**SmartHear: A Smartphone-Based Remote Microphone Hearing Assistive System Using Wireless Technologies**

Yu-Cheng Lin, Ying-Hui Lai, Hsiu-Wen Chang, Yu Tsao, Member, IEEE,
Yi-ping Chang, and Ronald Y. Chang, Member, IEEE

**Abstract**—In this paper, we propose a new smartphone-based hearing assistive system (SmartHear) using wireless technologies for individuals with mild-to-moderate hearing loss. Our system is a stigma-free implementation of the personal frequency modulation (FM) system for people with hearing loss, with enhanced accessibility, affordability, and customization and extension potentials. The SmartHear system consists of a smartphone running a mobile application and a Bluetooth handset coupled with the smartphone. The voice of the speaker is picked up by the smartphone placed near the speaker and transmitted wirelessly to the Bluetooth handset placed near the listener for listening. The transmission of the voice signals over radio waves overcomes the reverberation and ambient noise effects, and thus the listener can listen from a distance with better clarity and ease. Speech intelligibility experiments demonstrate the efficacy of the proposed SmartHear system, showing an average improvement of 0.2 speech intelligibility score (on the scale of 0–1) across four posited SmartHear system, showing an average improvement of 0.2 speech intelligibility score (on the scale of 0–1) across four typical audiograms for mild-to-moderate hearing loss and in four signal-to-noise ratio (SNR) conditions. A user survey reveals the favorable user experience with SmartHear in various dimensions as compared to the conventional FM system.

**Index Terms**—Wireless assistive hearing technology, e-health, smartphones, mobile applications, frequency modulation (FM) systems.

**I. INTRODUCTION**

Life expectancy has continuously increased in many countries due to medical advances, and age-related hearing loss has been one of the most common conditions affecting adults. According to World Health Organization (WHO), 15% of world’s adults and one-third of world’s population aged 65 or above have different degrees of hearing loss [1]. According to the WHO prediction, the number of adults over 65 years old will triple between 2010 and 2050, and the prevalence rate of age-related hearing loss is estimated to increase rapidly. Davila et al. [2] reported that 18% of older U.S. workers are experiencing hearing loss.

Hearing loss could cause great inconvenience in life. People with hearing loss may experience heightened difficulties in listening in noisy conditions [3]–[6]. People with mild hearing loss may lose 50% of speech in noise and people with moderate hearing loss may lose 50–70% of speech in noise. Moreover, uncorrected hearing loss may associate with loneliness, withdrawal from social activities, and sense of exclusion, leading to degraded quality of life in general [7], [8]. Lotfi et al. [9] showed that hearing difficulty may affect communicative relationships as well as social and emotional interactions.

For people with hearing loss, a common prescription is hearing aids [5], which magnify sound vibrations entering the ears. However, Kochkin [10] reported that the hearing aid adoption rate was only 23% in the adult population surveyed in their study. Kochkin [11] commented that only 29% of people are satisfied with their hearing aids. There are some reasons associated with the dissatisfaction. For example, the poor performance of hearing aids in noise has deterred people from using them [12]. Also, hearing aids have varying performance in conditions with background noise and reverberation, and when listening at a distance.

Personal frequency modulation (FM) systems have been proposed to alleviate these issues. FM systems carry the sound to the ears directly from the transmitter microphone used by the speaker to the receiver used by the listener using frequency modulation, effectively overcoming the obstacles of background noise, distance from the speaker, and poor room acoustics. Popular commercial FM systems include Phonak Dynamic FM [14], COMTEK AT-216 [15], and Comfort Contego [16], [17]. Studies have shown that adults with hearing loss prefer using FM systems in noisy conditions, and people using both hearing aids and FM systems perform better than those using hearing aids alone [18]–[20]. While the FM systems could be beneficial to people with hearing loss, there are two limitations of commercial FM systems. First, commercial FM systems usually adopt a relatively simple one-channel linear amplification scheme to complete sound delivery (while leaving customized multi-channel amplification to hearing aid processing). Second, the transmitter and the receiver of an FM system are paired when users desire to use some latest FM technologies (e.g., Phonak Dynamic FM). Furthermore, commercially available hearing aids or FM systems are quite expensive. In one study [10], 76% of respondents revealed that financial constraint is the main obstacle to hearing aid adoption. It is therefore imperative to increase the accessibility and affordability of hearing devices,
as also urged by the U.S. National Institute on Deafness and Other Communication Disorders (NIDCD) which sponsored a research working group focusing on adults with mild-to-moderate hearing loss, as this group of people are less likely to adopt hearing aids [21].

