# Introduction

## Hearing Loss (HL)

- Approx. 35-out-of-10,000 children suffer and 33% of adults (≥ 65 yrs.) are impacted by hearing loss[1,2]

## Hearing Aids (HA)

- Microphone-speaker based behind-the-ear (**BTE**) system to amplify incoming sounds

## Cochlear Implants (CI)

- Medical device used to generate electrical stimulation from an acoustic input
  - Implanted intra-cochlear electrode array
  - BTE sound processor (and mic)



## HA Signal Processing

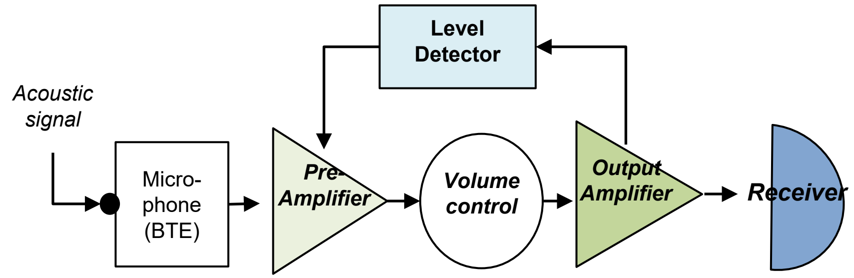



**Figure 1.** Example signal processing pipeline for **HAs**.

## CI Signal Processing

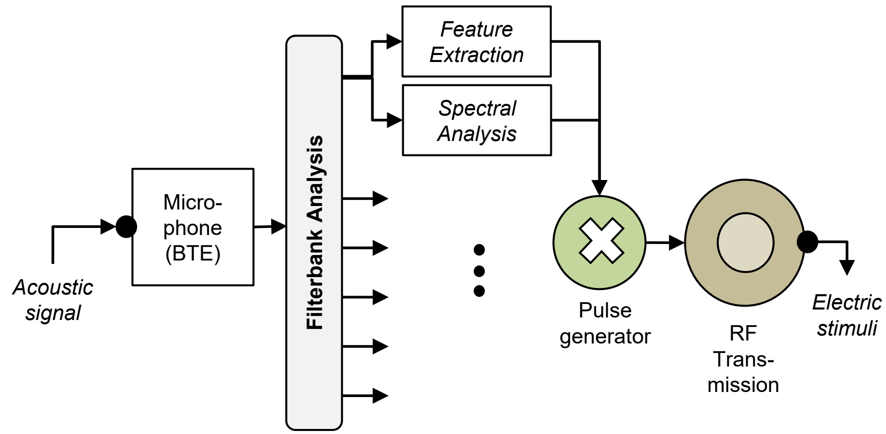



**Figure 2.** Example signal processing pipeline for **CIs**.

**[1]** C.C. Morton, W.E. Nance. (**2006**) New England Journal of Medicine, 354:2151-64.
**[2]** F.R. Lin, J.L. Niparko, and L. Ferrucci (**2011**) Archives of Internal Medicine, 171:1851-3.

# Motivation

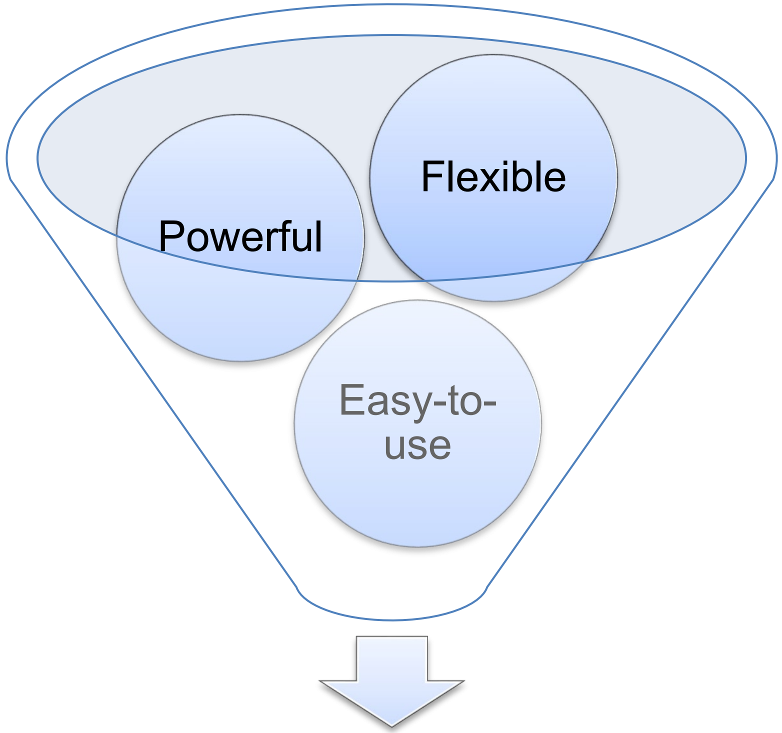
## Limitations in existing research interfaces

