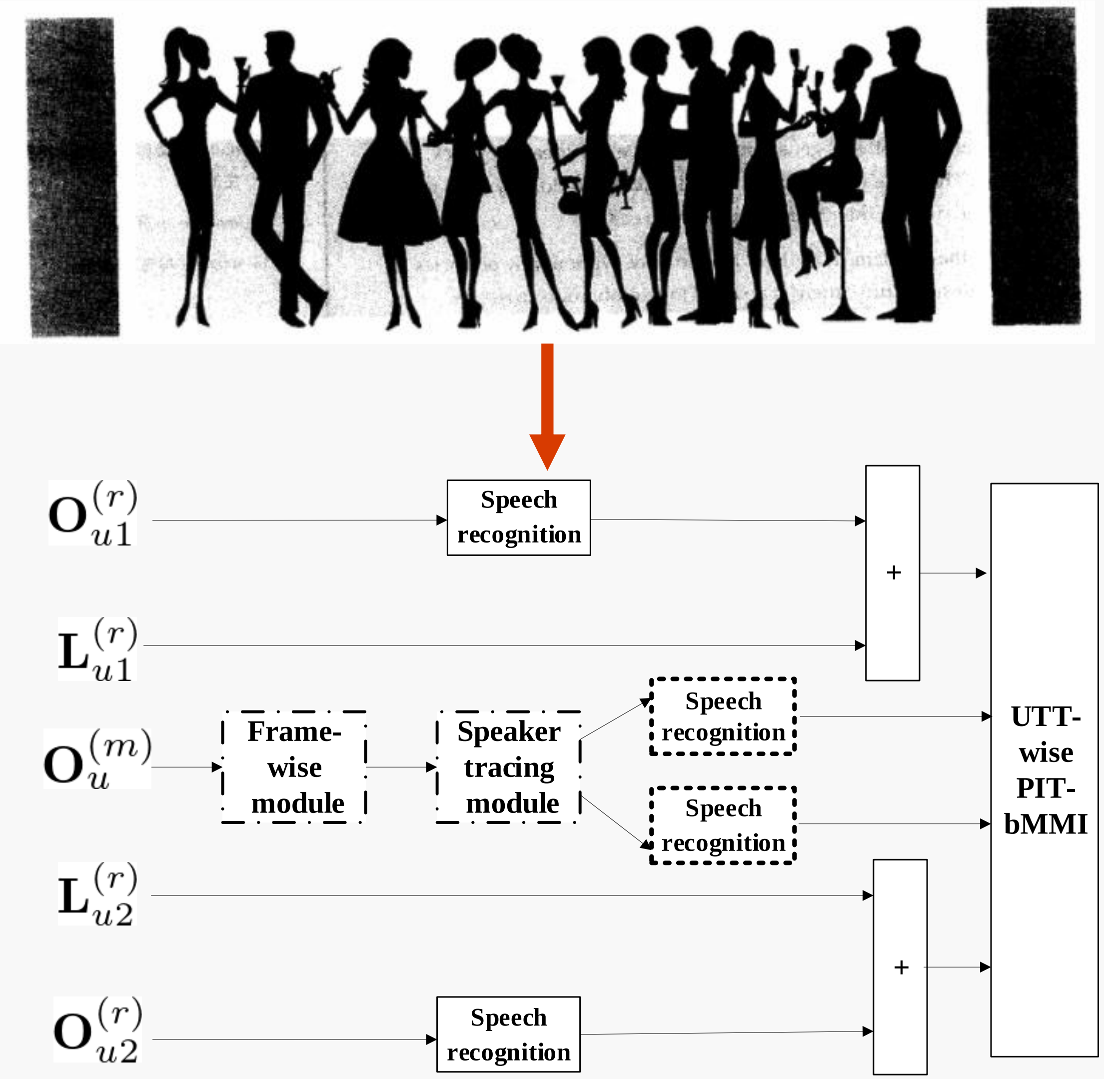
Experiments – Combination

Method	WER	Rel. (%)
baseline	38.9	0
+ Temporal Correlated	35.8	-8.0
+ LM Integration	34.4	-11.5
+ LF-DC-bMMI	31.6	-18.8
+ MMI clean teacher	35.8	-8.0
+ LF-DC-bMMI	35.2	-9.5

- Operate in different levels → can be combined
- Better than only utilize TS + discriminative training