Against this background, we propose a highly affordable, cost-effective, and accessible smartphone-based hearing assistive system (SmartHear) for individuals with mild-to-moderate hearing loss. The proposed SmartHear system is integrated with a five-channel amplification scheme, allowing users to optimize the amplification ratio for each of the five distinct frequency channels. When compared with conventional FM systems, the multiple-channel amplification scheme of SmartHear provides more flexibility and benefits for users with various types of hearing loss. Moreover, our system has the following features:

- **Anti-stigma:** Overcoming the stigma associated with hearing aids.
- **Accessibility:** Requiring only the user’s smartphone, Bluetooth handset, and our mobile application.
- **Customization:** Easy customization to audio preferences or needs.
- **Extension:** Extensible with advanced speech-audio processing in smartphones.

The speech intelligibility experiments on four typical audiograms for mild-to-moderate hearing loss and four signal-to-noise ratio (SNR) conditions have demonstrated an average improvement of 0.2 speech intelligibility score (on the scale of 0–1) by adopting SmartHear. The intelligibility score is as high as 0.85 even in the most challenging SNR condition (−10 dB) with SmartHear. A user survey conducted among five participants with various degrees of hearing loss reveals the favorable user experience with SmartHear as compared to the conventional FM system in many different dimensions.

The outline of this paper is as follows. Section II briefly reviews the current commercially available FM systems. Section III describes the system architecture for SmartHear. Section IV presents the evaluation methods. Experimental results and discussion are presented in Section V and Section VI, respectively. Finally, Section VII concludes the paper.

II. CONVENTIONAL FREQUENCY MODULATION (FM) SYSTEMS

The FM system is a hearing assistive device that consists of a transmitter-receiver pair. The speaker wears a transmitter whose voice is transmitted directly to the listener who wears a receiver, as shown in Fig. 1. The FM system may be coupled with hearing aids, but can also be used alone for people with mild-to-moderate hearing loss or with normal hearing. The FM system functions similarly to the FM radio broadcast. The transmission of the voice signals over radio waves overcomes the reverberation and ambient noise effects, and thus the listener can listen to the voice of the speaker at a distance with better clarity. It was shown [18] that an improvement of 15–20 dB in SNR can be achieved with the FM system. Studies have shown that adults with hearing loss will have better speech perception in noisy conditions when wearing hearing aids coupled with the FM system, as compared to wearing hearing aids alone [18]. Lewis et al. [22] reported a consistent finding that the combination of the FM system and hearing aids equipped with directional microphones enhances perception in noisy conditions in adults with hearing loss. If adults were to choose their preferred hearing assistive device for listening in noisy conditions, their choice is hearing aids coupled with the FM system [18]. For children with hearing loss, the FM system can effectively improve speech intelligibility for children with a wide spectrum of hearing loss conditions [23]–[25]. Despite the prospects of its practical use, the FM system has the limitations of unappealing appearance (stigma) and high cost (around NT$80,000 or US$2,600 according to the local market), which results in its lower adoption rates than promised by its benefits. According to a report by Sonova Holding AG [26], the largest manufacturer of the FM systems, hearing assistive wireless communication products including the FM systems account for only 5% of the company’s total sales of hearing aid products.

