A Phone-Assistive Device Based on Bluetooth Technology for Cochlear Implant Users

Haifeng Qian, Philipos C. Loizou, *Member, IEEE*, and Michael F. Dorman

***Abstract*—Hearing-impaired people, and particularly hearing-aid and cochlear-implant users, often have difficulty communicating over the telephone. The intelligibility of telephone speech is considerably lower than the intelligibility of face-to-face speech. This is partly because of lack of visual cues, limited telephone bandwidth, and background noise. In addition, cell-phones may cause interference with the hearing aid or cochlear implant. To address these problems that hearing-impaired people experience with telephones, this paper proposes a wireless phone adapter that can be used to route the audio signal directly to the hearing aid or cochlear implant processor. This adapter is based on Bluetooth technology. The favorable features of this new wireless technology make the adapter superior to traditional assistive listening devices. A hardware prototype was built and software programs were written to implement the headset profile in the Bluetooth specification. Three cochlear implant users were tested with the proposed phone-adapter and reported good speech quality.**

***Index Terms*—Assistive listening devices (ALD), Bluetooth, cochlear implants (CI), hearing aids, phone adapter.**

I. Introduction

TELEPHONE listening can be difficult and frustrating for hearing impaired (HI) people [1], [2]. This is partly due to the limited telephone bandwidth (300–3400 Hz), which eliminates high-frequency consonant cues, and partly due to the lack of visual cues. The acoustic output level of the handset is sometimes not enough for some HI listeners. There are numerous options available for enhancing the telephone signal and alleviating some of the effects of background noise: amplifying the acoustic signal from the handset, placing the handset near or over the hearing aid (HA) or the cochlear implant (CI) (acoustic coupling), making use of the telecoil in the HA or using add-on assistive devices (e.g., electromagnetic coupler).

HI listeners may use a self-contained acoustic amplifier that attaches over the earpiece of the handset [2]. To avoid acoustic feedback, the users need to properly position the handset near the microphone of the HA or CI. Alternatively, the amplifier can be directly connected to the hearing aid via a boot or to the CI processor via a telephone adapter. There are currently a few phone-adapters available for CI users. Two widely used phone adapters are the TEL-001 (Williams Sound) and TLP-102 (DynaMetric) adapters. These adapters plug into the handset jack of the telephone, and provide direct access to the telephone audio in the form of a mono-plug, which can be fed into the CI processor. The telephone signal can also be picked up inductively by the telecoil of the hearing aid, which is available in most hearing aids, and in some cochlear implants. A major drawback of inductive coupling is that the signal strength varies depending on the HA orientation, head positioning, and movement. In addition, a humming sound is sometimes present, which can be annoying to people with mild hearing loss. Several studies [1], [3] have shown that HA users prefer acoustic coupling and amplified handsets to t-coil coupling (and add-on assistive devices). However, even with adequate coupling (acoustic or magnetic) between the hearing aid and the phone, word recognition is not necessarily improved. For example, in the study reported in [4] no difference in speech recognition scores was found between unaided telephone use and aided telephone use when the subjects' hearing aid was acoustically coupled to the telephone handset.

The situation with CI listeners is different from that of HA users, since most cochlear implants do not have a t-coil. CI users do not have as many assistive-listening options as HA users. A few studies were conducted to assess CI listeners' speech understanding through telephone without the use of assistive listening devices (ALDs). In [5], one of the earliest studies on this topic, one CI implantee fitted with the first generation Nucleus implant processor (programmed with the F0/F2 strategy) was asked to listen to Central Institute for the Deaf (CID) sentences over the telephone and repeat them. She identified 21% of keywords correctly and 47% when listening twice. In a more systematic study reported in [6], eight subjects fitted with the Nucleus implant processor were tested in a soundproof room with sentences sent through an extension-telephone call, a local call and a long-distance call. Subject's performance over the telephone varied from 2% to 63% correct on monosyllabic word recognition and from 3% to 99% correct on sentence recognition. The authors in that study concluded that a 50% or higher score on the CID word recognition task was a good indicator of telephone communication ability in that it should enable CI users to have a two-way telephone conversation. A more recent study [7] reported that 68% of the adult Clarion CI users were able to understand at least half of the sentences over the phone, and half were able to understand at least 75% of the sentences 12 months post implantation. In [8], six children fitted with the Nucleus implant processor (programmed with the SPEAK strategy) were tested with monosyllabic, two-, and three-syllable words presented through the telephone. The average percentage of correct responses ranged from 50% to 83% for dif-

