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On the Design and Evaluation of the PDA-based Research Platform for Electric and Acoustic Stimulation*

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Abstract— **The aim of the paper is to describe the bimodal (combining electrical stimulation via the implant with acoustic stimulation via hearing aids) design of the PDA-based research platform and present results from a short-term evaluation with five bimodal cochlear implant users. The evolution of the PDA platform has been reported earlier in terms of development and its potential in various experiments. This paper focuses on the evaluation of the platform with bimodal users in terms of speech intelligibility in quiet, 10dB and 5dB SNR conditions and compares the results with the users' own clinical processor. The results of this clinical trial will encourage researchers in this area to use the platform in their future studies as it provides unparalleled flexibility along with a large suite of applications to conduct a wide variety of experiments for electric-only and combined electric and acoustic stimulation (EAS) for long-term chronic studies with great ease.**

I. Introduction

A number of studies recently have focused on the combined electric and acoustic stimulation (EAS) as a rehabilitative strategy for sensorineural hearing loss (HL) [1] - [8]. It is now well established that patients fitted with a cochlear implant (CI) and who have residual hearing in one or both ears and combine the use of hearing-aid with their implant, receive a larger benefit in speech understanding compared to electric-alone or acoustic-alone stimulation. That is to say, combined electric and acoustic (EAS) stimulation has a strong synergistic effect [1] both when acoustic information is delivered ipsilaterally to the implant (e.g., hybrid implants with partially inserted (short) electrode arrays) or when delivered contralaterally (implant in one ear and hearing-aid in the other) [9]. We refer to the latter mode of stimulation as bimodal stimulation. This improvement is more evident in the noisy conditions as suggested in [10], [11] and is primarily attributed to access to more reliable F0 cues in the acoustic portion. In our previous work [12] [13], we proposed a PDA-based research platform for researchers working in this domain to explore new ideas to improve cochlear implant devices. In the present work, we have extended the functionality of the platform to include acoustic stimulation in addition to electrical stimulation for researchers interested in experimenting with bimodal CI users. This functionality allows researchers to implement various speech processing strategies/algorithms in C or in MATLAB and evaluate the performance of their algorithms using a highly flexible, easy to use, versatile and portable platform suitable for long-term evaluation with bimodal subjects. While most implant manufacturers provide research speech processors which allow researchers to develop and test new signal processing algorithms, most of the research labs are unable to use them either due to limited technical resources or due to the constrained framework of the interface provided by the manufacturers. For bimodal studies, there is only one research processor SPEAR3 [14] which supports both electric and acoustic stimulation, but it requires programming in assembly language and is hence difficult to use by most researchers. The PDA-based research platform, on the other hand, overcomes these limitations and provides flexible software driven solution for both researchers and clinicians without requiring advanced programming skills or major hardware investment to undertake both human and animal clinical studies.

The PDA-based research platform can be operated in two modes, i) real-time mode and ii) offline-mode. In the real-time mode acoustic and electric stimuli are delivered to the user in real time just like their own clinical processor or hearing aid. All the processing is carried out in the PDA in real-time. The offline mode, on the other hand, is based on a PC running MATLAB. The user selects an audio file from the PC which is processed by a speech processing strategy in MATLAB and the stimuli are streamed to the implant. In addition to the speech processing, the PDA platform allows researchers to conduct psychophysical experiments in the offline mode by controlling stimulation parameters and amplitudes of individual electrodes. This makes the platform flexible for researchers working in either domain without the need for any software or hardware modifications.

This paper is organized as follows. Hardware overview of the platform is presented in Section II. Section III describes the software architecture of both real-time and offline modes from the bimodal perspective followed by Section IV which presents results from the clinical evaluation of the platform with bimodal CI subjects.

II. Hardware Overview

The research speech platform comprises of:

i. A portable processor in the form of a smart-phone or a PDA for implementing and evaluating novel speech processing algorithms after long-term use. Rationale behind using a PDA as the computing platform is portability, powerful microprocessor, easy and efficient programming in high-level language and user interface in the form of touch screen for enhanced interactivity.
ii. an interface board to connect the PDA with Freedom cochlear implant coil using secure digital input output (SDIO) port of the PDA [15], [16]. This custom board is driven by an FPGA and implements communication