With the advances of wireless technologies and the prevalence of smartphones, there is a potential to implement the working principles of the FM system on smartphone platforms that promise more affordability and less stigma, and consequently, a greater potential for wider acceptance. In the following, we describe the proposed system that incorporates
III. SYSTEM ARCHITECTURE FOR SMARTHEAR

The system architecture of SmartHear is shown in Fig. 2, where a person with hearing loss (shown at the right) wishes to listen to the talker (shown at the left) with better clarity and ease using SmartHear. The listener places his/her smartphone near the talker (in the figure, the talker is shown holding the smartphone in his hand) and wears his/her Bluetooth handset. The talker’s voice is captured by the microphone of the smartphone and converted from an analog signal to a pulse-code modulated (PCM) digital signal. The PCM signal is sent to the Bluetooth transmitter in the smartphone, where the PCM electrical signal is transformed into radio waves in the unlicensed industrial, scientific and medical (ISM) band at 2.4–2.5 GHz. A synchronous connection oriented (SCO) link, which is a type of baseband links mainly used for voice transmission, is established for point-to-point connection between the smartphone and the Bluetooth handset. The Bluetooth handset receives the radio waves and converts the PCM signal back to an analog signal for listening. Due to the proximity between the smartphone and the talker, and the transmission of voice signals over radio waves without reverberation and ambient noise effects, the listener can listen to the voice uttered from a distance with more ease. Fig. 3 shows the hardware components of SmartHear including the smartphone, Bluetooth handset, and headphones (earbuds), with detailed specifications summarized in Table I.

To facilitate the use of our system by elderly people with mild-to-moderate hearing loss, we develop a mobile application with an intuitive user interface, as shown in Fig. 4. The user only needs to press one button that initiates and completes the connection process in the SmartHear system. Also, SmartHear can be easily customized to different people with different degrees/configurations of hearing loss. The user can adjust the amplification in each of the five frequency channels (0.1, 0.3, 1, 3, and 10 kHz) as shown in Fig. 4 according to his/her audiogram or personal preferences. Furthermore, the user interface shows the sound characteristics at the top of the display screen including the sound pressure level (SPL) and zero-crossing rate (ZCR), which can be used for advanced speech-audio processing in an extension of SmartHear.

The connection between the smartphone and the Bluetooth handset is established in five stages, as described in Fig. 5. In Stage 1, the Bluetooth Android application programming interface (API) turns on the Bluetooth application if the Bluetooth status is currently off. The Bluetooth API also checks whether Bluetooth is supported on this smartphone. In Stage 2, Bluetooth API finds Bluetooth handsets either through discovering devices or by querying the list of bonded devices. If the Bluetooth handset has been paired with the smartphone previously, the Bluetooth API searches the Bluetooth handset on the bonded list. Once the Bluetooth handset is identified, the application is ready to connect. If the smartphone has
### TABLE I
#### SPECIFICATIONS OF SMARTHEAR

<table>
<thead>
<tr>
<th>Module</th>
<th>Items</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smartphone</td>
<td>CPU</td>
<td>Quad-core 1.7 GHz Krait 300</td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>Android 4.4.2</td>
</tr>
<tr>
<td></td>
<td>Bluetooth</td>
<td>v4.0 with A2DP</td>
</tr>
<tr>
<td>Bluetooth handset</td>
<td>Bluetooth</td>
<td>v3.0</td>
</tr>
<tr>
<td></td>
<td>Headphone connector</td>
<td>3.5 mm</td>
</tr>
<tr>
<td></td>
<td>Compatible</td>
<td>Bluetooth enabled smartphones, tablets and computers</td>
</tr>
<tr>
<td>Headphones</td>
<td>Ear coupling</td>
<td>Insert</td>
</tr>
<tr>
<td></td>
<td>Nominal impedance</td>
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</tr>
<tr>
<td></td>
<td>Driver type</td>
<td>Electro-dynamic</td>
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<td></td>
<td>Frequency range</td>
<td>20–20000 Hz</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>100.5 dB SPL/mW at 1 kHz</td>
</tr>
<tr>
<td></td>
<td>Total harmonic distortion</td>
<td>&lt; 0.5% (100–10000 Hz at 1 mW)</td>
</tr>
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Fig. 4. Mobile application with an intuitive user interface for SmartHear.