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ferent materials. A larger-scale study was reported in [9], which tested 150 prelingually deaf children, ranging from 1 to 5 years old, fitted with the Nucleus implant processor. A hierarchical test was used that started from recognizing rings to carrying an open conversation with unfamiliar callers. The performance of the children increased significantly over time and approached the level of normal-hearing children after 5 years.

Although these results are encouraging, most CI users are not able to carry on a conversation with unfamiliar callers about unfamiliar topics, and they describe the telephone speech quality as weak, hollow, tinny, having echo, fuzzy, or distorted [10]. A detailed survey [1] of hearing aid users on telephone usage showed that: background noise was a problem for 94% of the respondents; 76% of them said that telephone speech was too soft; 66% of them reported lack of clarity which could not be solved by amplification. 70% of the subjects found coupling a hearing aid with a telephone to be problematic due to feedback effects, and nearly half of them preferred not to use their hearing aids with telephones. The respondents also showed a strong desire for improvements of ALDs [1].

Digital-wireless phone listening can be even more difficult because of (1) the higher level of background noise typically present in a mobile environment (e.g., while driving) and (2) the interference caused by wireless phones. The interference is caused by the fact that some cellphones [particularly Groupe Speciale Mobile (GSM)] use pulsed radio transmissions with peak power levels up to 2 W and the radio frequency envelope is demodulated by nonlinearities contained in the amplifying part of the hearing aids. The amount of interference depends on the distance between the HA and the phone [11], the type of wireless phone technology used (GSM, TDMA, or CDMA) [11], [12], the phone power level [13] ,and the hearing aid [11]. The study in [12] showed that the GSM digital wireless telephones produced a low-frequency (215–225 Hz) interference with harmonics spread well into the speech frequency range. Interference was most intense when the antenna of the phone was placed very close to the hearing aid. Such interference is picked up by the hearing aid as an annoying, and often loud, buzzing sound [14]. Digital phones generate a broad-spectrum radio signal that appears to some cochlear implants as noise. The compatibility between two different implant processors (Nucleus' SPrint and Med-El's Combi 40+) and cellular phones (GSM) was explored in [15] with nine Finnish implant users. The study [15] showed that the Nucleus CI systems were not compatible with GSM phones, while the Med-El's Combi 40+ systems were compatible.

Although a few assistive devices exist for enhancing the telephone signal for HI people, most of these methods do not provide a satisfactory solution, particularly for cellphones. The interference produced by wireless digital telephones prevents HI people from enjoying the benefits of anywhere-anytime communication access provided today by cellular phones. In the survey done in [1], 45% of the HA users reported that current devices do not meet their needs because of either inconvenience or ineffectiveness.

To address these issues related to the use of wireless phones, we propose in this paper a cell-phone assistive device, which can be used by either HA or CI users. The cell-phone assistive device contains a programmable digital signal processor (DSP) chip and utilizes Bluetooth wireless technology to communicate between the cellphone and the HA/CI. The Bluetooth technology is currently an attractive option since Bluetooth-enabled cellphones are commercially available (e.g., Ericsson's T68 phone). A prototype cellphone adapter was built in this study and tested with CI users.