- Functionality
  - Lack of bimodal support (electric + acoustic hearing)
- Computation power
  - Must sustain complex signal processing algorithms
- Portability
- Real-time evaluation
- Barrier to entry for unfamiliar programming languages

## Not suitable for a broad range of experiments

## Proposed attributes

- Custom solutions (*i.e.*, direct connection to implants)




New research interface

# CCi-MOBILE

## CCi-MOBILE Research Platform

- USB/Wi-Fi research interface configured for both in-laboratory and field testing of sound processing strategies and/or data collection for CI/HA*
- Plug-and-play system (portable, wearable, on-the-go signal processing adjustments)
- Supports time synchronized acoustic and/or electric stimulation
  - Unilateral/bilateral CIs*
  - Bimodal (Electric-Acoustic-Stimulation)
- High-level language software suite (MATLAB, Java)

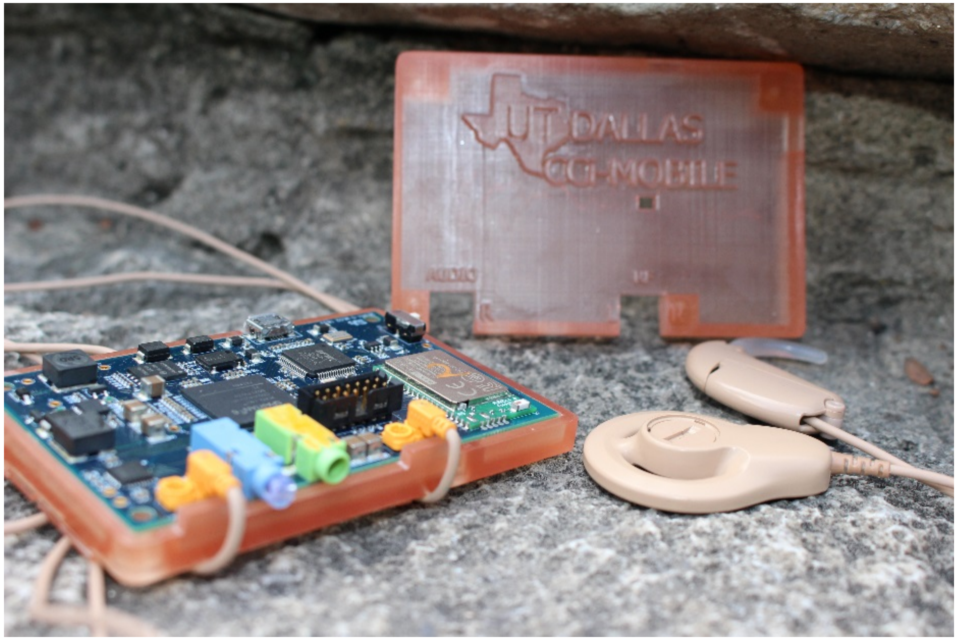



**Figure 3.** CCi-MOBILE Research Platform (open-case) in unilateral mode.

## Investigational Parameters

- No. electrodes/channels configurations
- Stimulation mode
- Stimulation rate (pps/ch)
- Pulse width (bi-phasic stimulation)
- Proposed signal processing strategies (CIS-based**) for unilateral/bilateral

* Supports cochlear implants (CIs) manufactured from Cochlear Ltd. from the CI24 implant series.
** Supports signal processing strategies adapted using the Continuous-Interleaved-Strategy (CIS).

# Hardware Design

- FPGA design programmed in Verilog using Xilinx ISE software
- Real-time performance (minimal processing delay) achieved via buffering of incoming and outgoing data on a frame-by-frame basis
- Variable rate electric stimulation uses 16-bit wide RAM buffers to store information: electrodes and current levels