never been paired with any Bluetooth handset previously, the Bluetooth API starts the discovering mode and scans the surrounding device, which lasts about 12 seconds. Once a Bluetooth handset is identified, it stops scanning and tries to pair with the device. The pairing mechanism is the secure simple pairing (SSP), which does not require the user to enter any personal identification number (PIN) codes. When the pairing procedure completes, the Bluetooth API receives information from the Bluetooth handset, such as the device name, device class, MAC address, etc. In Stage 3, after successful pairing, the Bluetooth API tries to connect to the Bluetooth handset with a shared link-key (which is used to distinguish the same Bluetooth handset) to build an encrypted connection. In Stage 4, the audio API starts to record the talker’s voice in the format of the PCM signal and sends it to the Bluetooth transmitter. In Stage 5, the Bluetooth API establishes the SCO link between the smartphone and the Bluetooth handset to complete the entire process.

There are three main APIs to establish the SCO link to route the audio from the smartphone to the Bluetooth handset in SmartHear, i.e., AudioRecord, AudioTrack, and AudioManager, as shown in Fig. 6. The AudioRecord manages sound recording and the AudioTrack manages sound playing. Both are set according to the parameters summarized in Table II. There are four options of sampling rates, i.e., 11.025 kHz, 16 kHz, 22.05 kHz, and 44.1 kHz. The higher the sampling rate, the longer the latency. Thus, for real-time audio applications like SmartHear, we select the 11.025 kHz sampling rate. Mono sound format is used in our system, which is supported by most of the Bluetooth devices. Most existing audio devices support the 16 bits PCM format and not the 8 bits PCM format. In order not to overwrite the audio buffer when it is written by the AudioRecord, the audio buffer is set to 640 bytes. After these settings are done, the AudioRecord starts recording the sound, reading audio data from the register, and storing audio data into the audio buffer just created. Then, the AudioTrack starts playing the audio by extracting the audio data from the audio buffer and writing into the audio sink for playback. The task of recording the talker’s voice and playing it back simultaneously is repeated in a loop. Then, the AudioManager establishes the Bluetooth SCO, which redirects the audio path from the smartphone to the Bluetooth handset.

The mobile application for SmartHear is available for download on Google Play, and a video introduction to SmartHear is available at [29].
IV. EVALUATION METHODS

A. Speech Intelligibility Index (SII) Test

We evaluate the performance of our system by the speech intelligibility index (SII) which is a standardized measure of intelligibility [30]. SII is a proportional value that sums importance-weighted speech audibility across frequencies, including corrections and computational procedures for the effects of distortion associated with inputs, reverberation, and masking [31]. The SII represents the amount of speech that is audible for an individual with hearing loss in aided or unaided conditions. The SII can be expressed as follows:

\[ \text{SII} = \sum_{n=1}^{N} I_n A_n \]  

where \( N \) is the number of frequency bands, \( A_n \) is the audibility for the \( n \)th band, and \( I_n \) is the band importance function (BIF) value of the \( n \)th band which is based on ANSI standard [30]. \( I_n \) and \( A_n \) are determined by three input parameters: equivalent speech spectrum level, equivalent noise spectrum level, and hearing threshold levels. Equivalent speech spectrum level and equivalent noise spectrum level are obtained from the long-term spectrum which is divided into 1/3-octave bands and its power is computed. A total of 18 1/3-octave bands within
150–8000 Hz are used in this paper. Hearing threshold levels can be defined by the user. The SII value maps to the speech intelligibility score according to the matching table provided by Verifit User’s Guide [32]. The speech intelligibility score ranges from 0 to 1.

