Real-Time Hardware Implementation of Telephone Speech Enhancement Algorithm

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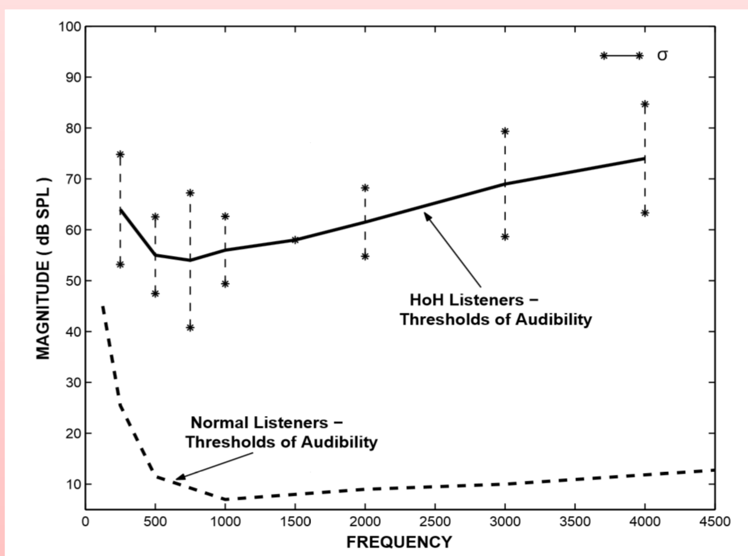
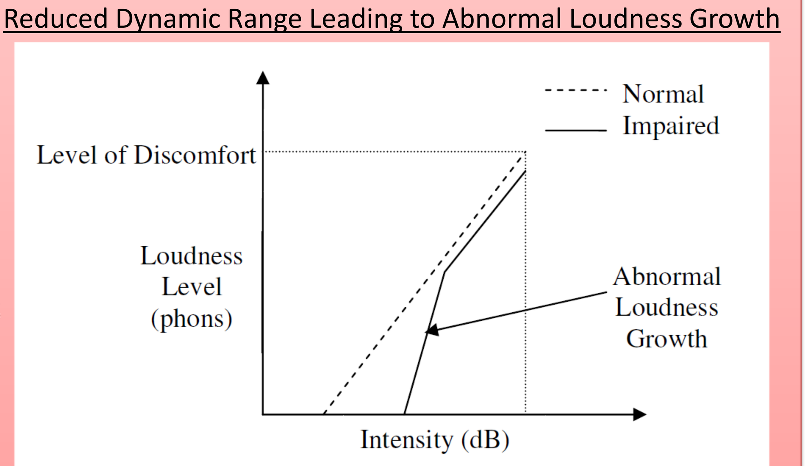
The Problem

- Hard of Hearing (HoH) people often struggle with telephone communication
- The Question: How can telephone communication be improved for the HoH?
- Hearing aids can be uncomfortable during telephone use
- The threshold of hearing for the HoH is much higher than normal which results in reduced dynamic range
- Reduced dynamic range creates abnormal loudness growth in HoH people which leads to discomfort and even pain

Threshold of Audibility for Normal and HoH Listeners



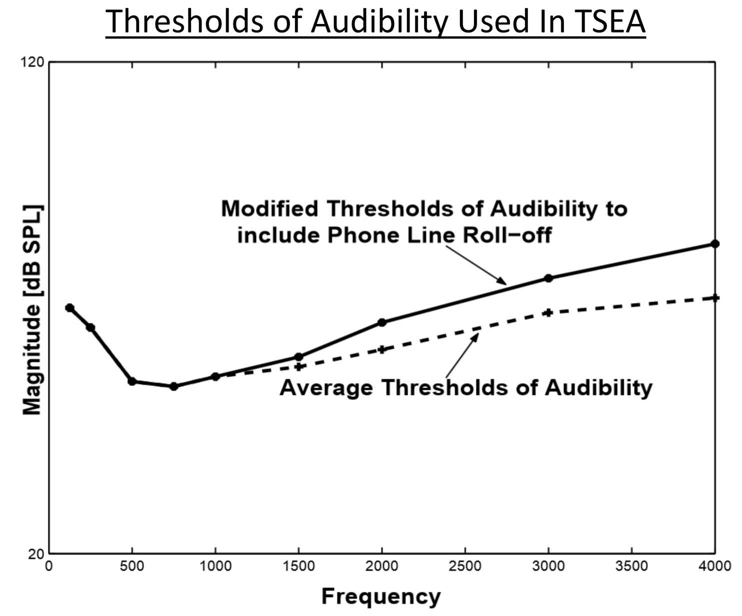
Reduced Dynamic Range Leading to Abnormal Loudness Growth