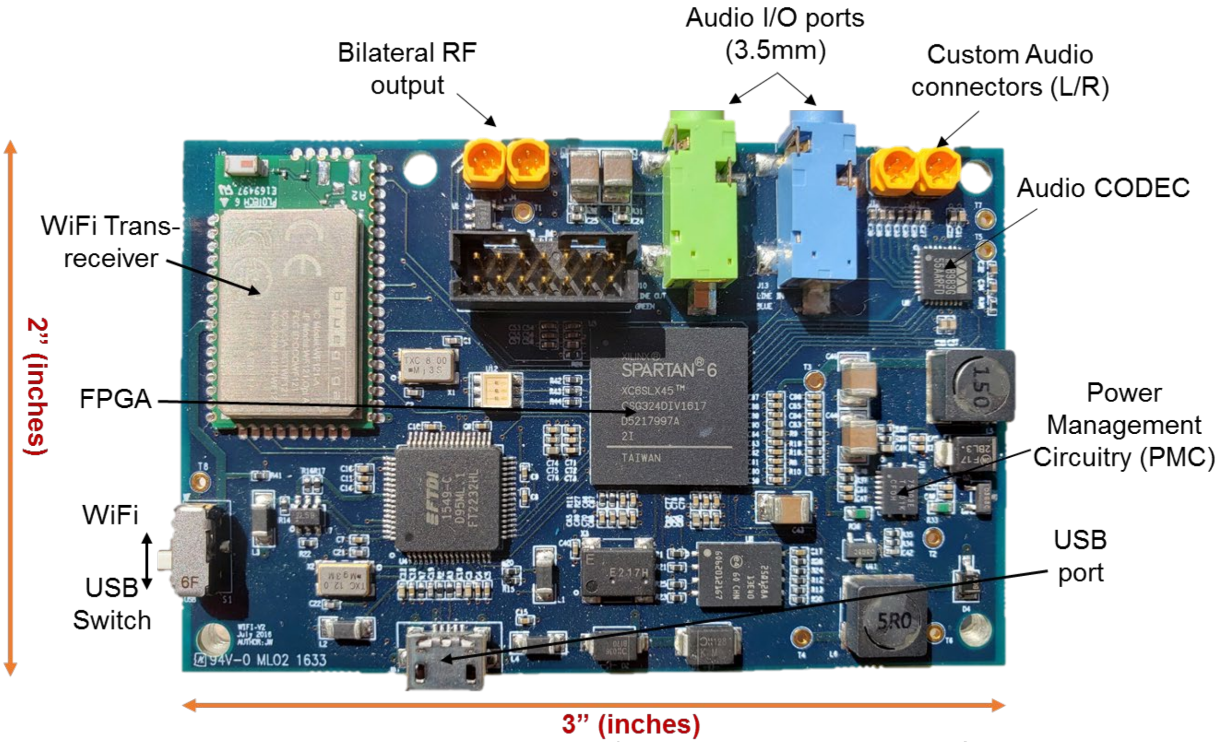



**Figure 5.** Hardware implementation & layout orientation of components.

- Parameter matching using **inter-pulse-gap**, **pulse-width**, and **inter-phase-gap** used to determine accuracy received at the RF-coil
- Parameters are measured and verified using an externally connected oscilloscope

# Design Flow

- Data synchronization managed via RAM and handshake design techniques
- Communication between computing platform and CCi-MOBILE at 5 Mbps
- Sampling of audio data and stereo playback is achieved at 16 kHz
- CI24 implants require a data burst at 5 MHz while the platform operates at 80 MHz

- Four internal concurrent state machines run at different clock speeds:
  1. WM8983 codec
  2. UART-TX
  3. UART-RX
  4. RF-coil