We consider four typical audiograms for mild-to-moderate hearing loss (HL) [27], [28] in our experiment, as shown in Fig. 7. The four audiograms can be divided into two groups, namely, precipitous and sloping, according to the shape of audiometric configurations [27]. Audiogram 1 and Audiogram 2 are precipitous audiograms, and Audiogram 3 and Audiogram 4 are sloping audiograms. We adopt the four frequency average hearing loss (4FAHL), which is the average of thresholds at 500, 1000, 2000, and 4000 Hz, to indicate the degrees of hearing loss. In the two groups of audiograms, Audiogram 1 has a smaller 4FAHL value than Audiogram 2, and Audiogram 3 has a smaller 4FAHL value than Audiogram 4. The testing data (IEEE sentences) and the implementation software (the MATLAB code) for calculating the SII value are provided by [31]. Each IEEE sentence is randomly selected among the 72 lists, and its duration is designed to last more than 13 seconds. The energy of all the sentences is normalized to the value of 3276 (corresponds to 70 dB SPL), where the maximum volume of the speaker is 32768 (corresponds to 90 dB SPL).

Our experimental setup is shown in Fig. 8. The speech speaker plays the IEEE sentences, and the noise speaker plays the speech shaped noise (SSN). The Verifit Real Ear Hearing Aid Analyzer model (VF-1) made by Audioscan is used to calculate the equivalent sound spectrum level for the various sound from both speakers and SmartHear. The Verifit system is also used to facilitate the sound level calibration process. The volume of the noise speaker is calibrated at 70 dB SPL.

B. User Experience Questionnaire

We evaluate the user experience with SmartHear in comparison with the conventional FM system through a questionnaire-based survey. Five participants (three males and two females; aged 34–70 years with a mean age of 49 years), whose audiograms for the tested ear are shown in Fig. 9, participated in this survey. The configurations of these participants’ hearing losses are similar to the four typical audiograms considered in the SII testing. Each participant was given a trial of the SmartHear device and a conventional personal FM system by listening to recorded materials using each device. The FM transmitter used for the study was the Phonak iSensio Micro, which was a small behind-the-ear headset designed for hearing-impaired users who do not wear hearing aids. At the beginning of the trial session, the participants received a copy of the user experience questionnaire, and were given instructions and explanations regarding each item on the questionnaire. During the trial session, each participant was instructed to set the SmartHear device or the conventional FM system to a comfortable listening level (which was kept constant throughout the testing) and wear the device in the better ear. In the event that the participant has symmetric hearing loss he/she was asked to wear the device in the ear used to listen to the telephone in daily life. At the end of the device trials, the participant was asked to rate items regarding different situations on the questionnaire. This study was reviewed and approved by the local institutional review board (IRB) committees. Informed consent was obtained from all participants. All participants were compensated for their participation in this study.

We developed the user experience questionnaire based on the Satisfaction with Amplification in Daily Living (SADL) questionnaire [33] with modifications. The original SADL questionnaire aims to investigate hearing aid satisfaction. As shown in Table III, the questionnaire contains 17 items representing six dimensions: positive effect (4 items), self-confidence (3 items), appearance (3 items), cost (2 items), ease of use (3 items), and willingness to purchase (2 items). The questionnaire was presented to the participants in the order of the numbered items. The dimensions are not shown to the participants. Each item was rated on a seven-point rating scale.
from 1 (“strongly disagree”) to 7 (“strongly agree”). Reversed items are assigned reverse scores (e.g., an item receiving rating of 1 will be assigned score 7). The average score was calculated for each dimension from responses to corresponding items.

V. RESULTS

A. Speech Intelligibility Index (SII) Test

We measure and compare the intelligibility performance of people with different degrees/configurations of hearing loss in different SNR conditions and different cases (i.e., using SmartHear or not). The intelligibility scores were obtained in several steps. First, the speech of IEEE sentences and the SSN noise were received and analyzed by VF-1. Second, in order to compute the SII value, the output result from VF-1 and the typical audiograms were fed into the SII computation in MATLAB. Third, according to the matching table provided by Verifit User’s Guide, we mapped the SII value to the intelligibility. Finally, repeating all the steps in different SNR conditions, the intelligibility scores for the four typical audiograms in four SNR conditions were obtained.

