

Lecture 9

Robustness

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Where Are We?

- 1 Robustness through Training
- 2 Explicit Handling of Noise and Channel Variations
- 3 Robustness via Adaptation

Where Are We?

- 1 Robustness through Training
 - Introduction to Robustness Issues
 - Training-Based Robustness

Robustness - Things Change

- Background noise can increase or decrease.
- Channel can change.
 - Different microphone.
 - Microphone placement.
- Speaker characteristics vary.
 - Different glottal waveforms.
 - Different vocal tract lengths.
 - Different speaking rates.
- Heaven knows what else can happen.

Effects on a Typical Spectrum



Base Spectrum



Effect of Noise



Different Channel



Different Glottal
Waveform



Different Vocal
Tract Length

What happens when things change?

Recognition performance falls apart!

Why?

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How do we mitigate the effects of such changes? What components of the system should we look at?

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Why?

Because the features on which the system was trained have changed.

How do we mitigate the effects of such changes? What components of the system should we look at?

The Acoustic Model: $P(O|W, \theta)$ and the features O seem to be the most logical choices. So what can we do?

Robustness Strategies

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Robustness Strategies

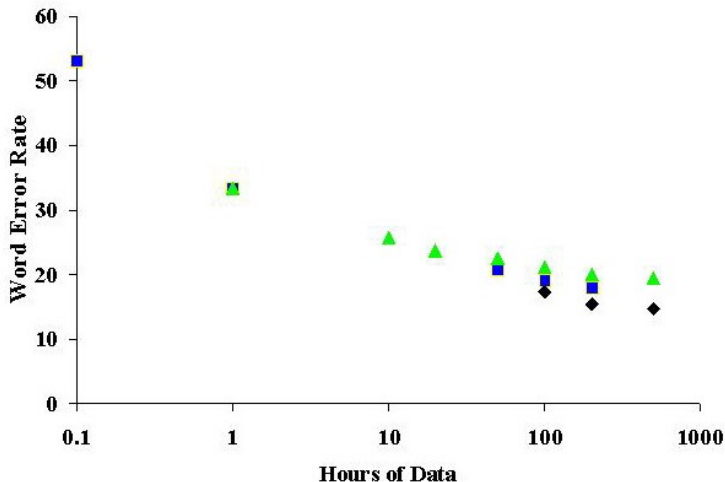
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 - Works well when model fits, requires less data.
- **Adaptation:** Update estimate of θ from new observations.
 - Very powerful but often requires the most data
 $\theta' = f(D, p(O|W, \theta))$.

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General Training Requirements

Most systems today require > 200 hours of speech from > 200 speakers to train robustly for a new domain.



General Retraining

- If the environment changes, retrain system from scratch in new environment.
 - Very expensive - cannot collect hundreds of hours of data for each new environment.
- Two strategies.
 - Environment simulation.
 - Multistyle Training.

Environment Simulation

- Take training data.
- Measure parameters of new environment.
- Transform training data to match new environment.
- Retrain system, hope for the best.

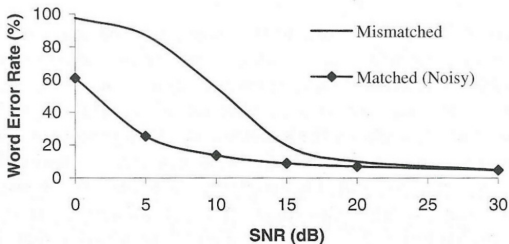


Figure 10.31 Word error rate as a function of the testing data SNR (dB) for Whisper trained on clean data and a system trained on noisy data at the same SNR as the testing set as in Figure 10.30. White noise at different SNRs is added.

Multistyle Training

- Take training data.
- Corrupt/transform training data in various representative fashions.
- Collect training data in a variety of representative environments.
- Pool all such data together; retrain system.

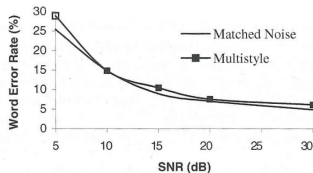


Figure 10.32 Word error rates of multistyle training compared to matched-noise training as a function of the SNR in dB for additive white noise. Whisper is trained as in Figure 10.30. The error rate of multistyle training is between 12% (for low SNR) and 25% (for high SNR) higher in relative terms than that of matched-condition training. Nonetheless, multistyle training does better than a system trained on clean data for all conditions other than clean speech.

Issues with System Retraining

- Simplistic models of degradations
 - E.g. telephony degradations more than just a decrease in bandwidth.
- Hard to anticipate every possibility.
 - In high noise environment, person speaks louder with resultant effects on glottal waveform, speed, etc.
- System performance in clean environment can be degraded.
- Retraining system for each environment is very expensive.
- Therefore other schemes - noise modeling and general forms of adaptation - are needed and sometimes used in tandem with these other schemes.

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- 2 Explicit Handling of Noise and Channel Variations
- 3 Robustness via Adaptation

Where Are We?

2 Explicit Handling of Noise and Channel Variations

- Cepstral Mean Normalization
- Spectral Subtraction
- Codeword Dependent Cepstral Normalization
- Parallel Model Combination

Cepstral Mean Normalization

We can model a large class of **channel** and **speaker** distortions as a simple linear filter applied to the speech:

$$\hat{y}[n] = \hat{x}[n] * \hat{h}[n]$$

where $\hat{h}[n]$ is our linear filter and $*$ denotes convolution (Lecture 1). In the frequency domain we can write

$$\hat{Y}(k) = \hat{X}(k)\hat{H}(k)$$

Taking the logarithms of the amplitudes:

$$\log \hat{Y}(k) = \log \hat{X}(k) + \log \hat{H}(k)$$

that is, the effect of the linear distortion is to add a constant vector to the amplitudes in the log domain.