Our final system

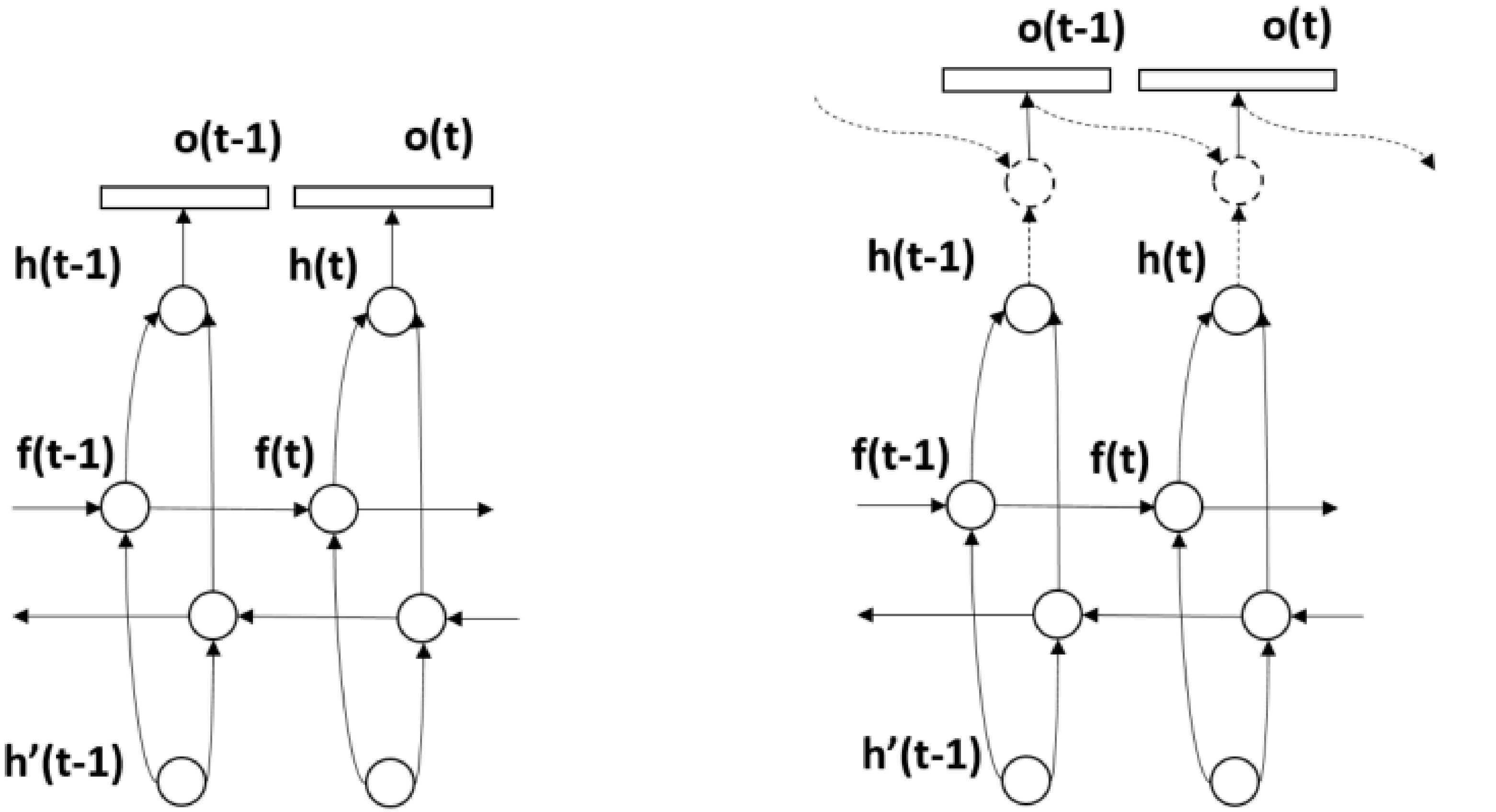
- Acoustics
  - Modular Initialization 4%
    - CNN 10%
  - Transfer Learning Based Joint Training 20%
  - **Temporal Correlation Modeling** 8%
- Linguistics
  - Multi-outputs Sequence Discriminative Training 8%
  - **Integrating Language Model in Assignment Decision** 4%



[1] Zhehuai Chen, Jasha Droppo, Sequence Modeling in Unsupervised Single-channel Overlapped Speech Recognition, accepted by IEEE International Conference on Acoustics, Speech and Signal Processing(ICASSP), Calgary, Canada, 2018.
[2] Zhehuai Chen, Jasha Droppo, Jinyu Li, Wayne Xiong, Progressive Joint Modeling in Unsupervised Single-channel Overlapped Speech Recognition. IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 26, no. 1, pp. 184-196, Jan. 2018. doi: 10.1109/TASLP.2017.2765834.