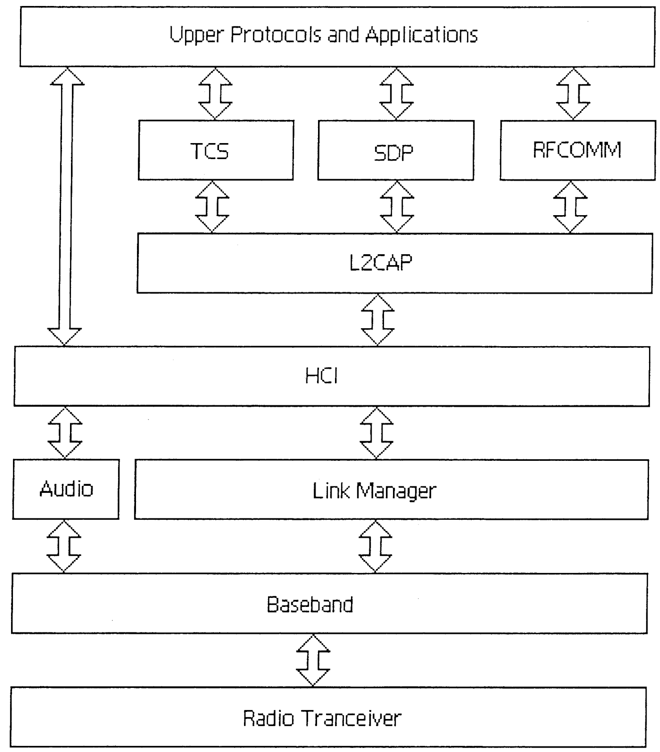

Fig. 1. Structure of the Bluetooth stack. The protocol stack is composed of various layers: the telephony control specification (TCS), the service discovery protocol (SDP), the logical link control and adaptation protocol (L2CAP), and the host controller interface (HCI) layers.

II. Bluetooth Technology: Background

Wireless technology has dramatically changed the way people interact with one another and receive information. Bluetooth, a short-distance wireless communication standard, aims at replacing cables and therefore making the world truly wireless [16], [17]. It defines a universal radio interface, through which devices within 10 m can form short-distance ad-hoc networks. With the use of dynamic Bluetooth links between various mobile devices, a large number of new products and services will become possible.

The physical carrier of Bluetooth connections is the 2.4–2.5-GHz band, which is available for public use in most countries. This band is divided into 79 1-MHz-width channels, with each channel divided into 625-ms-length time slots. The modulation scheme used for each time slot in each channel is based on binary frequency shift keying (BFSK). A Bluetooth link, with one side called "the master device" and the other side called "the slave device," uses one channel in each time slot and jumps to another channel in the next time slot. The sequence of channels to be used is a pseudorandom sequence decided by the master device. The above scheme is called frequency

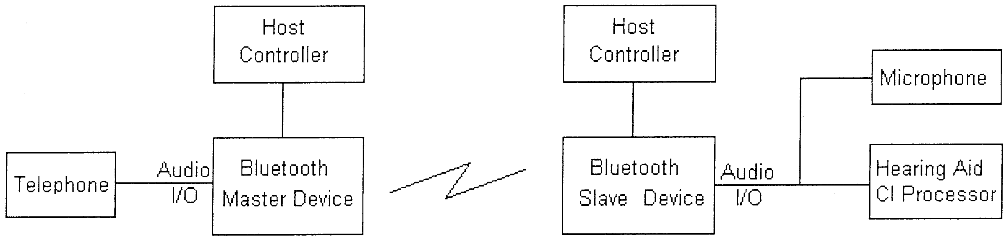

Fig. 2. Architecture of the phone adapter. A pair of Bluetooth transceivers forms the wireless link, and each transceiver is connected to a host controller running the software protocol stack. The telephone signal is connected to the duplex audio interface of the master device with the audio output of the slave device connected to the hearing aid or the CI processor, and the input connected to a lapel microphone.

hopping code division multiple access (FHCDMA). The device that initiates the ad-hoc network becomes the master, and the other devices in the network remain the slaves. Two sides of a link alternately transmit and receive, i.e., there is only one-way traffic in one time slot.

Two types of links are supported: synchronous connection-oriented (SCO) links and asynchronous connectionless links (ACL). An SCO link is composed of evenly spaced pairs of time slots in the hopping sequence at a 64 Kb/s bit-rate. ACL links use the slots not reserved by SCO links. One Bluetooth link can simultaneously support ACL links and up to three SCO links, and its theoretical maximum bit-rate is 1 Mb/s [16], [18].