Cepstral Mean Normalization (con't)

Now if we examine our normal cepstral processing, we can write this as the following processing sequence.



$$\begin{aligned} O'[k] &= \text{Cepst}(\log \text{Bin}(\text{FFT}(\hat{x}[n] * \hat{h}(n)))) \\ &= \text{Cepst}(\log \text{Bin}(\hat{X}(k)\hat{H}(k))) \\ &\approx \text{Cepst}(\log(\hat{X}(k)\hat{H}(k))) \\ &\approx \text{Cepst}(\log \hat{X}(k)) + \text{Cepst}(\log \hat{H}(k)) \end{aligned}$$

Cepstral Mean Normalization (con't)

So, we can essentially model the effect of linear filtering as just adding a constant vector in the cepstral domain:

$$\mathbf{O}'[k] = \mathbf{O}[k] + \mathbf{b}[k]$$

and robustness can be achieved by estimating $\mathbf{b}[k]$ and subtracting it from the observed $\mathbf{O}'[k]$.

Cepstral Mean Normalization - Implementation

How do we eliminate effects of linear filtering?

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Basic Idea: Assume all speech is linearly filtered but that the linear filter changes slowly with respect to speech (many seconds or minutes).

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Given a set of cepstral vectors \mathbf{O}_t we can compute the mean:

$$\bar{\mathbf{O}} = \frac{1}{N} \sum_{t=1}^N \mathbf{O}_t$$

In "Cepstral mean normalization" we subtract the mean of a set of cepstral vectors from each vector individually

$$\hat{\mathbf{O}}_t = \mathbf{O}_t - \bar{\mathbf{O}}$$

Cepstral Mean Normalization - Implementation (con't)

If we apply a linear filter to the signal, the output \mathbf{O}_t is "distorted" by the addition of a vector \mathbf{b} :

$$\mathbf{y}_t = \mathbf{O}_t + \mathbf{b}$$

The mean of \mathbf{y}_t is

$$\bar{\mathbf{y}} = \frac{1}{N} \sum_{t=1}^N \mathbf{y}_t = \frac{1}{N} \sum_{t=1}^N (\mathbf{O}_t + \mathbf{b}) = \bar{\mathbf{O}} + \mathbf{b}$$

so after "Cepstral Mean Normalization"

$$\hat{\mathbf{y}}_t = \mathbf{y}_t - \bar{\mathbf{y}} = \hat{\mathbf{O}}_t$$

That is, the same output as if the filter \mathbf{b} had not been applied.

Cepstral Mean Normalization - Issues

- Error rates for utterances even in the same environment improves (Why?).
- Must be performed on both training and test data.
- Bad things happen if utterances are very short (Why?).
- Bad things happen if there is a lot of variable length silence in the utterance (Why?)
- Cannot be used in a real time system (Why?).

Cepstral Mean Normalization - Real Time Implementation

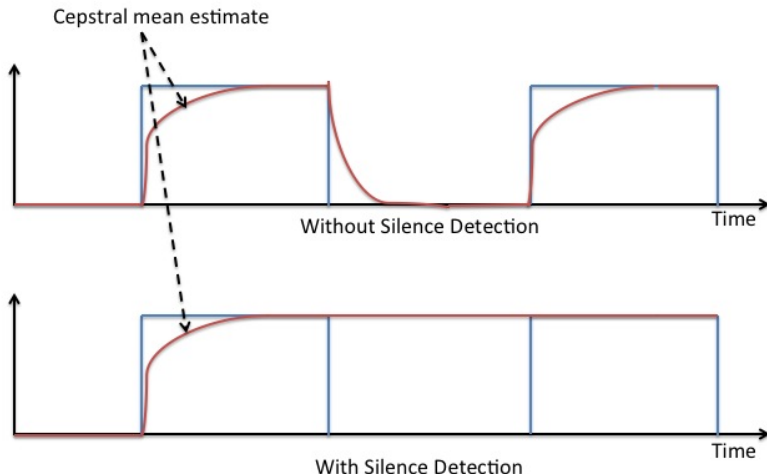
Can estimate mean dynamically as

$$\bar{\mathbf{O}}_t = \alpha \mathbf{O}_t + (1 - \alpha) \bar{\mathbf{O}}_{t-1}$$

In real-life applications, it is useful run a silence detector in parallel and turn adaptation off (set α to zero) when silence is detected, hence:

$$\bar{\mathbf{O}}_t = \alpha(s) \mathbf{O}_t + (1 - \alpha(s)) \bar{\mathbf{O}}_{t-1}$$

Cepstral Mean Normalization - Real Time Illustration



Cepstral Mean Normalization - Typical Results

From “Environmental Normalization for Robust Speech Recognition Using Direct Cepstral Compensation” F. Liu, R. STern, A. Acero and P. Moreno Proc. ICASSP 1994, Adelaide Australia

	Close Talking	Other Microphones
Base	8.1	38.5
CMN	7.6	21.4
Best Noise Immunity Scheme	8.4	13.5

Task is 5000-word WSJ LVCSR

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Spectral Subtraction - Background

Another common type of environmental distortion is additive noise. In such a case, we may write

$$y[i] = x[i] + n[i]$$

where $n[i]$ is some noise signal. Since we are dealing with linear operations, we can write in the frequency domain

$$Y[k] = X[k] + N[k]$$

Spectral Subtraction - Background

The power spectrum (Lecture 1) is therefore

$$|Y[k]|^2 = |X[k]|^2 + |N[k]|^2 + X[k]N^*[k] + X^*[k]N[k]$$

If we assume $n[i]$ is zero mean and uncorrelated with $x[i]$, the last two terms on the average would also be zero. Even though we window the signal and also bin the resultant amplitudes of the spectrum in the mel filter computation, it is still reasonable to assume the net contribution of the cross terms will be zero.

In such a case we can write

$$|Y[k]|^2 = |X[k]|^2 + |N[k]|^2$$

Spectral Subtraction - Background



Base Spectrum



Effect of Noise

Spectral Subtraction - Basic Idea

In such a case, it is reasonable to estimate $|X[k]|^2$ as:

$$|\hat{X}[k]|^2 = |Y[k]|^2 - |\hat{N}[k]|^2$$

where $|\hat{N}[k]|^2$ is some estimate of the noise.