Fig. 10 shows the improvement in the speech intelligibility score when SmartHear is used, for the four typical audiograms for mild-to-moderate hearing loss and in four SNR conditions. As can be seen, SmartHear yields a greater improvement in the sloping group (Audiogram 3 and Audiogram 4) than in the precipitous group (Audiogram 1 and Audiogram 2) in general and especially when SNR ≤ 0. In the sloping group, the improvement is proportional to the degree of hearing loss (i.e., greater improvement for Audiogram 4 than Audiogram 3). In the precipitous group, however, the improvement is not proportional to the degree of hearing loss. Besides, there is a heightened difference between Audiogram 1 and Audiogram 2 when SNR = 5.

Fig. 11 presents the Speechmap [32] which displays the relationship between hearing thresholds, loudness discomfort levels (LDLs), and the amplified speech spectrum. The white dotted line is the normal hearing threshold and the red circled line represents an individual with a flat audiogram of 55 dB HL, which is the most severe degree of moderate hearing loss. The asterisks are LDLs, which indicate points of uncomfortable sensitiveness to sound predicted from the degree of hearing loss. The green shaded region is called the speech envelope. The top and bottom curves of the speech envelope represent the level in each band that is exceeded by 99% and 70% of the samples, respectively, and the middle curve represents the long term average speech spectrum (LTASS). If the speech envelope is above the hearing threshold, the speech will be detectable. The speech envelope entirely above the threshold will be maximally audible, and one that extends above the LDLs will be uncomfortable. Fig. 11 shows a sharp magnification decrease above 4 kHz, due to the specification of the Bluetooth system [34] that the spectrum of the sound at the transmitter side should be below 4 kHz and the spectrum above 4 kHz should be 20 dB below the maximum in the 0–4 kHz range at the receiver side.

Fig. 12 shows the speech intelligibility scores averaged over the four typical audiograms when using SmartHear or not, in four SNR conditions. As can be seen, SmartHear can improve speech intelligibility for people with sloping and precipitous hearing loss alike by approximately 0.2 score at each SNR condition. As the SNR decreases, the intelligibility generally decreases more significantly when SmartHear is not used. The same score at SNR = −5 dB and −10 dB when SmartHear is not used indicates that it is difficult to distinguish the clean speech from the noise. In such challenging conditions, SmartHear can still achieve an average intelligibility score of 0.85 for people with hearing loss.
Fig. 10. Improvements in the speech intelligibility scores by using SmartHear, for the four audiograms in Fig. 7 and in four SNR conditions (5, 0, −5, −10 dB). Positive values indicate better speech intelligibility performance by using SmartHear as compared to not using SmartHear in the corresponding condition.

B. User Experience Questionnaire

Fig. 13 shows the difference of average ratings (SmartHear subtracted by the conventional FM system) in the six dimensions in the user experience survey. Positive values represent higher satisfaction of SmartHear and negative values represent higher satisfaction of the conventional FM system in the corresponding dimensions. As can be seen, SmartHear has a clear advantage in the dimensions of self-confidence, appearance, and cost. SmartHear and the conventional FM system received nearly the same preference ratings on average in the dimension of positive effect. For the dimensions of ease of use and willingness to purchase, most participants considered SmartHear more favorable, except for Participant 4.

VI. DISCUSSION

Fig. 10 observes a greater improvement for the sloping group when SNR ≤ 0. As shown in Fig. 7, the hearing level in the precipitous group is higher than 55 dB (i.e., more severe than moderate hearing loss) above 2 kHz, while the hearing level in the sloping group is generally below the degree of moderate hearing loss, resulting in the higher benefits of using SmartHear for the sloping group. In the precipitous group, Audiogram 1 observes a greater improvement than Audiogram 2 at SNR = 5, 0, and −5 dB. This may be due to the masking effect [30], [31]. The shape in Audiogram 1 (with better hearing at low frequencies) intensifies the masking effect more than Audiogram 2, leading to a better intelligibility performance of Audiogram 2 than Audiogram 1 without SmartHear. On the other hand, since SmartHear equally magnifies all the speech spectrum below 4 kHz, the masking effect only mildly affects the intelligibility. Thus, Audiogram 1 exhibits a better intelligibility performance than Audiogram 2 with SmartHear.