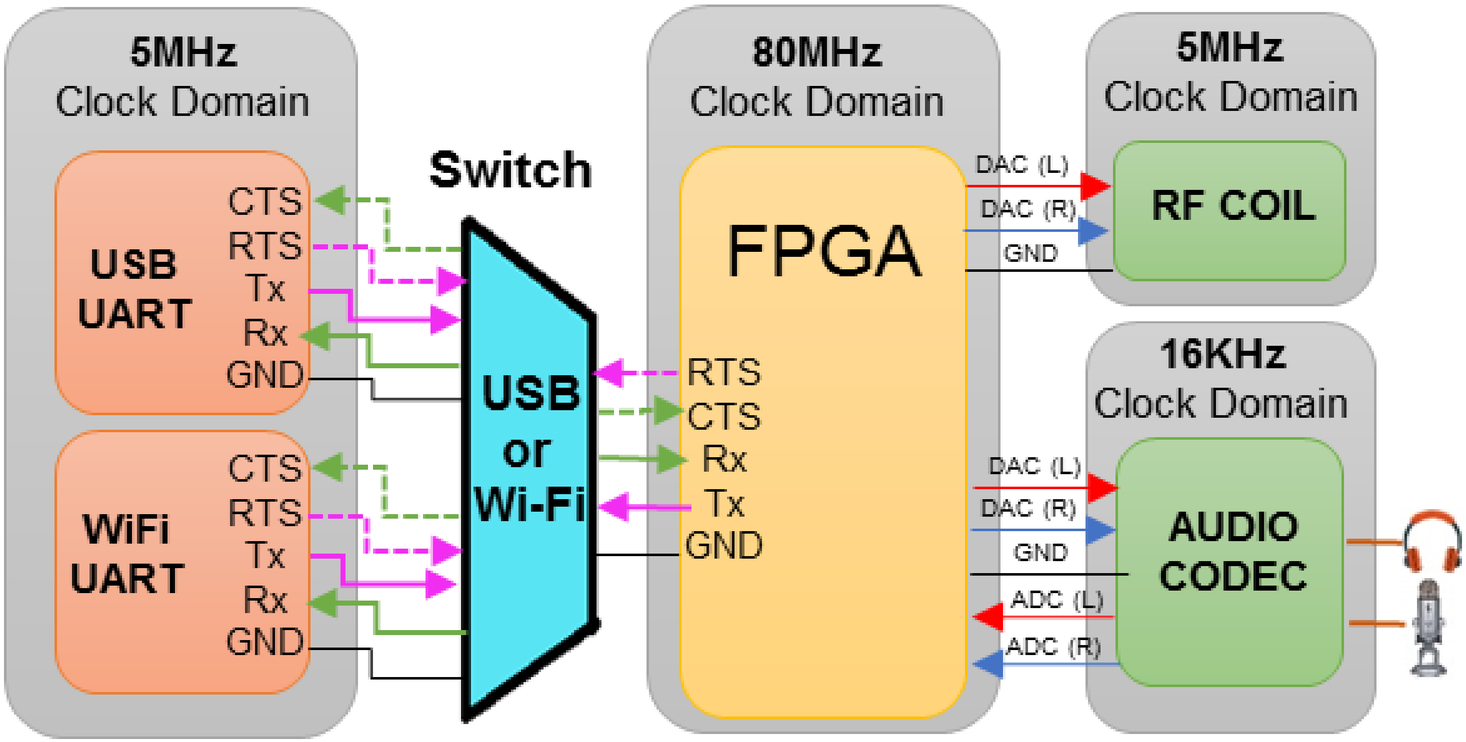



**Figure 6.** Hardware design architecture for electric and acoustic stimulation (EAS) and variable rate stimulation.

# Communication Pipeline

1) Hardware/interface-board continuously samples incoming analog signals from **BTE** mic
2) Digitizes 512 bytes of audio
3) PC/smartphone processes digitized audio into electrical stimuli using signal processing routines
4) Generation of electrical signals from electrical stimuli