Spectral Estimate

Spectral Subtraction - Basic Idea

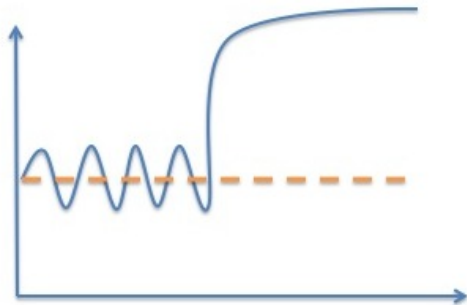
One way to estimate $N(k)$ is to average $|Y[k]|^2$ over a sequence of frames known to be silence (by using a silence detection scheme):

$$|\hat{N}[k]|^2 = \frac{1}{M} \sum_{t=0}^{M-1} |Y_t[k]|^2$$

Note that $Y[k]$ here can either be the FFT output (when trying to actually reconstruct the original signal) or, in speech recognition, the output of the FFT after Mel binning.

Spectral Subtraction - Issues

The main issue with Spectral Subtraction is that $|\hat{N}[k]|^2$ is only an estimate of the noise, not the actual noise value itself. In a given frame, $|Y[k]|^2$ may be less than $|\hat{N}[k]|^2$. In such a case, $|\hat{X}[k]|^2$ would be negative, wreaking havoc when we take the logarithm of the amplitude when computing the mel-cepstra.

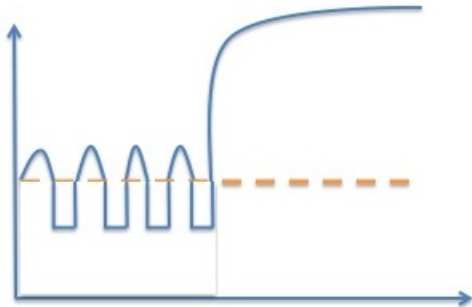


Spectral Subtraction - Issues

The standard solution to this problem is just to “floor” the estimate of $|\hat{X}[k]|^2$:

$$|\hat{X}[k]|^2 = \max(|Y[k]|^2 - |\hat{N}[k]|^2, \beta)$$

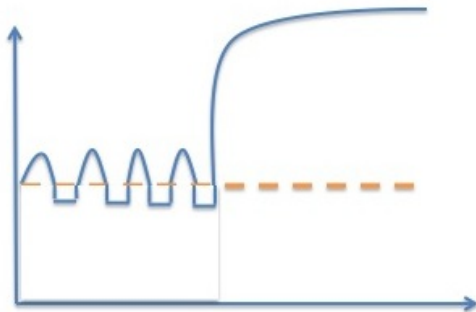
where β is some appropriately chosen constant.



Spectral Subtraction - Issues

Given that for any realistic signal, the actual $|X(k)|^2$ has some amount of background noise, we can estimate this noise during training similarly to how we estimate $|N(k)|^2$. Call this estimate $|N_{\text{train}}[k]|^2$. In such a case our estimate for $|X(k)|^2$ becomes

$$|\hat{X}[k]|^2 = \max(|Y[k]|^2 - |\hat{N}[k]|^2, |N_{\text{train}}[k]|^2)$$

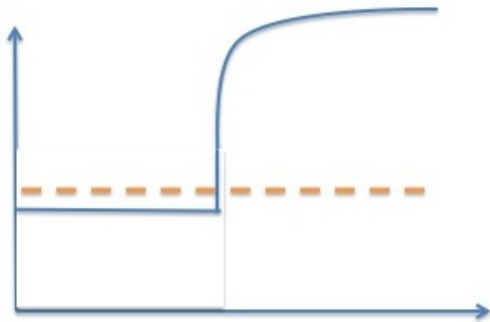


Spectral Subtraction - Issues

Because of the variance of the noise process, little “spikes” still arise. To deal with this, sometimes “oversubtraction” is used:

$$|\hat{X}[k]|^2 = \max(|Y[k]|^2 - \alpha|\hat{N}[k]|^2, |N_{\text{train}}[k]|^2)$$

where α is some constant chosen to minimize the noise spikes when there is no speech.



Spectral Subtraction - Performance

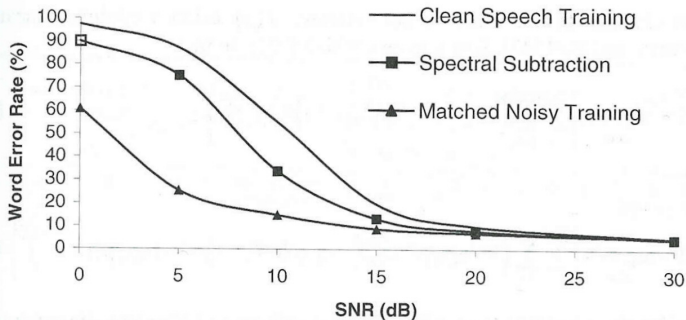


Figure 10.28 Word error rate as a function of SNR (dB) using Whisper on the *Wall Street Journal* 5000-word dictation task. White noise was added at different SNRs. The solid line represents the baseline system trained with clean speech, the line with squares the use of spectral subtraction with the previous clean HMMs. They are compared to a system trained on the same speech with the same SNR as the speech tested on.

Administrivia

- Lab 4 due tonight at 11:59pm.
- Reading projects: If you haven't already ...
 - E-mail Stan paper selection ASAP!
- Make-up class: Wednesday, **December 12**, 4:10–6:40pm.
 - Location: right here, Mudd 633.
- Non-reading projects.
 - A couple things in setups left to finish.
 - Ask Stan if you need anything!

Where Are We?

2 Explicit Handling of Noise and Channel Variations

- Cepstral Mean Normalization
- Spectral Subtraction
- **Codeword Dependent Cepstral Normalization**
- Parallel Model Combination

Speech Model Based Robustness

Yet another problem with Spectral Subtraction is that the reconstructed speech vector may not look like "real" speech.



Base Spectrum



Spectral Estimate

Why?

Speech Model Based Robustness

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Base Spectrum



Spectral Estimate

Why? There is no explicit model of speech used - just a model for the "noise".

Generalization: Minimum Mean Square Error Estimation

Let x be a speech vector and y be some corrupted version of x . We get to observe y and wish to devise an estimate for x , \hat{x} . One possibility: find an estimate such that the average value of $(x - \hat{x})^2$ is minimized.

It can be shown that the best estimator \hat{x} in such a case is:

$$\hat{x} = E(x|y) = \int x p(x|y) dx$$

Observe that implicitly through $p(x|y)$ there is a model for the input speech x (why?).