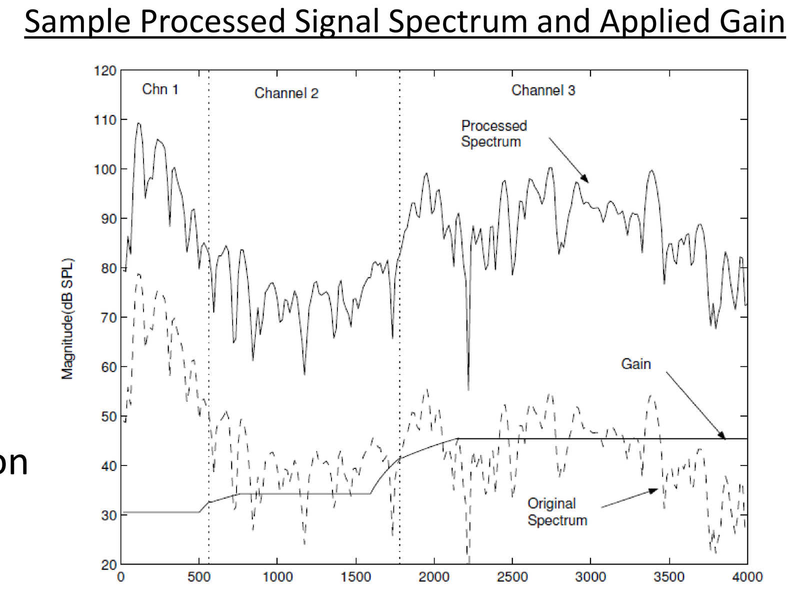
The Solution

- The Telephone Speech Enhancement Algorithm (TSEA) developed by Natarajan
- This solution is unique in the fact that it preprocesses speech signals before transmission over the phone line
- The goal is to process speech signals so they lie within the HoH listener's dynamic range
- TSEA is a three-channel compression algorithm
- Dynamically varies channel boundaries based on formant frequency peaks
- Boosts higher frequencies important to speech perception that are limited by HoH audibility thresholds and reduced phone line bandwidth
- Gain calculations based on the dynamic range ratios of normal and HoH listeners
- Low amplitude consonant sounds are amplified while higher amplitude vowel sounds remain comfortably loud
- TSEA proven effective at improving speech perception