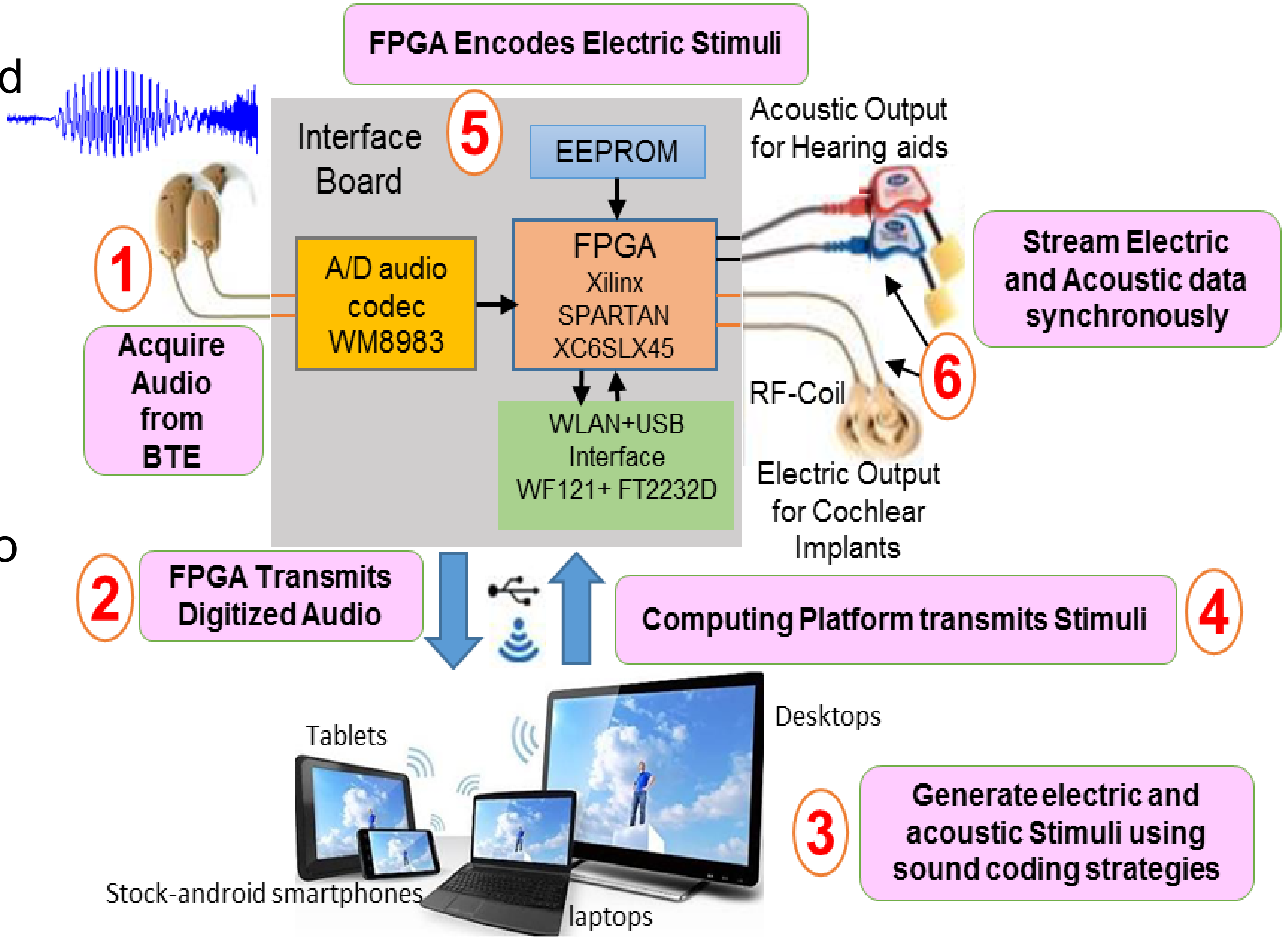



**Figure 7.** Processing data communication between CCI-MOBILE & FPGA.

5) Streams data using proprietary communication routines (Cochlear Ltd.) on a frame-by-frame basis for CI24 cochlear implant systems

*** For bimodal applications, acoustic & electric signals are sent synchronously**

# Applications & Android



## CCi-MOBILE Applications

- Easily record naturalistic audio using build-in audio-recording application(s)
    - Stereo and mono recordings
- Perform lateralization and localization experiments
- Implementation of novel signal processing algorithms for CIs/HAs
    - Speech enhancement, noise suppression, etc.
- Built-in vocoder application to simulate electric-hearing for normal hearing (NH) listeners[3]

## Android App

- Real-time performance on Android smartphones and tablets


- Highly suitable for in-field or take-home trials
- Easily adjust signal processing/MAP parameters in real-time
- Quickly select/define pre-programmed environments

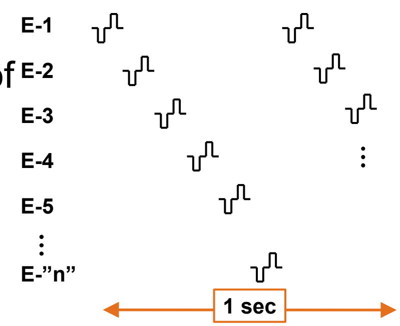
**Figure 4.** Android app for CCi-MOBILE program windows.

[3] H. Ali, N. Mamun, A. Brueggeman, R.C.M.C. Shekar, J.N. Saba, J.H.L. Hansen (**2018**) Conf. Acoust. Soc. Am., 144:1872.

# Custom Signal Processing

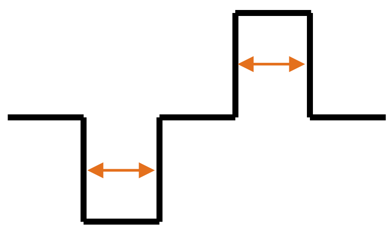
## Stimulation Rate (pps/ch)

- Temporal measurement controlling the number of pulses per second per electrode/channel



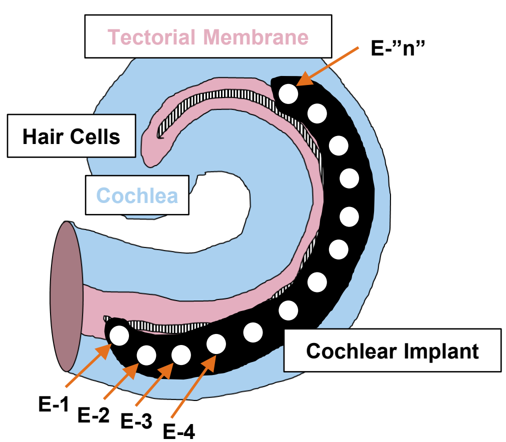

## Pulse-width (PW)

- Width (μs) of anodic and cathodic pulses



## Number of Electrodes

- Number of available electrodes for stimulation within a single cycle
- Max number of electrodes = 22 (**"n-maxima"**)

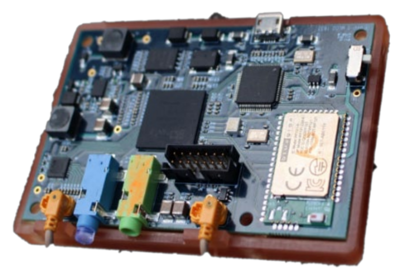



**Audio (BTE)**

**Custom SP Parameters**

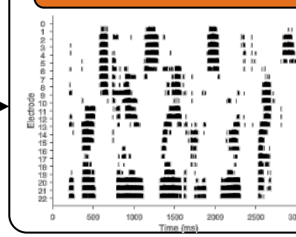
1. **Signal Processing Parameters:** Stimulation rate, pulse-width, # electrodes, etc.
2. **User-Specific Parameters:** channel/electrode level configuration, known as 'MAP' (set by audiologist)