Modeling $p(x|y)$ via Gaussian Mixtures

Now

$$p(x|y) = p(x, y)/p(y)$$

Let us model $p(x, y)$ as a function of a sum of K distributions:

$$p(x, y) = \sum_{k=1}^K p(x, y|k)p(k)$$

Let us write

$$p(x, y|k) = p(y|x, k)q(x|k)$$

where

$$q(x|k) = \frac{1}{K} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu_k)^2}{2\sigma^2}}$$

Questions: What is the speech model? What is the degradation model?

Model for Noise and Channel Degradations

Let's combine the effects of speaker/channel distortion and additive noise on the spectrum:

$$Y = HX + N$$

Taking logarithms

$$\ln Y = \ln X + \ln H + \ln\left(1 + \frac{N}{HX}\right)$$

Switching to the log domain we get

$$y^l = x^l + h^l + \ln(1 + e^{n^l - x^l - h^l})$$

Using the notation $y = Cy^l$ to move to the cepstral domain we get

$$y = x + h + C \ln(1 + e^{C^{-1}(n-x-h)}) = x + h + r(x, n, h)$$

so to reconstruct x given estimates of h and n

$$x = y - h - r(x, n, h)$$

Incorporating a Model of Noise and Channel Degradation

From above, our degradation model is

$$x = y - h - r(x, n, h)$$

which is equivalent to saying $p(y|x, k)$ is just a deterministic mapping. Mathematically, this can be written as

$$p(y|x, k) = \delta(x - (y - h - r(x, n, h)))$$

where $\delta(t)$ is a delta (impulse) function.

What's the problem with just using this to estimate x ?

CDCN - Codeword Dependent Cepstral Normalization

Remember that

$$r(x, n, h) = C \ln(1 + e^{C^{-1}(n-x-h)})$$

The main assumption in CDCN is that the correction vector $r(x, n, h)$ is constant for a given mixture component k and only depends on the mean of the component.

$$r[k] = C \ln(1 + e^{C^{-1}(n-\mu_k-h)})$$

In this case we can write

$$p(y|x, k) = \delta(x - (y - h - r[k]))$$

CDCN - Codeword Dependent Cepstral Normalization

Note also that because of the nature of the delta function:

$$\begin{aligned} p(y) &= \int p(x, y) dx \\ &= \int \sum_{k=1}^K \delta(x - (y - h - r[k])) q(x|k) dx \\ &= \sum_{k=1}^K \int \delta(x - (y - h - r[k])) q(x|k) dx \\ &= \sum_{k=1}^K q(y - h - r[k]|k) \end{aligned}$$

Estimation Equations

We now may write the estimate for x as

$$\begin{aligned}\hat{x} &= \int x p(x|y) dx \\ &= \int x \frac{p(x, y)}{\sum_{l=1}^K q(y - h - r[l]|l)} dx \\ &= \int x \frac{\sum_{k=1}^K \delta(x - (y - h - r[k])) q(x|k)}{\sum_{l=1}^K q(y - h - r[l]|l)} dx \\ &= \sum_{k=1}^K \frac{(y - h - r[k]) q(y - h - r[k]|k)}{\sum_{l=1}^K q(y - h - r[l]|l)}\end{aligned}$$

Note the term involving q is just the mixture of gaussian posterior probability we saw in Lecture 3. Iterative equations for estimating h and n can also be developed; refer to the reading for more information.

Other Variations

Vector Taylor Series is a CDCN variant in which r is approximated as a linearized function with respect to x and μ_k rather than assumed constant.

Algonquin is a more sophisticated CDCN variant in which $p(y|x, k)$ is assumed to have an actual probability distribution (e.g., Normal) to model noise phase uncertainty.

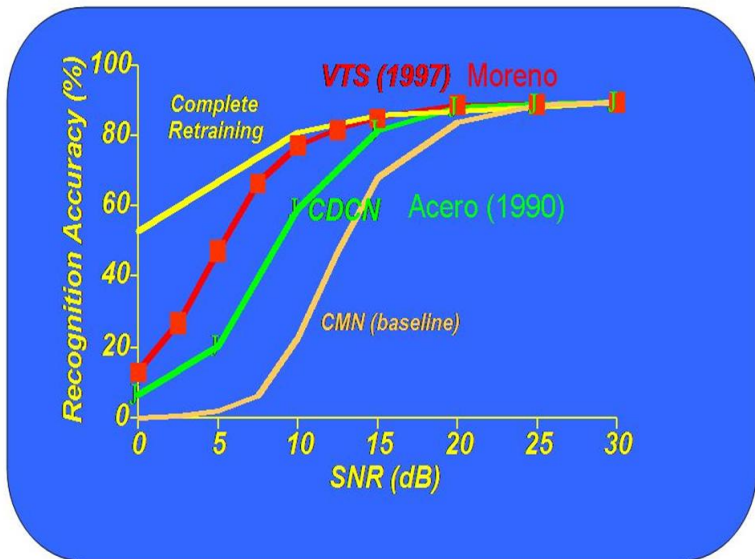
CDCN Performance

From Alex Acero's PhD Thesis "Acoustical and Environmental Robustness in Automatic Speech Recognition" CMU (1990):

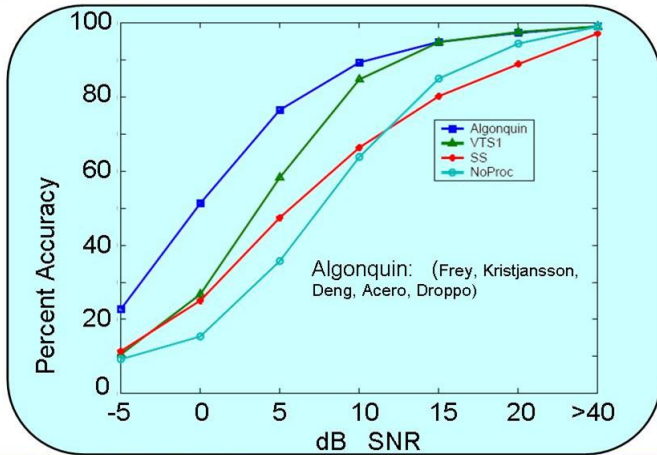
TRAIN/TEST	CLS/CLS	CLS/PZM	PZM/CLS	PZM/PZM
BASE	14.7	81.4	63.1	23.5
CMR	N/A	61.7	49.1	23.5
PSUB	N/A	61.4	29.4	29.9
MSUB	N/A	37.4	28.3	28.7
CDCN	14.7	25.1	26.3	22.1

Error rates for a SI alphanumeric task recorded on two different microphones.