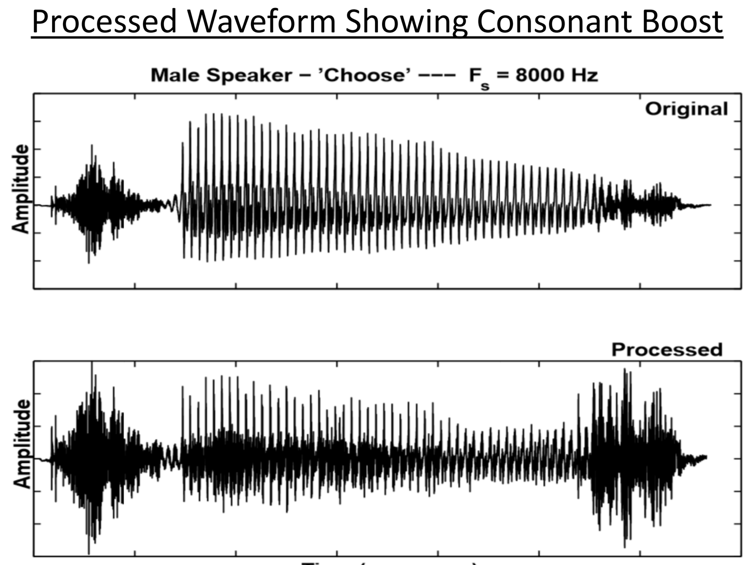
Thresholds of Audibility Used In TSEA



Sample Processed Signal Spectrum and Applied Gain



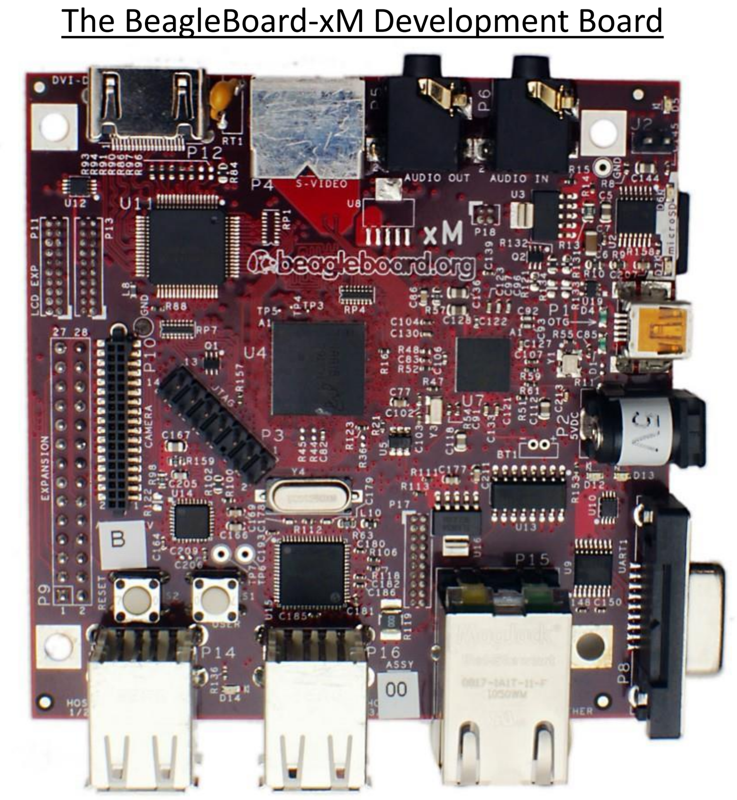
Processed Waveform Showing Consonant Boost



The Hardware Implementation

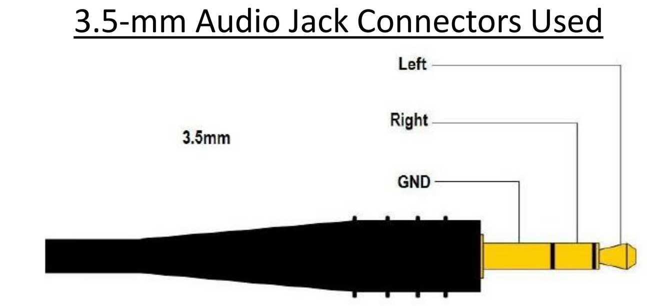
- This project implements the TSEA on the BeagleBoard-xM
- Audio input and output connectors on the BeagleBoard are used to transfer signals to and from the board
- Speech signals are sent into the board and processed using an adapted version of the original Simulink TSEA model developed by Kommatil
- Processed speech output is recorded via the output jack connector and used for analysis
- Now three versions of TSEA exist: the original MATLAB model, the Simulink model ,and the BeagleBoard model