**CCi-MOBILE SIGNAL PROCESSING**



- Pre-emphasis
- Filterbank Decomposition
- Spectral Energy Calculation
- Channel Selection ("n")
- Log-based Compression
- Channel-to-Electrode Mapping

**Electric Stimuli**



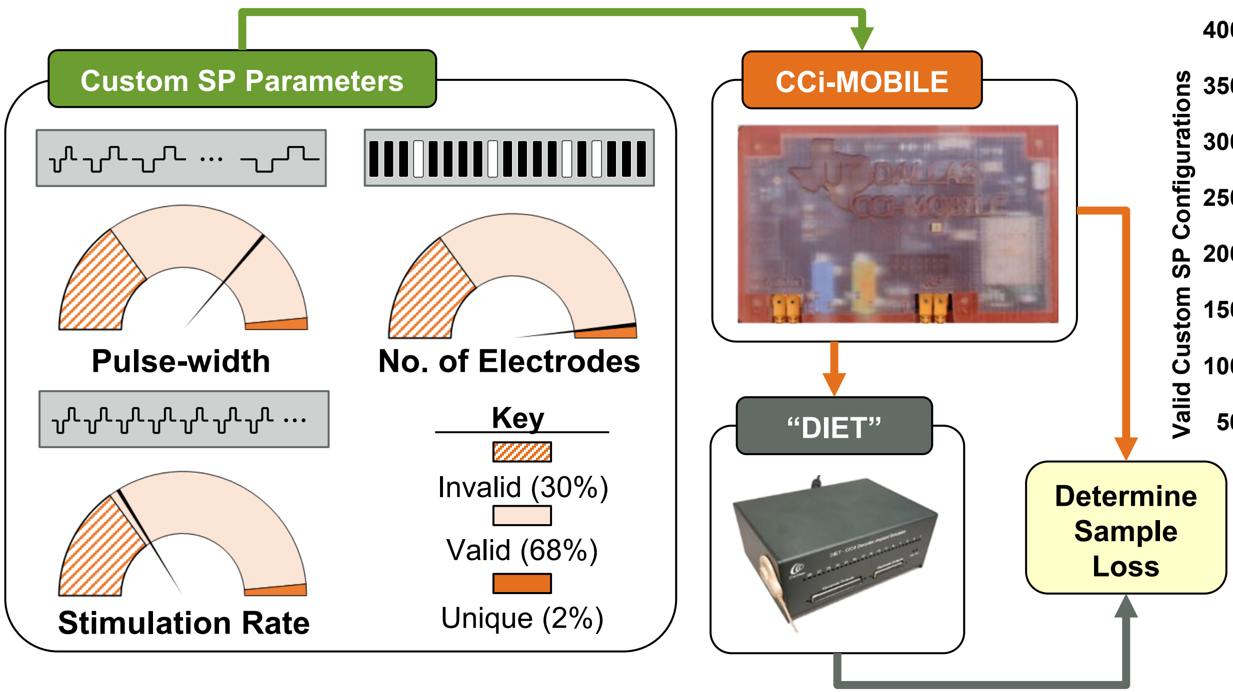
# Custom-Parameter Evaluation

## Custom Signal Processing (SP) Parameter Evaluation

- Determine sample loss from customized SP input parameters (stimulation rate, pulse-width, number of electrodes) using a standard **0-150 user-defined MAP**

## Experimental Set-Up and Results

- 99.008% of valid configurations resulted in <1% sample loss



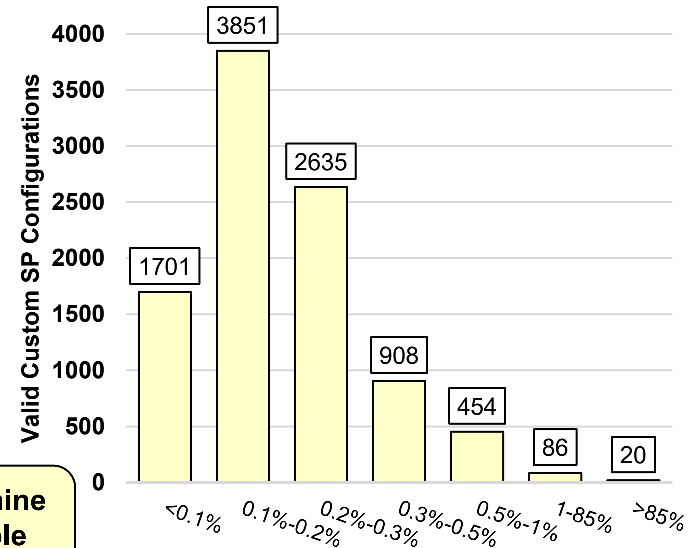




**Figure 10.** Histogram of 7 different categories of sample loss as a percentage of the total number of valid configurations.