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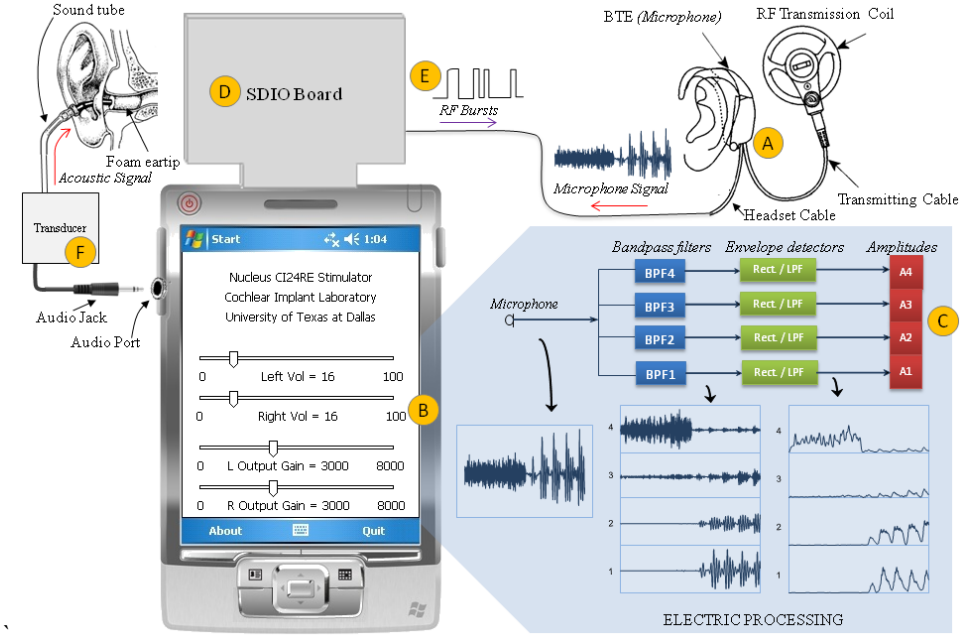

Figure 1. A schematic of the signal flow for the real-time speech processor. The acoustic signal is picked up by the microphone (A), sent (via the headset cable) to the SDIO interface board (D), which is then sampled and transmitted to the PDA. The PDA (B) processes the signal and generates a set (one for each channel of stimulation) of amplitudes (C). The example shows amplitudes generated for the CIS strategy while the platform supports both CIS and ACE strategies. These amplitudes are sent to the SDIO interface board (D), which are then coded for transmission to the cochlear implant in the form of RF bursts (E). At the same time, the processed audio buffer is sent to the tranducer (F) which presents the acoustic signal to the contralateral ear via the insert eartips. Both electric and acoustic stimuli are synchronized without any delay.

protocols (embedded protocol for CI24 implant [17] and expanded protocol for CI22 implant [18]) to interface with the Nucleus device.

iii. HS8 BTE housing a microphone and a modified flex circuit to connect to the Freedom coil and

iv. Commercially available insert earphones which can provide up to 120dB SPL acoustic stimuli.

Offline mode requires a PC running MATLAB in addition to the above hardware. For hardware details, please refer to [12] and [13].

III. Software Overview

A. Real-time Speech Processor

Fig. 1 provides a general overview of the signal flow involved in the PDA-based real-time speech processor. The acoustic signal is picked up by a microphone located in the BTE and sent to the SDIO interface board via the headset cable. The interface board samples the signal binaurally at a rate of 22050 Hz/channel and sends frames of the sampled (digital) signal to the PDA via the SD slot. The PDA processes each frame of 11.2ms simultaneously through a speech coding algorithm (e.g., ACE or CIS) for electric stimulation and via an audio processing routine for acoustic stimulation. The electric processing routine requires a patient's clinical electrical map while the audio processing routine utilizes patient's audiogram for subjective processing. Electric processing produces a set of amplitudes representing the energy levels in each of 22 frequency bands, a subset (8-12) of which are used for stimulation. These amplitude levels are then sent to the SDIO board which transmits them to the implant using RF protocols specific to the implant. Concurrent with this, the processed acoustic buffer is streamed to the audio port of the PDA for acoustic stimulation. In this way, both electric and acoustic stimulations are perfectly synchronized. This is a remarkable feature of the PDA platform. Hearing aids and cochlear implants in practical use are completely independent of each other. They have their own, usually different, audio buffer sizes and audio processing delays. Hence, acoustic and electrical stimulation are not necessarily in perfect synchronization.

B. Offline Speech Processor

The offline version of the PDA platform is based on a PC running MATLAB where all processing takes place while the PDA acts as an interface to the implant. The software architecture is designed such that the PDA acts a server which accepts the incoming connections and the PC acts as a client with MATLAB as a front-end. The overall design can be broken down into three main software components:

i. Server running on the PDA,

ii. MATLAB client (.mexw32 or .mexw64 dll) called from the MATLAB front-end, and

iii. MATLAB front-end running on PC.