The BeagleBoard-xM Development Board

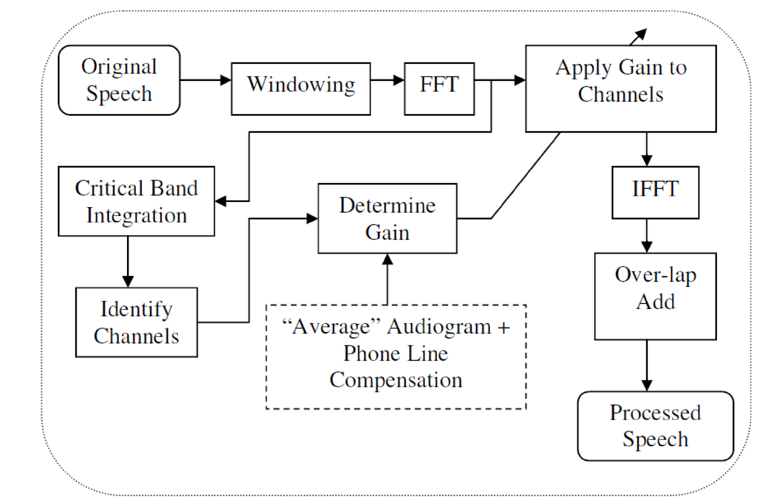


- A 1 GHz Texas Instruments processor provides the power to run the algorithm
- The BeagleBoard-xM has an onboard audio codec for audio processing at all standard sampling rates
- Stereo audio is converted to mono to simulate telephone speech signals

3.5-mm Audio Jack Connectors Used



Block Diagram of the TSEA Algorithm Used

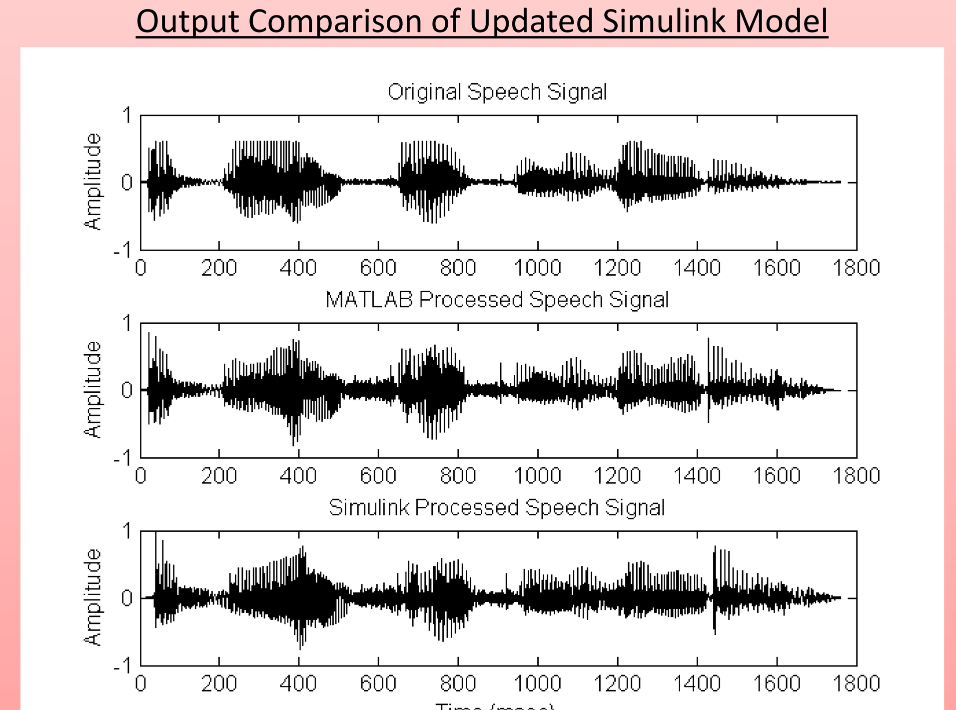


- The BeagleBoard model introduces internal audio artifacts into the signal
- Testing and analysis was performed to determine exactly what effects the BeagleBoard has on the algorithm

Preliminary Testing

- The old original Simulink model was updated to the newest version of Simulink and compared to the original MATLAB version of TSEA
- Error calculations yielded an average of 2.42% RMS error and 13.51% maximum error between the MATLAB and Simulink versions of TSEA

Output Comparison of Updated Simulink Model



Conclusion

- The Telephone Speech Enhancement Algorithm (TSEA) successfully implemented on the BeagleBoard-xM
- This hardware model could be the foundation used to preprocess telephone signals sent to hearing impaired listeners to help improve speech perceptibility
- Noise characteristics of the BeagleBoard-xM influence the model's behavior and performance