To ensure interoperability between Bluetooth devices, the protocol layers and application profiles defined in the Bluetooth Specification need to be followed. Fig. 1 shows the structure of a Bluetooth protocol stack. The top layers including the HCI layer can be viewed as software layers, while the rest of the stack can be viewed as hardware layers. The Baseband and Link Manager layers implement the transport actions described in the previous paragraph, and provide a command interface, the HCI layer. The L2CAP layer divides large packets in higher layers into smaller packets for lower-layer transmission, and reassembles received small packets into large packets intelligible to higher layers. The L2CAP layer also supports multiple applications by assigning logical channels. The TCS, SDP, and RFCOMM layers are unaware of physical communication details. The RFCOMM layer emulates a serial port so that conventional applications can be employed with minor, if any, changes. Application profiles for different scenarios are also included in the Bluetooth Specification to guide implementation, since devices following the same profile are guaranteed to be compatible with each other [17].

Currently available products equipped with Bluetooth technology include cellphones, phone adapters, headsets, PC cards, modems, printers, and printer adapters. Aside from replacing cables, Bluetooth technology can also be used for auto-synchronization applications. Personal mobile devices, such as cellphones, PDAs and laptops, can form a mobile network and always be updated with each other. The personal devices can automatically find the local Bluetooth-enabled devices and make use of the information and services provided.

The Bluetooth technology has several advantages that are attractive for assistive-listening applications.

1) The fact that Bluetooth operates in the 2.4–2.5 GHz industrial, scientific, and medical (ISM) band suggests that the devices can be marketed worldwide without significant regulatory hindrance.
2) The high operating frequency of Bluetooth suggests that very small antennas are required, allowing compact packaging and low-power consumption.
3) The likelihood of Bluetooth causing interference in cochlear implants is small due to low-power transmission (typically 1 mW) and high operating frequency.
4) The Bluetooth protocols ensure that large numbers of devices can coexist in a relatively small area without the need for manual selection of channels.

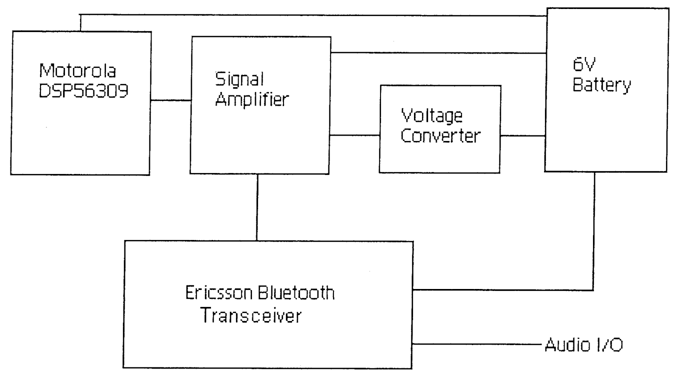

Fig. 3. Hardware design. The DSP56309 evaluation-module (EVM) board is programmed to send HCI commands to the Ericsson Bluetooth Starter Kit (EBSK). A signal amplifying and shifting circuit was designed to meet the electrical requirements of the host interface of the EBSK.

III. Phone Adapter Design

The architecture of the proposed phone adapter is illustrated in Fig. 2. A pair of Bluetooth transceivers forms the wireless link, with each transceiver being connected to a host controller running the software protocol stack. The host controller can be a PC, a microcontroller, or a DSP. The telephone signal is connected to the duplex audio interface of the master device. The audio output of the slave device is connected to the hearing aid or the CI processor, and the input is connected to a lapel microphone.