Additional Performance Figures



Additional Performance Figures



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- Spectral Subtraction
- Codeword Dependent Cepstral Normalization
- **Parallel Model Combination**

Parallel Model Combination - Basic Idea

Idea: Incorporate model of noise directly into our GMM-based HMMs.

If our observations were just the FFT outputs this would be straightforward. In such a case, the corrupted version of our signal x with noise n is just:

$$y = x + n$$

If $x \sim N(\mu_x, \sigma_x^2)$ and $n \sim N(\mu_n, \sigma_n^2)$ then $y \sim N(\mu_x + \mu_n, \sigma_x^2 + \sigma_n^2)$

But our observations are cepstral parameters - extremely nonlinear transformations of the space in which the noise is additive. What do we do?

Parallel Model Combination - One Dimensional Case

Let us make a Very Simple approximation to Cepstral parameters: $X = \ln x$, $N = \ln n$.

Pretend we are modeling these “cepstral” parameters with “HMMs” in the form of univariate Gaussians. In such a case, let us say $X \sim N(\mu_X, \sigma_X^2)$ and $N \sim N(\mu_N, \sigma_N^2)$. We can then write:

$$Y = \ln(e^X + e^N)$$

What is the probability distribution of Y ?

Parallel Model Combination - Log Normal Distribution

If X is a Gaussian random variable with mean μ and variance σ^2 then $x = e^X$ follows the *lognormal* distribution:

$$p(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right)$$

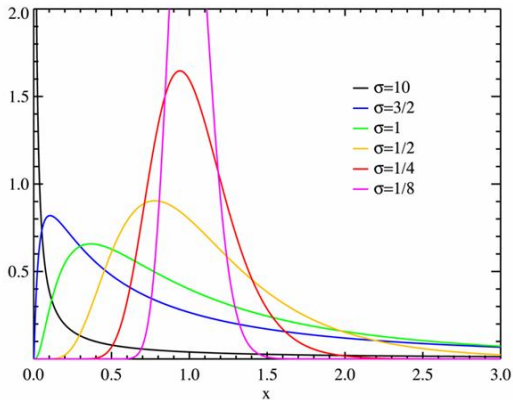
The mean of this distribution can be shown to be

$$E(x) = \int x p(x) dx = \exp(\mu + \sigma^2/2)$$

and the variance

$$E((x - E(x))^2) = \int (x - E(x))^2 p(x) dx = \mu^2(\exp(\sigma^2) - 1)$$

Parallel Model Combination - Log Normal Distribution



Parallel Model Combination - Lognormal Approximation

Since back in the linear domain

$$y = x + n$$

the distribution of y will correspond to the distribution of a sum of two lognormal variables x and n .

$$\mu_x = \exp(\mu_X + \sigma_X^2/2)$$

$$\sigma_x^2 = \mu_X^2(\exp(\sigma_X^2) - 1)$$

$$\mu_n = \exp(\mu_N + \sigma_N^2/2)$$

$$\sigma_n^2 = \mu_N^2(\exp(\sigma_N^2) - 1)$$

If x and n are uncorrelated, we can write:

$$\mu_y = \mu_x + \mu_n$$

$$\sigma_y^2 = \sigma_x^2 + \sigma_n^2$$

Parallel Model Combination - Lognormal Approximation

Unfortunately, although the sum of two Gaussian variables is a Gaussian, the sum of two lognormal variables is not lognormal.

As good engineers, we will promptly ignore this fact and act as if y DOES have a lognormal distribution (!). In such a case, $Y = \ln y$ is Gaussian and the mean and variance are given by:

$$\mu_Y = \ln \mu_y - \frac{1}{2} \ln \left[\frac{\sigma_y^2}{\mu_y^2} + 1 \right]$$
$$\sigma_Y^2 = \ln \left[\frac{\sigma_y^2}{\mu_y^2} + 1 \right]$$

The matrix and vector forms of the modified means and variances, similar to the unidimensional forms above, can be found in HAH pg. 533

Parallel Model Combination - Actual Cepstra

Remember that the mel-cepstra are computed from mel-spectra by the following formula:

$$c[n] = \sum_{m=0}^{M-1} X[m] \cos(\pi n(m - 1/2)/M)$$

We can view this as just a matrix multiplication:

$$\mathbf{c} = \mathbf{C}\mathbf{x}$$

where \mathbf{x} is just the vector of the $X[m]$ s and the components of matrix \mathbf{C} are

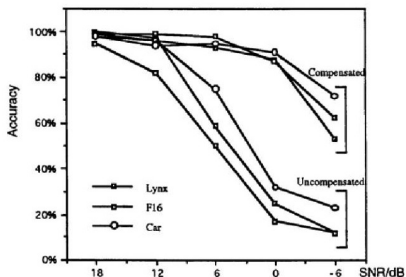
$$C_{ij} = \cos(\pi j(i - 1/2)/M)$$

In such a case, the mean and covariance matrix in the mel-spectral domain can be computed as

$$\begin{aligned}\mu_{\mathbf{x}} &= \mathbf{C}^{-1} \mu_{\mathbf{c}} \\ \Sigma_{\mathbf{x}} &= \mathbf{C}^{-1} \Sigma_{\mathbf{c}} (\mathbf{C}^{-1})^T\end{aligned}$$

and similarly for the noise cepstra.

Parallel Model Combination - Performance



"PMC for Speech Recognition in Convolutional and Additive Noise" by Mark Gales and Steve Young TR-154 Cambridge U. 1993.

Although comparisons seem to be rare, when PMC is compared to schemes such as VTS, VTS seems to have proved somewhat superior in performance. However, the basic concepts of PMC have been recently combined with EM-like estimation schemes to significantly enhance performance.

Where Are We?

- 1 Robustness through Training
- 2 Explicit Handling of Noise and Channel Variations
- 3 Robustness via Adaptation

Where Are We?