Testing and Results

- Output of the BeagleBoard TSEA signals were compared to the Simulink version of TSEA
- Six speech signals (sampled at 8kHz) were processed to find an average error
- Errors caused due to analog filtering of the audio jacks and internal noise of the board
- The RMS error between the BeagleBoard and Simulink model can largely be attributed to the error from the internal noise and analog connection filters

Error Between BeagleBoard and Simulink Model Output

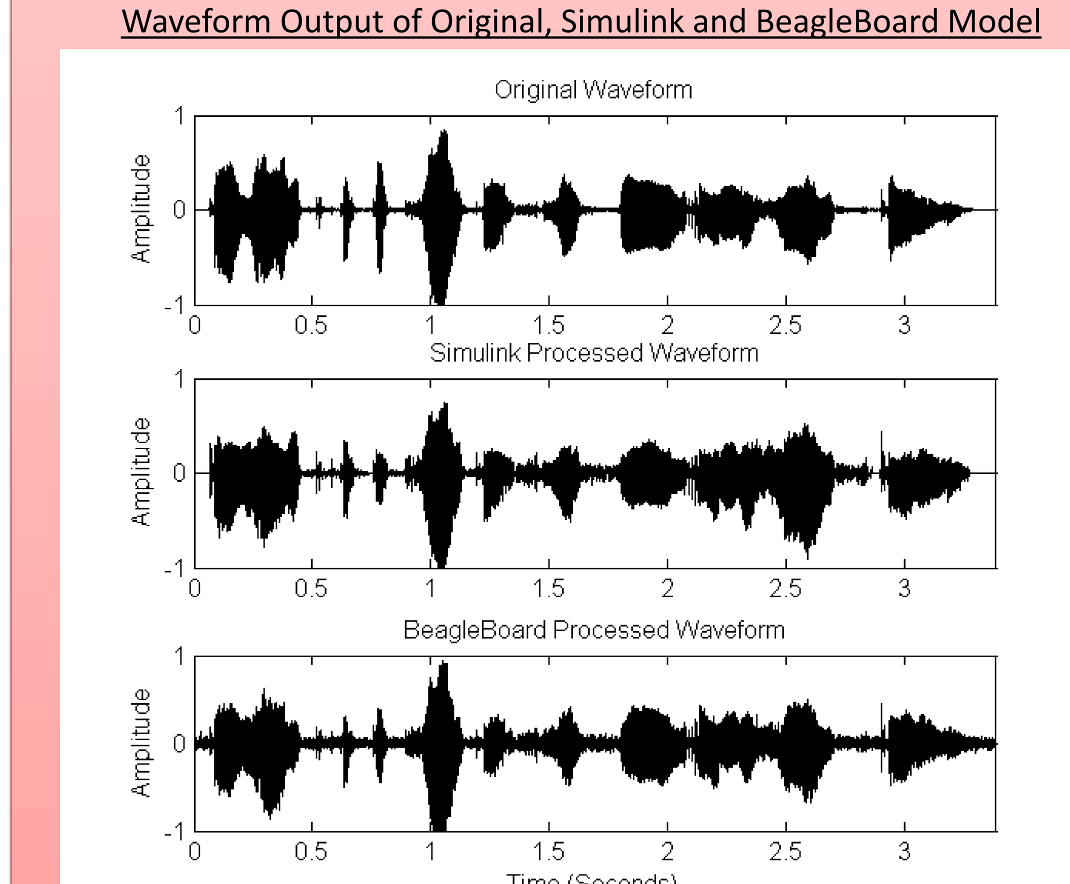
Speech Signal Test	RMS Error	Maximum Error
Test 1	4.93%	28.68%
Test 2	4.13%	24.00%
Test 3	4.24%	37.58%
Test 4	4.38%	29.44%
Test 5	4.74%	29.48%
Test 6	3.74%	27.24%
Average	4.36%	29.40%