Fig. 2 depicts the software architecture for the offline processor in bimodal mode. MATLAB reads patient's map and processes the given audio file (.wav format) through a speech processing routine. Using Windows RAPI libraries the audio file and map file are copied to the PDA. The processed signal in the PC comprises of a set of amplitude levels and stimulation parameters which are streamed to the

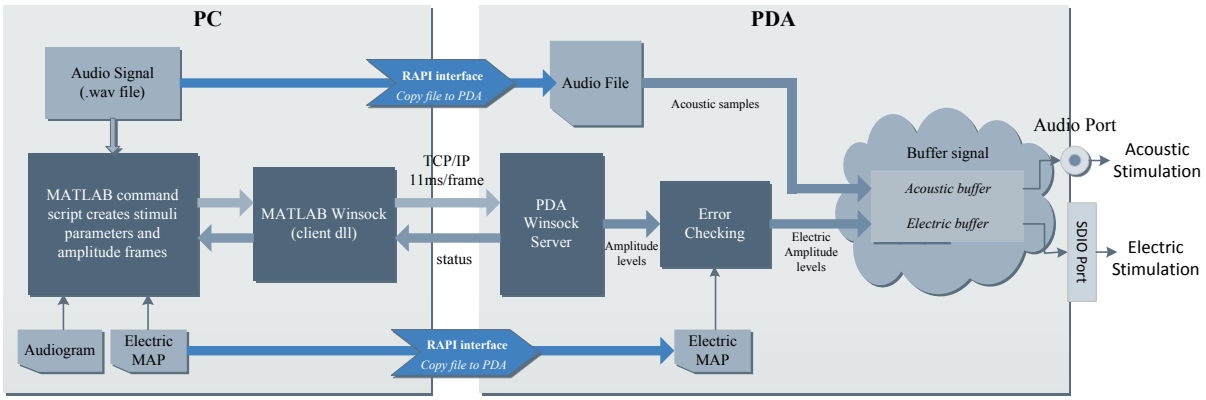

Figure 2. Software architecture of the offline speech processor for bimodal stimulation.

PDA server using Windows Sockets (Winsock) API, a technical specification that defines how Windows network software should access network services, e.g. TCP/IP [19]. After successful transfer, the PDA server performs error checking on the received data and buffers the electrical amplitudes and acoustic samples in frames of 11ms. These frames are then continuously and synchronously transmitted to the implant and the earphones respectively. For detailed description of the software architecture in offline mode, please refer to [13].

IV. Evaluation And Results

The IDE application for the PDA-based research processor was approved by the FDA in May 2011 for clinical evaluation with human subjects. Since then, the platform has been tested with unilateral, bilateral and bimodal CI users. The results presented in this paper are from an acute study (i.e., users were allowed to wear the processor for a few hours in the lab environment) on five bimodal subjects who had implant in one hear and hearing aid in the other. All participants were adults and native speakers of American English with post-lingual deafness and with a minimum of one year experience with cochlear implant(s) from Cochlear Ltd.

The aim of the current study was to evaluate the performance of the platform on a speech intelligibility task and compare the performance against the users' own clinical implant and hearing aid. All subjects were tested with offline, real-time and their own clinical processors electric-alone (E), acoustic-alone (A) and electric plus acoustic stimulation (EAS). (Subject S5 was not available for some conditions.) The intelligibility scores from their own clinical processor were taken as benchmark scores. The clinical processor and real-time processor evaluations were done in free-field in a sound booth at an average of 65dB SPL. (Speech stimuli for the offline processor were presented via audio files on the PC.) In all the cases, volume and gain adjustments were done on the respective processors. For all the tests, the subjects' everyday MAP was used. In the current study, no hearing-aid type of processing was used for acoustic stimulation. A short training with the PDA processor was carried out before each test.

The speech stimuli used for testing were sentences from the IEEE database [20]. Two lists for each test condition were used and the scores from the two were averaged. Each list comprises of 10 sentences with an average of 80 words per list. Three conditions were tested for each test, speech in quiet environment, speech in 10dB SNR and speech in 5dB SNR. Speech-shaped noise was used in all tests.

Fig. 3 shows the percentage correct scores in: (a) quiet, (b) 10dB and (c) 5dB SNR with combined EAS. The results are reported for clinical processor, PDA-offline and PDA-Real Time (PDA-RT) processors. As a comparison acoustic-alone and electric-alone scores are given in (d) and (e). Mean thresholds for all subjects in the non-implanted ear were 64dB HL or better for frequencies lower than 500 Hz. Thresholds at 1 kHz and above were 72dB HL or poorer. Analysis of the data suggests that:

i) EAS shows an improvement in scores as compared to A-only and E-only scores. This effect is more pronounced in noisy conditions. For example, percentage correct scores drastically improved from 21 percent with A-only to 60 percent with EAS. This is even greater than the sum of A and E alone. Significant improvement in noise is in line with studies published in [10] and [11].

ii) There is a strong correlation between all three processor types in all conditions. Fig. 3f shows a scatter plot of the scores and associated correlation between the clinical processor and RT-PDA in quiet environment. The Pearson's correlation coefficients for RT and clinical processor in 10dB and 5dB SNR were 0.99 and 0.85 respectively. For the offline processor in the same SNR, correlation coefficients were 0.97 and 0.80 respectively. These strong correlations suggest that the PDA platform delivers comparable performance with the commercial clinical processor.