Backup materials

Temporal correlation modeling in BLSTM



(a) BLSTM

(b) Temporal Correlated BLSTM

Experiments – Example 50hrs (F-F)

- Clean ASR (90+WER)
- 1 PIT-CE
- 2 Transf.
- 3 +MMI teacher
- 4 +seq. disc. tr.

```
id: (sw_4776_a-006)
Labels: <>
File: sw_4776
Channel: a

REF:  i just ** **** ** **** GO   WALKING AND  I  USUALLY TRY TO go for about an hour (e-) and i HAVE TRIED DOING IT      EVERY DAY BUT i mean some times I do NOT EVEN DO     IT   ONCE DURING THE WEEK  but you know MOST OF THE TIME I T

Scores: (#C #S #D #I) 18 22 11 4
HYP:  i just SO LONG AS THEY HAVE COME     HERE AS MUCH    AS  WE go for about an hour      and i **** ***** WAS    READING IN     ANY WAY i mean some times * do *** IT    LONGER THAN A     WOMAN  AND STUFF but you know **** ** *** **** * *
Eval:        I  I    I  I    S     S       S     S  S       S   S                                  D     D       S      S          S      S    S                         D      D    S      S          S      S      S        S     S                 D      D   D      D      D D
```

1 PIT-CE

```
Scores: (#C #S #D #I) 34 7 10 1
HYP:  i just go OUT YOU     and i usually *** HAVE go for about an hour      *** i **** tried ***** IN every day but i mean some times i do not even do it once during the week but you know **** ** *** **** * *** ONCE WE  TURN DEFINITE
Eval:             I   S                   D    S                             D       D          D      S                                                                                  D      D   D     D      D D   S     S    S     S
```

2 Transf.

```
Scores: (#C #S #D #I) 36 9 6 2
HYP:  i just go OUT HERE    and i HAD     LIKE to HAVE go for about an hour      *** i **** ***** AM     TRYING every day but i mean some times i do not even do it once during the week but you know **** ** *** WHAT REALLY TRYING to get
Eval:             I   S             S       S         I                          D      D    D      S      S                                                                                         D      D   D    S      S        S
```

3 +MMI teacher

```
Scores: (#C #S #D #I) 37 9 5 1
HYP:  i just go OUT HERE    and i usually HAVE to go for about an hour      and i **** tried ***** IN ANOTHER day but i mean some times i do not even do it once during the week but you know **** ** WE  ARE  REALLY TRYING to get *** IT
Eval:             I   S                   S                                       D          D      S  S                                                                                     D      D  S    S     S      S                 D   S
```

4 +seq. disc. tr.

```
id: (sw_4854_b-009)
Labels: <>
File: sw_4854
Channel: b

REF:  well I (don-) i DO NOT CAMP NEAR AS MUCH AS WE USED TO WE    USED TO     go *** TO    THE LAKE all the time (%hesitation) WE (USE-) WE    ALL SKI and everything *** WE USED    TO ALL GO TO    THE LAKE ALL   the TIME AND MY PARENTS H

Scores: (#C #S #D #I) 20 22 20 2
HYP:  well *        i ** *** **** **** ** **** ** ** **** ** THINK AND   HERE'S go FOR ABOUT AN  HOUR all the time              I  WOULD  TRADE OFF NOW and everything BUT I  REALLY DO NOT I  MEAN I   AM    SURE the **** *** ** ******* *
Eval:      D          D  D   D    D    D  D    D  D  D    D  S     S      S        I   S     S   S                           S  S      S     S   S                   I   S  S      S  S   S  S    S   S     S         D    D   D  D         D

Scores: (#C #S #D #I) 42 9 11 0
HYP:  well i        i ** *** CAMPED near as much as we used to we **** ** ** ** FEEL LIKE all the time               we        we all *** SCAN everything ** **** ** *** THESE DOGS OVER LIKE all the time and my parents had a cabin IN th
Eval:                 D  D   S                                  D    D  D  D  S    S                                           D   S                D  D    D  D   S     S    S    S                                              S

Scores: (#C #S #D #I) 42 10 10 0
HYP:  well *        i ** THINK CAMPED near as much as we used to we **** ** ** ** FEEL LIKE all the time              we         we all SCREAM and everything ** **** ** *** YOU STILL HAVE LIKE all the time and my parents had a cabin IN
Eval:      D          D  S     S                                  D    D  D  D  S    S                                           S                   D  D    D  D   S   S     S    S                                         S

Scores: (#C #S #D #I) 47 8 7 0
HYP:  well *        i ** THINK CAMPED near as much as we used to we used to go to *** lake all the time             we        we all SCREAM and everything ** **** ** *** THESE DOGS BUT LIKE all the time and my parents had a cabin IN
Eval:      D          D  S     S                                              D                                                S                   D  D    D  D   S     S    S   S                                          S
```