Error From Internal Noise and Analog Connections

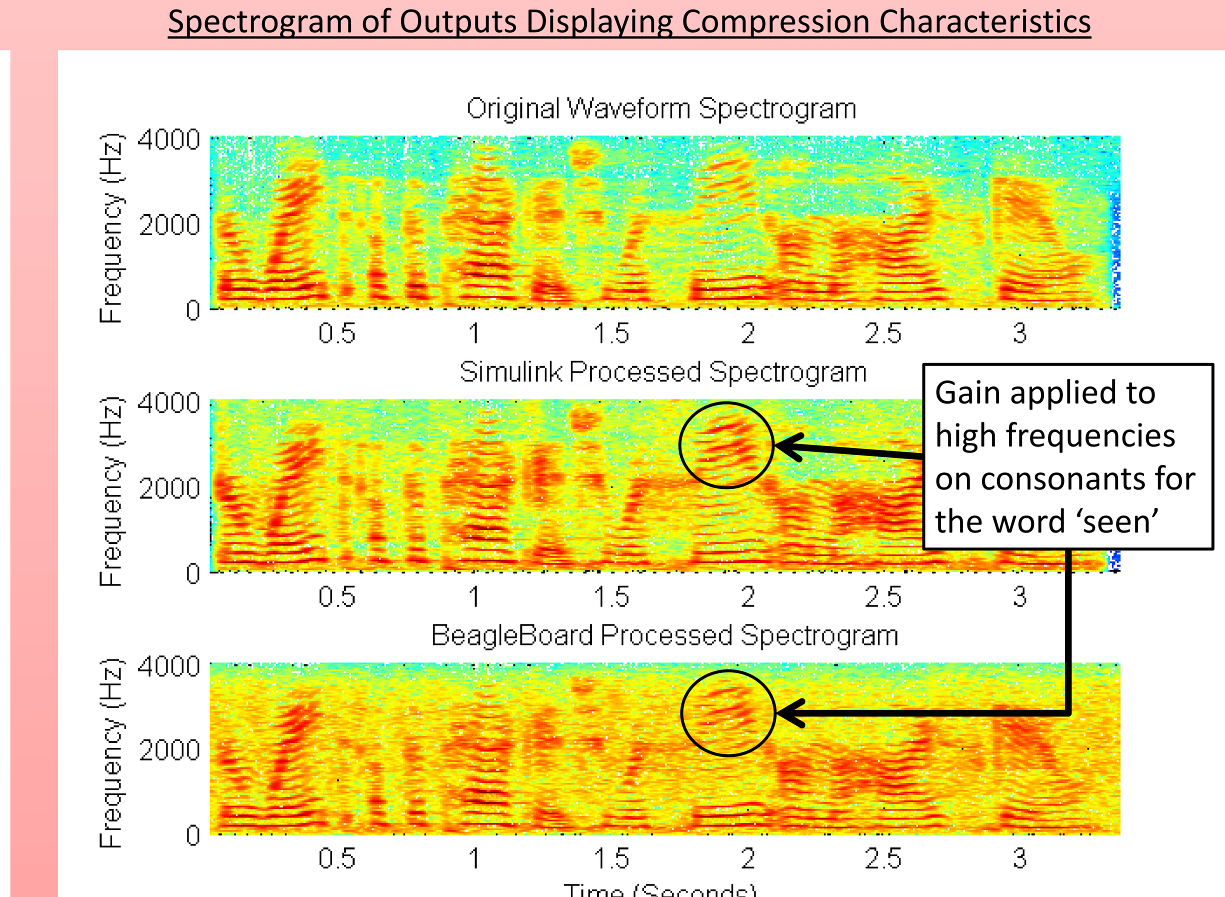
Sinusoid Frequency	RMS Error	Maximum Error
100 Hz	1.34%	4.08%
500 Hz	2.87%	6.44%
1000 Hz	4.50%	8.88%
2000 Hz	2.71%	7.42%
3500 Hz	3.66%	12.02%
Average	3.02%	7.77%

- Output of the BeagleBoard TSEA processed signals were compared to the original waveforms to verify the compression characteristics of TSEA
- Spectrogram analysis was used to analyze the frequency components as a function of time and to validate applied gain to high frequencies in the algorithm

Waveform Output of Original, Simulink and BeagleBoard Model



Spectrogram of Outputs Displaying Compression Characteristics



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