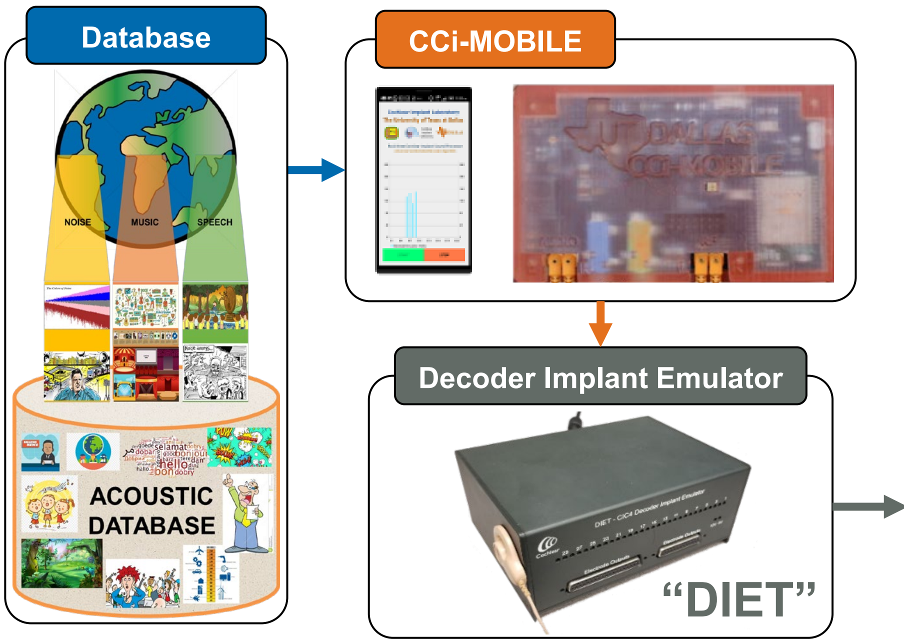
# Acoustical Evaluation

## Acoustic-Diversity Evaluation

- Determine charge (current) from various acoustic input (**380 hrs.**) of audio, speech, music, noise, etc.

## Experimental Set-Up and Results

- All charge/current values produced from CCi-MOBILE were **within clinical safety** limits (safety limit = 350 mC/s)