The slave device is first initialized in active slave mode while waiting for the connection request from the master. When a telephone call comes in, or the user initiates a call, the master device sends out paging messages to find the slave device, and initiates an SCO link. After the connection is confirmed by both sides, the user can talk through this Bluetooth link without the need to

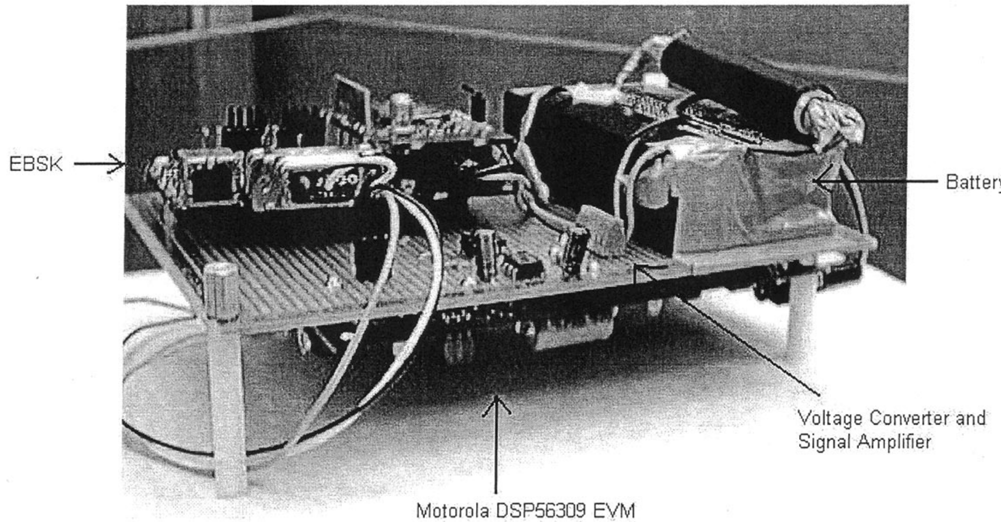

Fig. 4. Photograph of the phone adapter prototype. The DSP EVM board is shown underneath, and the Ericsson Bluetooth board is shown on the upper-left corner. The signal amplifying and shifting circuits are shown in the center.

hold the telephone handset or the need to connect the hearing aid or CI processor directly to the telephone jack. Since the audio signal is directly transmitted from the phone to the hearing aid or CI processor, environmental noise is disabled, thus allowing the user to enjoy high speech quality even under extreme noisy situations (e.g., in a crowded restaurant, in a car).

IV. Hardware Design

A prototype system was built in this paper, consisting of the Bluetooth hardware, a PC and a DSP. A pair of Ericsson's Bluetooth Starter Kits (EBSKs) was used for the transceiver hardware. The PC functioned as the host controller of the master device, and the Motorola DSP56309 processor functioned as the host controller of the slave device, providing portability for the user side.

Fig. 3 shows the block diagram of the hardware design of the slave device. The host I/O port of the DSP56309 evaluation-module (EVM) board was programed to send HCI commands to the EBSK. A sequence of nine HCI protocol commands was implemented in this device in assembly language. These commands reset the EBSK, set basic transmission settings, and put the EBSK in an active slave mode. The assembly program was written in the flash memory of the EVM board and was executed when the DSP was reset. To meet the electrical requirements of the host interface of the EBSK, a signal amplifying and shifting circuit was designed based on a LM318N chip (National Semiconductors). A voltage converter circuit was designed based on a LMC7660IN chip (National Semiconductors) to provide a negative voltage for the amplifier. Fig. 4 shows a photograph of the portable slave-side device.

V. Software Design for Wireless Link

The ultimate goal of this project is not only to design a phone adapter, but an ALD that can receive audio signals from all Bluetooth-enabled sources, such as TVs, stereos, and computers. An audio source with a Bluetooth transceiver should be able to find this device with a function description and set up an SCO link, all through the procedures defined in the Bluetooth Specification. To achieve this interoperability, the host controller needs to support the L2CAP, the RFCOMM and the SDP protocols, as well as the application profile defined in the Bluetooth specification.