3 Robustness via Adaptation

- MAP Adaptation
- Maximum Likelihood Linear Regression
- Feature-Based MLLR

Maximum A Posteriori Parameter Estimation

- Basic Idea

Another way to achieve robustness is to take a fully trained HMM system, a small amount of data from a new domain, and combine the information from the old and new systems together.

To put everything on a sound framework, we will utilize the parameters of the fully-trained HMM system as *prior* information.

Maximum A Posteriori Parameter Estimation

- Basic Idea

In Maximum Likelihood Estimation (Lecture 3) we try to pick a set of parameters $\hat{\theta}$ that maximize the likelihood of the data:

$$\hat{\theta} = \arg \max_{\theta} \mathcal{L}(O_1^N | \theta)$$

In Maximum A Posterior Estimation we assume there is some prior probability distribution on θ , $p(\theta)$ and we try to pick $\hat{\theta}$ to maximize the a posteriori probability of θ given the observations:

$$\begin{aligned} \hat{\theta} &= \arg \max_{\theta} p(\theta | O_1^N) \\ &= \arg \max_{\theta} \mathcal{L}(O_1^N | \theta) p(\theta) \end{aligned}$$

Maximum A Posteriori Parameter Estimation

- Conjugate Priors

What form should we use for $p(\theta)$? To simplify later calculations, we try to use an expression so that $\mathcal{L}(O_1^N|\theta)p(\theta)$ has the same functional form as $\mathcal{L}(O_1^N|\theta)$. This type of form for the prior is called a *conjugate prior*.

In the case of a univariate Gaussian we are trying to estimate μ and σ . Let $r = 1/\sigma^2$. An appropriate conjugate prior is:

$$p(\theta) = p(\mu, r) \propto r^{(\alpha-1)/2} \exp\left(-\frac{\tau r}{2}(\mu - \mu_p)^2\right) \exp(-(\sigma_p^2 r/2))$$

where μ_p and σ_p^2 are prior estimates/knowledge of the mean and variance from some initial set of training data. Note how ugly the functional forms get even for a relatively simple case!

Maximum A Posteriori Parameter Estimation

- Univariate Gaussian Case

Without torturing you with the math, we can plug in the conjugate prior expression and compute μ and r to maximize the a posteriori probability. We get

$$\hat{\mu} = \frac{N}{N + \tau} \mu_O + \frac{\tau}{N + \tau} \mu_p$$

where μ_O is the mean of the data computed using the ML procedure.

$$\hat{\sigma}^2 = \frac{N}{N + \alpha - 1} \sigma_O^2 + \frac{\tau(\mu_O - \hat{\mu})^2 + \sigma_p^2}{N + \alpha - 1}$$

Maximum A Posteriori Parameter Estimation

- General HMM Case

Through a set of similar manipulations, we can generalize the previous formula to the HMM case.

- 1 Align adaptation data against a set of existing HMM models.
- 2 Collect counts $C_t(i, j)$, the fractional count (aka the posterior probability) at time t for being in mixture component j of state i

Either a simple Viterbi alignment or the complete F-B algorithm can be used to estimate $C_t(i, j)$

Maximum A Posteriori Parameter Estimation

- General HMM Case

c_{ik} is the prior estimate for the mixture weight k for state i

ν_{ik} , μ_{ik} , Σ_{ik} are the prior estimates for the mixture counts, mean and covariance matrix of mixture component k for state i from a previously trained HMM system. In this case:

$$\hat{c}_{ik} = \frac{\nu_{ik} - 1 + \sum_t C_t(i, k)}{\sum_l (\nu_{il} - 1 + \sum_t C_t(i, l))}$$

$$\hat{\mu}_{ik} = \frac{\tau_{ik} \mu_{ik} + \sum_{t=1}^N C_t(i, k) \mathbf{O}_t}{\tau_{ik} + \sum_t C_t(i, k)}$$

Maximum A Posteriori Parameter Estimation

- General HMM Case

$$\begin{aligned}\hat{\Sigma}_{ik} = & \frac{(\alpha_{ik} - D)\Sigma_{ik}}{\alpha_{ik} - D + \sum_{t=1}^N C_t(i, k)} \\ & + \frac{\tau_{ik}(\hat{\mu}_{ik} - \mu_{ik})(\hat{\mu}_{ik} - \mu_{ik})^t}{\alpha_{ik} - D + \sum_{t=1}^N C_t(i, k)} \\ & + \frac{\sum_{t=1}^N C_t(i, k)(\mathbf{O}_t - \hat{\mu}_{ik})(\mathbf{O}_t - \hat{\mu}_{ik})^t}{\alpha_{ik} - D + \sum_{t=1}^N C_t(i, k)}\end{aligned}$$

Both τ and α are balancing parameters that can be tuned to optimize performance on different test domains. In practice, a single τ is adequate across all states and Gaussians, and variance adaptation rarely has been successful.

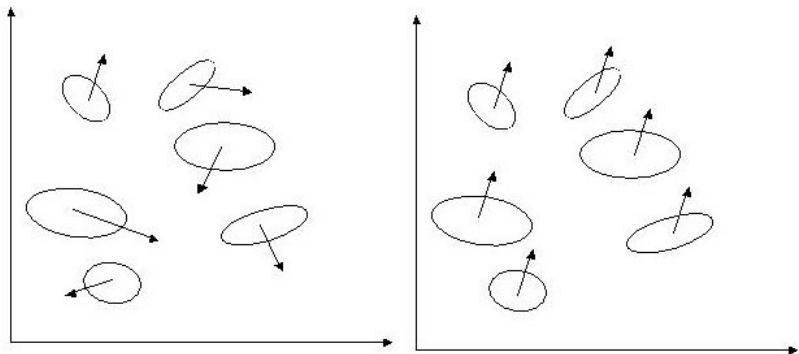
Where Are We?

3 Robustness via Adaptation

- MAP Adaptation
- Maximum Likelihood Linear Regression
- Feature-Based MLLR

Maximum Likelihood Linear Regression - Basic Idea

In MAP, the different HMM Gaussians are free to move in any direction. In Maximum Likelihood Linear Regression the means of the Gaussians are constrained to only move according to an affine transformation ($Ax + b$).