It should be pointed out that the results reported here are from acute studies. Given the differences in microphones used in the BTE (Fig. 1) and those used in the commercially available speech processors, differences in hardware, as well as differences in the implementation of the ACE coding strategy, it is reasonable to expect that the bimodal users would need to acclimate to the use of PDA processor.

Our next step is to undertake long-term clinical evaluation of the platform with take-home trials. Portability and wearability of the PDA platform makes it possible for the users to wear the platform on a daily basis until they fully adapt to the new processor. The possibility of conducting chronic studies with the PDA processor allows researchers to

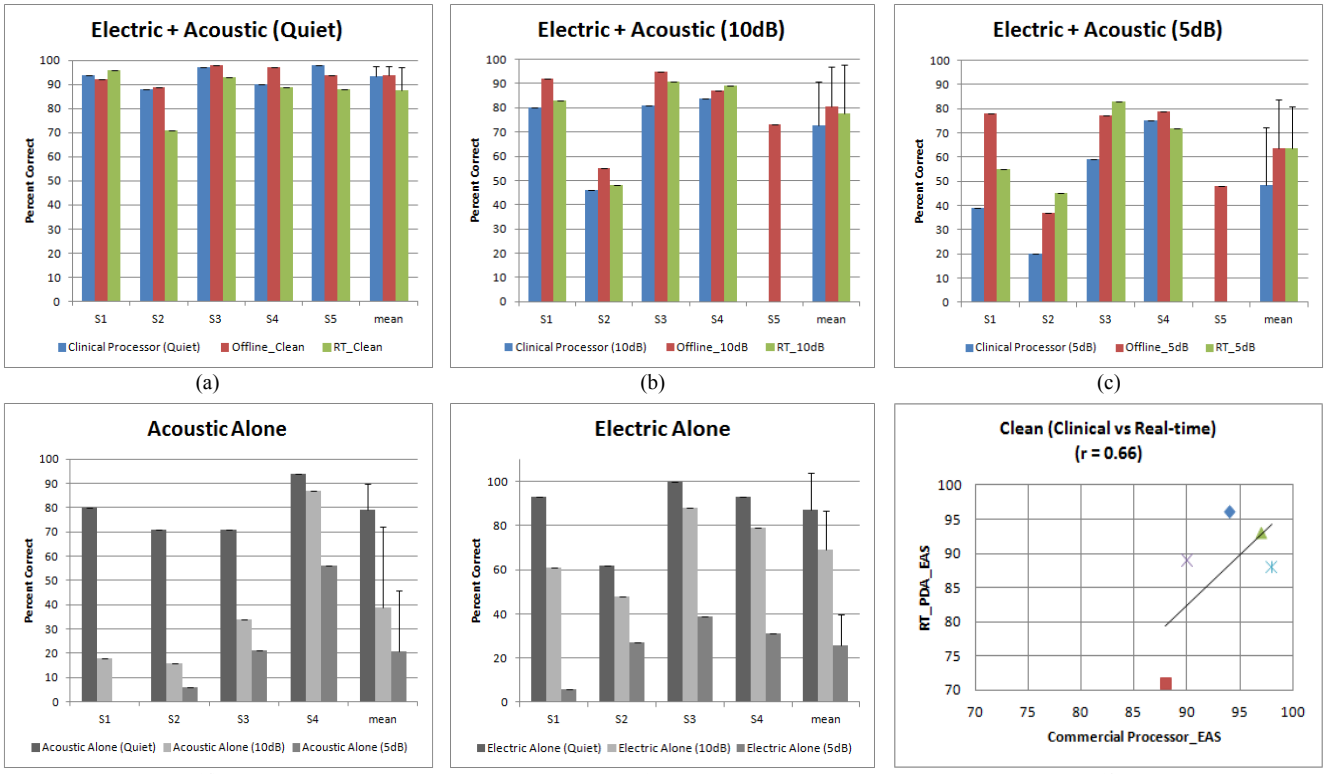

Figure 3. Percentage correct scores obtained by five bimodal users using clinical processor, PDA-offline mode, and PDA real-time mode in: (a) quiet environment, (b) 10dB SNR, (c) 5dB SNR in speech shaped noise. Panels (d) and (e) depict acoustic-only and electric-only scores for the three conditions. Panel (f) shows correlation between clinical processor and PDA in realtime mode in EAS mode. Note that subject S5 was not available for A-only and E-only conditions as well as for the 10dB and 5dB RT EAS and clinical processor conditions.

carry out long-term evaluation of novel coding algorithms and conduct experiments that would otherwise not be possible. This in turn will open new possibilities in cochlear implant research and development.

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