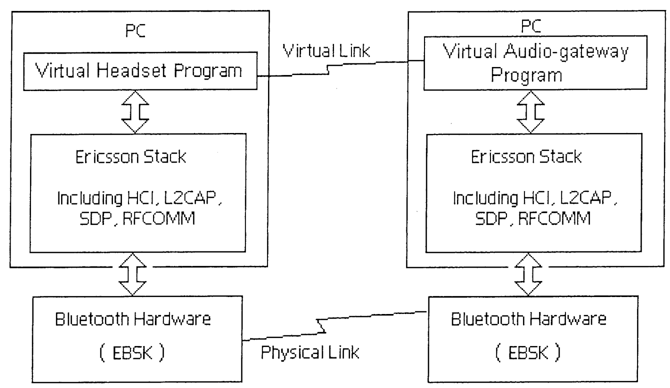

Fig. 5. Emulating the headset profile. The application programs running on the top of the Ericsson software stack emulate the headset and the audio gateway and set up a virtual link to carry the audio and control signals.

The headset profile is most similar in function to our phone adapter. It defines the procedure required to set up a Bluetooth audio link between an audio-gateway device and a headset device. In our phone adapter, the telephone-side device corresponds to the audio gateway, and the user-side device corresponds to the headset. The transceiver hardware consists of a pair of EBSKs. The host controllers in both sides comprise of two computers loaded with the Ericsson Bluetooth PC Reference Stack software. This software stack includes the component object model (COM)-server program in the form of an executable file. The stack contains the HCI, L2CAP, RFCOMM, and SDP layers, and provides a programming interface [19]. Application programs, written in C++, communicate with the protocol layers by sending commands and receiving event-messages. These programs emulate the operations of the audio gateway and the headset, as defined in the Bluetooth