Simple Linear Regression - Review

Say we have a set of points $(x_1, y_1), (x_2, y_2), \dots, (x_N, y_N)$ and we want to find coefficients a, b so that

$$\sum_{t=1}^N (O_t - (ax_t + b))^2$$

is minimized. Define \mathbf{w} to be the column vector consisting of (a, b) , and the column vector \mathbf{x}_t corresponding to $(x_t, 1)$. We can then write the above set of equations as

$$\sum_{t=1}^N (O_t - \mathbf{x}_t^T \mathbf{w})^2$$

Taking derivatives with respect to \mathbf{w} we get

$$\sum_{t=1}^N 2\mathbf{x}_t(O_t - \mathbf{x}_t^T \mathbf{w}) = 0$$

so collecting terms we get

$$\mathbf{w} = \left[\sum_{t=1}^N \mathbf{x}_t \mathbf{x}_t^T \right]^{-1} \sum_{t=1}^N \mathbf{x}_t O_t$$

In MLLR, the x values will turn out to correspond to the means of the Gaussians.

MLLR for Univariate GMMs

We can write the likelihood of a string of observations $O_1^N = O_1, O_2, \dots, O_N$ from a Gaussian Mixture Model as:

$$\mathcal{L}(O_1^N) = \prod_{t=1}^N \sum_{k=1}^K \frac{p_k}{\sqrt{2\pi}\sigma_k} e^{-\frac{(O_t - \mu_k)^2}{2\sigma_k^2}}$$

It is usually more convenient to deal with the log likelihood

$$L(O_1^N) = \sum_{t=1}^N \ln \left[\sum_{k=1}^K \frac{p_k}{\sqrt{2\pi}\sigma_k} e^{-\frac{(O_t - \mu_k)^2}{2\sigma_k^2}} \right]$$

MLLR for Univariate GMMs

Let us now say we want to transform all the means of the Gaussian by $a\mu_k + b$. It is convenient to define \mathbf{w} as above, and to the augmented mean vector μ_k as the column vector corresponding to $(\mu_k, 1)$.

In such a case we can write the overall likelihood as

$$L(O_1^N) = \sum_{t=1}^N \ln \left[\sum_{k=1}^K \frac{p_k}{\sqrt{2\pi}\sigma_k} e^{-\frac{(O_t - \mu_k^T \mathbf{w})^2}{2\sigma_k^2}} \right]$$

To maximize the likelihood of this expression we utilize the E-M algorithm we have briefly alluded to in our discussion of the Forward-Backward (aka Baum-Welch) algorithm.

E-M Review

The E-M Theorem states that if

$$\begin{aligned} Q(\mathbf{w}, \mathbf{w}') &= \sum_x p_{\mathbf{w}}(X_1^N | O_1^N) \ln p_{\mathbf{w}'}(X_1^N, O_1^N) \\ &> \sum_x p_{\mathbf{w}}(X_1^N | O_1^N) \ln p_{\mathbf{w}}(X_1^N, O_1^N) \end{aligned}$$

then

$$p_{\mathbf{w}'}(O_1^N) > p_{\mathbf{w}}(O_1^N)$$

Therefore if we can find

$$\hat{\mathbf{w}}' = \arg \max_{\mathbf{w}'} Q(\mathbf{w}, \mathbf{w}')$$

we can iterate to find a \mathbf{w} that maximizes $p_{\mathbf{w}}(O_1^N)$ or equivalently $L(O_1^N)$

E-M for MLLR

For a Gaussian mixture, it can be shown that

$$Q(\mathbf{w}, \mathbf{w}') = \sum_{k=1}^K \sum_{t=1}^N C_t(k) [\ln p_k - \ln \sqrt{2\pi\sigma_k} - (O_t - \boldsymbol{\mu}_k^T \mathbf{w}')^2 / 2\sigma_k^2]$$

where

$$C_t(k) = p_{\mathbf{w}}(k|O) = \frac{\frac{p_k}{\sqrt{2\pi\sigma_k}} e^{-\frac{(O_t - \boldsymbol{\mu}_k^T \mathbf{w})^2}{2\sigma_k^2}}}{\sum_{l=1}^K \frac{p_l}{\sqrt{2\pi\sigma_l}} e^{-\frac{(O_t - \boldsymbol{\mu}_l^T \mathbf{w})^2}{2\sigma_l^2}}}$$

E-M for MLLR

We can maximize $Q(\mathbf{w}, \mathbf{w}')$ by computing it's derivative and setting it equal to zero:

$$\sum_{t=1}^N \left[\sum_{k=1}^K C_t(k) \frac{\mu_k}{\sigma_k^2} (O_t - \mu_k^T \mathbf{w}') \right] = 0$$

Collecting terms we get

$$\sum_{t=1}^N \sum_{k=1}^K C_t(k) \frac{\mu_k \mu_k^T}{\sigma_k^2} \mathbf{w}' = \sum_{t=1}^N \sum_{k=1}^K C_t(k) \frac{\mu_k}{\sigma_k^2} O_t$$

Switching the summations we get

$$\sum_{k=1}^K \frac{\mu_k \mu_k^T}{\sigma_k^2} \mathbf{w}' \sum_{t=1}^N C_t(k) = \sum_{k=1}^K \frac{\mu_k}{\sigma_k^2} \sum_{t=1}^N C_t(k) O_t$$

E-M for MLLR

Define $C(k) = \sum_t C_t(k)$ and $\bar{O}(k) = \frac{1}{C(k)} \sum_t C_t(k) O_t$, we can rewrite the above as

$$\left[\sum_{k=1}^K C(k) \frac{\mu_k \mu_k^T}{\sigma_k^2} \right] \mathbf{w}' = \sum_{k=1}^K C(k) \frac{\mu_k}{\sigma_k^2} \bar{O}(k)$$

so we may compute \mathbf{w}' as just:

$$\mathbf{w}' = \left[\sum_{k=1}^K C(k) \frac{\mu_k \mu_k^T}{\sigma_k^2} \right]^{-1} \sum_{k=1}^K C(k) \frac{\mu_k}{\sigma_k^2} \bar{O}(k)$$

compare to the expression for simple linear regression:

$$\mathbf{w} = \left[\sum_{t=1}^N \mathbf{x}_t \mathbf{x}_t^T \right]^{-1} \sum_{t=1}^N \mathbf{x}_t O_t$$

E-M for MLLR

In actual speech recognition systems, the observations are vectors, not scalars, so the transform to be estimated is of the form

$$\mathbf{A}\mu + \mathbf{b}$$

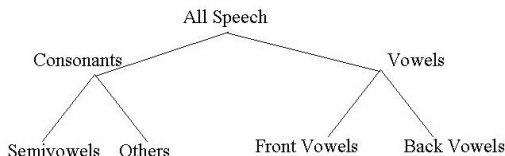
where \mathbf{A} is a matrix and \mathbf{b} is a vector. The resultant MLLR equations are somewhat more complex but follow the same basic form. We refer you to the readings for the details.