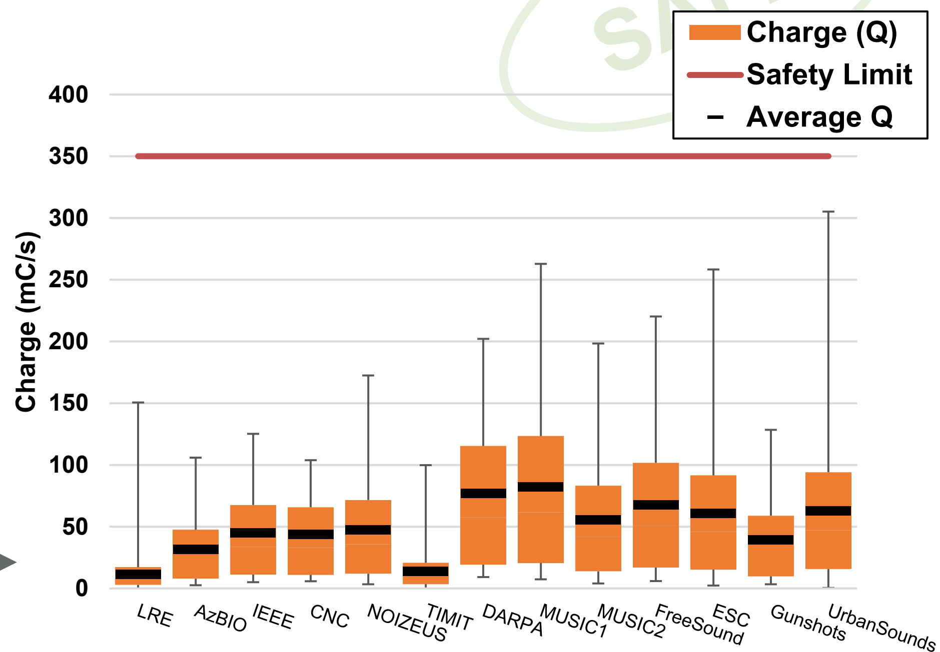



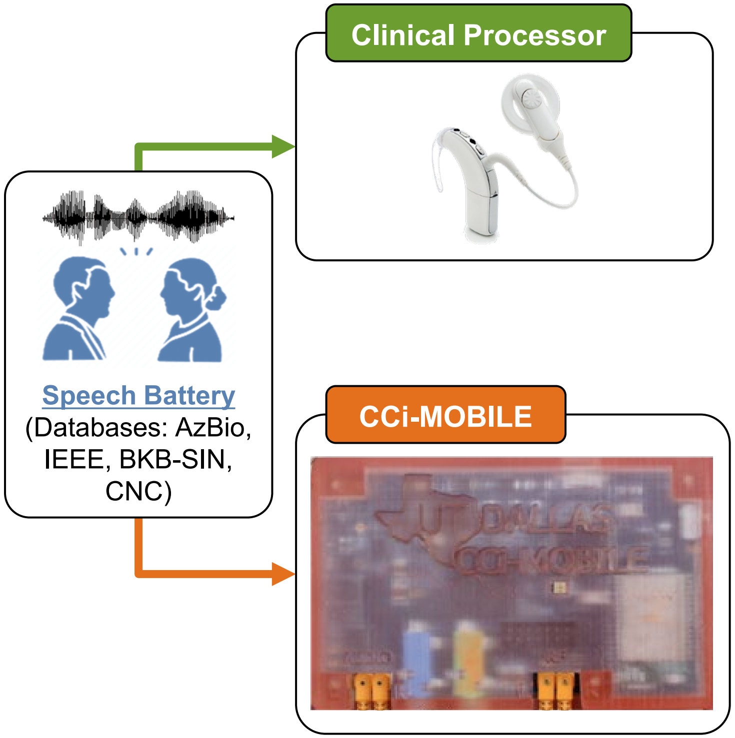

**Figure 9.** Box plot of charge associated with each acoustical database (orange) compared to the clinical safety limit (green).

## Clinical-Processor-vs-CCi-MOBILE Evaluation

- Compare speech intelligibility of CI users (N=8) using their commercial processors (Cochlear Ltd.) and CCi-MOBILE

## Experimental Set-Up and Results

- Comparable performance to clinical processors achieved (F[7,49]=4.882, $p$<0.069)



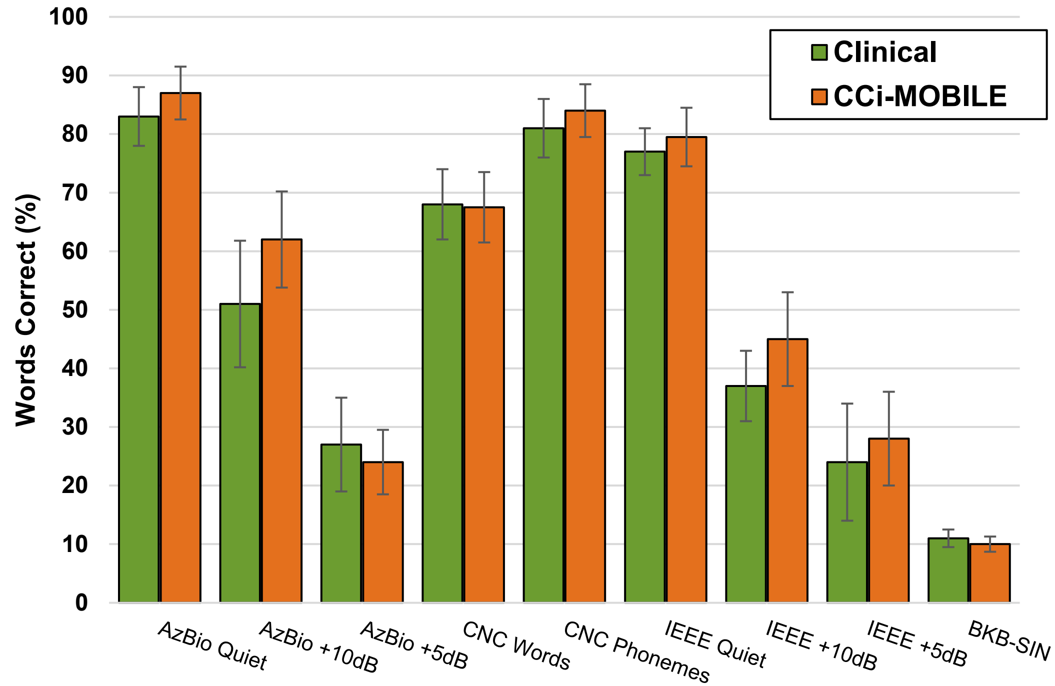




**Figure 8.** Subject evaluation of commercial processor (green) compared to performance using CCi-MOBILE (orange).

# Conclusions

- CCi-MOBILE is an open-source, flexible research platform compatible with cochlear implants and hearing aids
- Easy-to-use, adaptable applications and templates available for speech scientists in a high-language environment
- Hardware and software verification routines ensure safety and reliability of CCi-MOBILE
- Suited to address multi-disciplinary hearing research topics such as: speech-in-noise, sound localization/lateralization, speech enhancement, custom environmental MAP changes, etc.
- Enables bench-top, in-lab, and field experiments for all speech and hearing scientists