Experiments – Example 150hrs (F-F)

- Clean ASR (90+WER)
- 1 PIT-CE
- 2 Transf.
- 3 +CNN
- 4 +seq. disc. tr.

```
id: (sw_4776_a-006)
Labels: <>
File: sw_4776
Channel: a

REF:  i just go WALKING and i usually TRY TO       go for about an hour (e-) AND i have tried DOING IT EVERY DAY  but i mean some times i do not even do it once during the week but you know MOST OF THE TIME i TRY  to get out there

                                                                          1 PIT-CE
Scores: (#C #S #D #I) 38 5 8 0
HYP:  i just go ON      and i usually *** THOUSAND go for about an hour      *** i have tried ***** ** TO    NAME but i mean some times i do not even do it once during the week but you know **** ** *** **** i LIKE to get out there
Eval:           S                     D   S                                  D                D     D  S     S                                                                                D    D  D   D      S

                                                                                           2 Transf.
Scores: (#C #S #D #I) 39 6 6 2
HYP:  i just go OUT TO EAT     and i usually *** HAVE go for about an hour      *** i WOULD TRY   doing it every day but i mean some times i do not even do it once during the week *** you know **** ** *** WE   WE try to get out there
Eval:           I   I  S                     D   S                              D     S     S                                                                             D            D    D  D  S    S

                                                                                                  3    +CNN
Scores: (#C #S #D #I) 42 5 4 1
HYP:  i just go OUT AND     and i usually *** HAVE go for about an hour      and i **** tried doing it every day but i mean some times i do not even do it once during the week but you know **** ONCE the **** SAME TRYING to get out ther
Eval:           I  S                      D   S                                    D                                                                                                D    S        D    S    S

                                                                                                           4      +seq. disc. tr.
Scores: (#C #S #D #I) 41 8 2 0
HYP:  i just go WATCHING and i usually DO  NOT go for about an hour      and i **** tried doing it every day but i mean some times i do not even do it once during the week but you know **** ONCE IN  SOME WAY TRYING to get out there
Eval:           S                      S   S                                   D                                                                                                D    S    S   S    S    S

id: (sw_4854_b-009)
Labels: <>
File: sw_4854
Channel: b

REF:  well I (don-) i DO NOT   camp NEAR as much as we used to we used TO GO to THE LAKE  all the time (%hesitation) we (use-) we all SKI  AND everything WE USED TO ALL GO TO THE LAKE ALL   THE     time AND my parents HAD a CABIN AT TH

Scores: (#C #S #D #I) 36 10 16 0
HYP:  well *        i ** THINK camp HERE as much as we used to we used ** ** to *** LEAVE all the time                we        we all STAY IN  everything ** **** ** *** ** ** *** YOU  STILL ILLEGAL time *** my parents GOT a ***** ** **
Eval:      D          D  S          S                                  D  D     D   S                                              S    S               D  D    D  D   D  D  D   S    S     S            D                S     D     D  D

Scores: (#C #S #D #I) 42 10 10 0
HYP:  well *        i AM A   camp near as much as we used to we **** ** ** ** FEEL LIKE all the time               we        we all *** SCAN everything ** **** ** *** THESE DOGS ARE LIKE all the time and my parents had a cabin IN the l
Eval:      D          S  S                                       D    D  D  D  S    S                                               D   S               D  D    D  D   S     S    S   S                                     S

Scores: (#C #S #D #I) 40 9 13 0
HYP:  well *        i ** THINK camp near as much as we used to we **** ** ** ** FEEL LIKE all the time                **        we *** WILL SCAN everything ** **** ** *** ** THESE DOGS LIKE all the time and my parents had a cabin ON the
Eval:      D          D  S                                        D    D  D  D  S    S                                 D            D   S    S               D  D    D  D   D  S     S    S                                    S

Scores: (#C #S #D #I) 46 9 7 0
HYP:  well *        i ** THINK CAMPED near as much as we used to we used to go to *** lake all the time                we        we all *** SCAN everything ** **** ** WITH THESE DOGS OVER LIKE all the time and my parents had a cabin IN
Eval:      D          D  S     S                                                  D                                              D   S               D  D    D  S    S     S    S    S                                       S
```