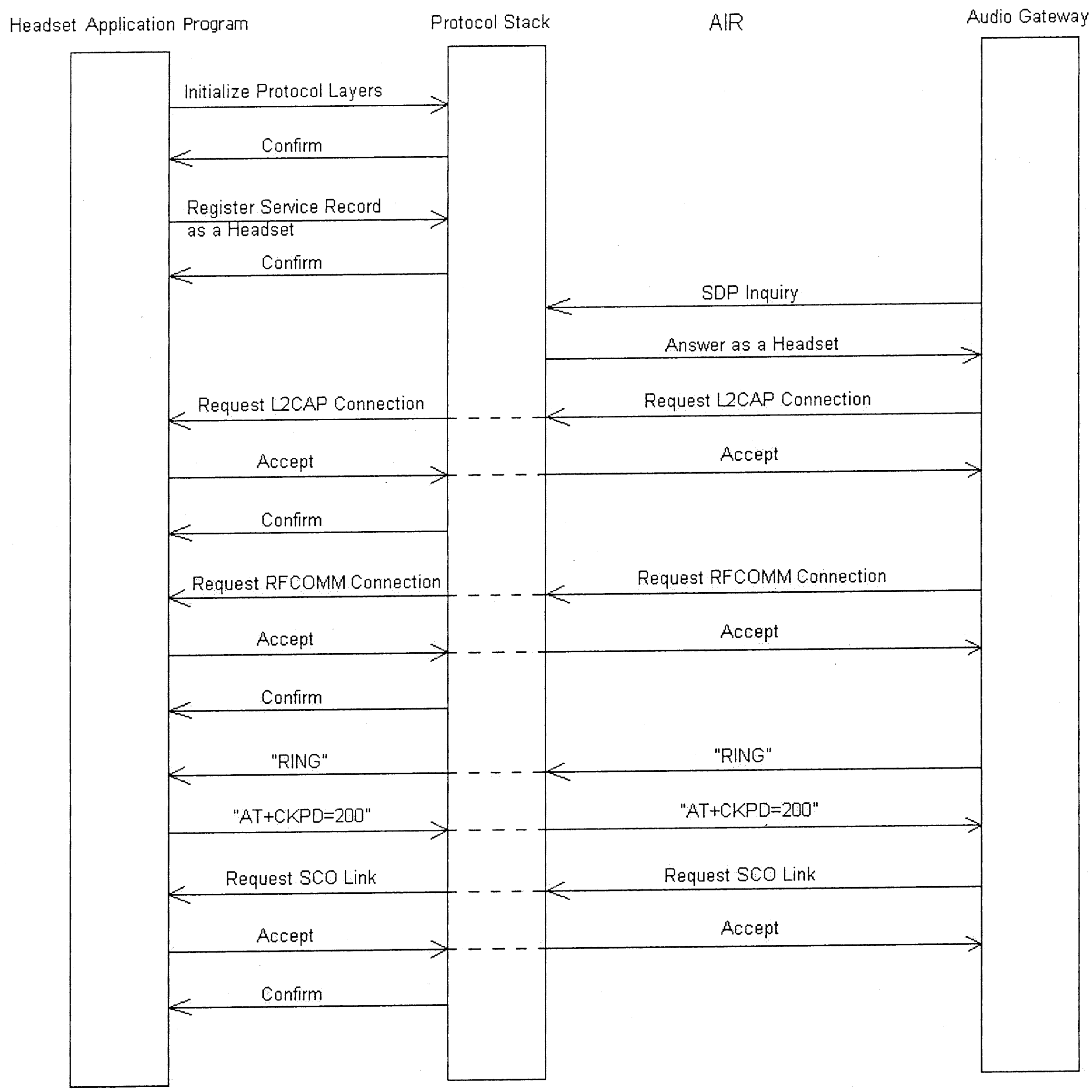

Fig. 6. Message flow (adapted from [18] and [19]). Application programs communicate with the protocol layers by sending commands and receiving event-messages according to the procedures defined in the Bluetooth specification.

Specification. The software structure of the prototype system is shown in Fig. 5.

Fig. 6 shows the message flow for setting up the headset link. The application program first initializes itself by registering the protocol layers, and starts by writing the SDP service record as a headset. When the remote audio gateway inquires the function description, SDP answers with the information written by the program. After answering the L2CAP and RFCOMM connection requests properly, a virtual serial-port link is established between the two devices. A “RING” command (an AT command [20]) is sent from the audio gateway to the headset, and the program responds with the “$AT + CKPD = 200$” command [21], indicating that the incoming call is accepted. Finally, the audio gateway initializes the SCO link that contains the speech signal, and the process is complete.

Application programs were developed using sample programs provided in the Ericsson stack. Those programs were modified for our application. When both host controllers used our emulating programs, the EBSKs successfully completed the whole process given in Fig. 6.

VI. Testing and Discussion

To evaluate the effectiveness of the wireless transmission with regard to the quality of the audio signal, three CI users were invited to use the phone-adapter prototype. All users were previously fitted with the Med-El/CIS-LINK processor. The three CI subjects were using their daily Med-El implant processor and were fitted with the CIS strategy operating at a rate of 1000–2000 pulses/s/channel. The audio I/O of the portable device was split to two monojacks, one leading to the audio input of the CI processor and the other leading to a microphone. The users listened through the CI processor and talked to the microphone. Good quality was reported by the CI users when both parties stayed within a reasonable distance inside our lab (within a 7×6 m^2 area). The CI users reported that the quality was as good as the quality obtained using a direct connection with a commercial phone adapter.

The present study evaluated the performance, at least qualitatively, of the Bluetooth device. Further studies are needed to quantify the performance, in terms of speech intelligibility, of the Bluetooth device. There are several factors that may affect the quality (and perhaps intelligibility) of speech transmitted via a Bluetooth link. One potential factor is the accumulation of processing delays in the cellular telephone network and in the Bluetooth link. Another factor is the potential loss or damage of data packets. The speech signal is coded in the Bluetooth link using a 64 kb/s continuous variable slope delta modulation (CSVD) scheme [18], and is, therefore, unlikely that it gets impaired since it is not compressed. Packet losses or damages, however, may impair the received signal and therefore need to be considered and possibly accounted for. The individual assessment of these factors on speech intelligibility/quality needs further investigation.

VII. Conclusion

The work in this paper addressed the problem of assisting hearing-impaired people (CI users in this study) to use telephones. A wireless assistive phone adapter was designed based on Bluetooth technology. The proposed phone adapter routes the telephone audio signal to the CI processor via a wireless Bluetooth connection, thereby disabling environmental noise. Unlike commercially available phone adapters, the proposed adapter provides mobility to the users, as they no longer need to be confined by cables. A prototype system was tested with three CI users and good quality was reported.

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