MLLR - Additional Considerations

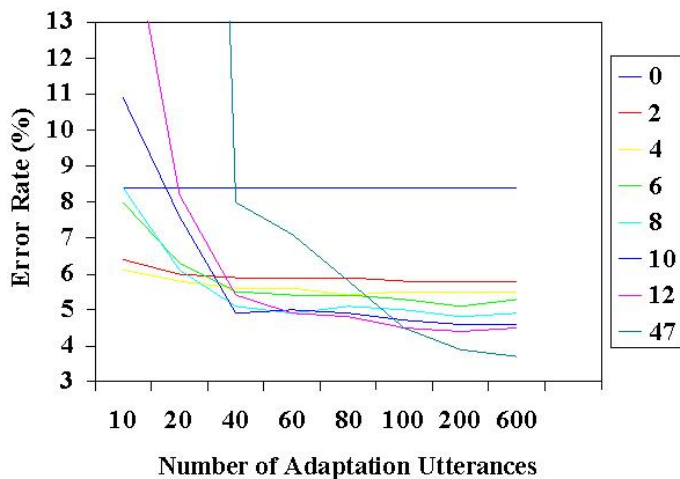
- Typical parameter vector: 39 dimensions (why?)
- So the number of matrix parameters to be estimated is roughly 1600.
- Approximately one frame of data gives you enough information to estimate one parameter
- Therefore, need at least 16 seconds of speech to estimate a full 39x39 MLLR matrix.

MLLR - Multiple Transforms

- Single MLLR transform for all of speech is very restrictive.
- Multiple transforms can be created having state dependent transforms.
- Arrange states in form of tree
- If there are enough frames at a node, a separate transform is estimated for all the phones at the node.



MLLR - Performance



Where Are We?

3 Robustness via Adaptation

- MAP Adaptation
- Maximum Likelihood Linear Regression
- **Feature-Based MLLR**

Feature Based MLLR

Let's say we now want to transform all the means by

$$\mu_k / a - b / a$$

and the variances by

$$\sigma_k^2 / a^2$$

Define \mathbf{O}_t as the augmented column observation vector $(O_t, 1)$, $\mathbf{w} = (a, b)^T$ as above, and $\mathbf{r} = (1, 0)^T$. We can therefore write

$$\begin{aligned} Q(\mathbf{w}, \mathbf{w}') &= \sum_{k=1}^K \sum_{t=1}^N C_t(k) [\ln p_k \\ &\quad - \ln \sqrt{2\pi\sigma_k} + \ln \mathbf{r}^T \mathbf{w}' - (\mathbf{O}_t^T \mathbf{w}' - \mu_k)^2 / 2\sigma_k^2] \end{aligned}$$

with $C_t(k)$ defined similarly as in the MLLR discussion.

Feature-Based fMLLR

The primary advantage is that the resultant likelihood can also be produced by just linearly transforming the input features

$$\mathbf{O}'_t = \mathbf{w}'\mathbf{O}_t$$

Therefore, the transformation can be easily applied at runtime rather than updating the models (why is that expensive?)

The details on how to solve the optimization equations are given in the paper in the readings (“Maximum Likelihood Linear Transformations for HMM-Based Speech Recognition”, Mark Gales, Computer Speech and Language 1998 Volume 12).

Performance of MLLR and fMLLR

	Test1	Test2
BASE	9.57	9.20
MLLR	8.39	8.21
fMLLR	9.07	7.97
SAT	8.26	7.26

Task is Broadcast News with a 65K vocabulary.

SAT refers to “Speaker Adaptive Training”. In SAT, a transform is computed for each speaker during test and training; it is a very common training technique in ASR today.

MLLR and MAP - Performance

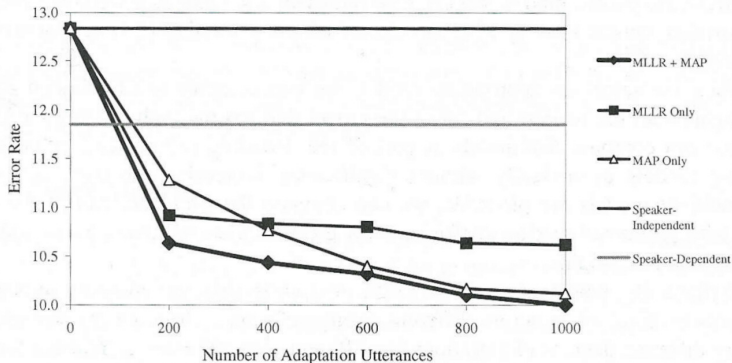


Figure 9.11 Comparison of Whisper with MLLR, MAP, and combined MLLR and MAP. The error rate is shown for a different amount of adaptation data. The speaker-dependent and speaker-independent models are also included. The speaker-dependent model was trained with 1000 sentences.

MLLR - Comments on Noise Immunity Performance

Last but not least, one can also apply MLLR and fMLLR as a noise compensation scheme.

it is claimed that MLLR/fMLLR alone is inferior to the most recent sophisticated model-based noise compensation schemes incorporating E-M estimation of PMC updates but comprehensive comparisons are not readily available.

See “HIGH-PERFORMANCE HMM ADAPTATION WITH JOINT COMPENSATION OF ADDITIVE AND CONVOLUTIVE DISTORTIONS VIA VECTOR TAYLOR SERIES” Jinyu Li¹, Li Deng, Dong Yu, Yifan Gong, and Alex Acero” (ASRU 2007, Japan) for more details.

COURSE FEEDBACK

- Was this lecture mostly clear or unclear? What was the muddiest topic?
- Other feedback (pace, content, atmosphere)?