Fig. 12 shows that there is a 0.1–0.15 score gap to full intelligibility when SmartHear is used. This may be explained as follows. First, most voice communication devices only transmit the sound below 4 kHz. Likewise, SmartHear only amplifies the sound below 4 kHz. However, the calculation of SII takes the sound spectrum between 4 kHz and 8 kHz into account. Second, we adopt a relatively low sampling rate at 11.025 kHz in our configuration (Table II), which may distort the original sound. It is an option to adopt a higher sampling rate for the sound quality at the tradeoff of transmission latency. Third, in our current configuration, SmartHear amplifies all the frequency channels at the same fixed amplification ratio of 17 dB. However, different types of hearing loss require different fitting strategies. Developing a customized fitting strategy that maximizes the listening experience with SmartHear within the hardware capabilities is a worthwhile future study.

Fig. 13 shows an overall higher satisfaction toward SmartHear as compared to the conventional FM system according to our user experience survey. The results confirm the many attractive features of SmartHear based on user feedback. Specifically, the remarkable differences of ratings on the dimensions of cost and willingness to purchase justify the better affordability and cost-effectiveness of SmartHear. The results for the dimension of ease of use suggest that the developed mobile application with an intuitive user interface meets the participants’ needs and habits, making SmartHear a user-friendly device. Participant 4 gave low ratings for SmartHear on the dimensions of ease of use and willingness to purchase,
possibly due to his/her preference of the conventional cell phone and lack of user experience with smartphones. The optimistic responses on the dimensions of self-confidence and appearance (especially the unanimous and strong preference toward SmartHear in the dimension of appearance) verify the anti-stigma feature of SmartHear. The results for the dimension of positive effect suggest that the proposed SmartHear is comparable to the conventional commercial FM system in terms of the sound quality of the device. Note that in this user experience survey the amplification scheme in SmartHear was not customized to the participant’s audiogram. As mentioned earlier, a worthwhile future endeavor is to develop a customized fitting strategy for SmartHear, which may very likely further enhance the perceived sound quality of SmartHear. Participant 1 responded that he/she was not impressed by the sound from SmartHear, possibly due to the earphone not fitted to his/her ear and the insufficient amplification of the sound, which results in the poor performance on the dimension of positive effect. Participant 4’s lower satisfaction with the sound quality of SmartHear on the dimension of positive effect may be related to his/her precipitous hearing loss as shown by the audiograms in Fig. 9. This lower satisfaction for Participant 4 with precipitous hearing loss is in agreement with the SII testing results in Fig. 10 which shows that SmartHear yields a smaller improvement in the precipitous group. This points to an important and promising future work for SmartHear: realize the full customization potential of SmartHear by adapting the amplification in each channel to the audiograms or preferences of users.

SmartHear is one of the many examples in mobile health, aiming to expand the smartphone hardware capabilities to potentially replace existing technologies. With more and more hearing aid related mobile applications launched in the iOS and Android mobile application stores, it can be anticipated that the hearing product industry will be changing as individuals with hearing loss can easily access affordable personal hearing assistance on smartphones. Few studies, however, address the issue of the scientific validity of these mobile hearing aid applications [35]. Our study presents the development of SmartHear and its validation process carried out in parallel in an effort to provide the potential users with a scientifically proven hearing assistive technology on smartphones.

VII. Conclusion

We have developed a novel hearing assistive system using smartphones and wireless technologies for individuals with mild-to-moderate hearing loss. The proposed SmartHear system is highly affordable and accessible compared to the existing commercially available FM systems, and carries promising potential in customization and extension by designing advanced speech-audio processing techniques and user-friendly mobile applications. Our speech intelligibility experiments have shown an average improvement of 0.2 speech intelligibility score (on the scale of 0–1) across four typical audiograms for mild-to-moderate hearing loss and in four SNR conditions. Our survey conducted among five participants with
various degrees of hearing loss compares the SmartHear and the conventional FM systems, and confirms the many attractive features of SmartHear including more affordability and cost-effectiveness, and less stigma. Future work includes developing a customized fitting strategy that maximizes the listening experience for users with different degrees/configurations of hearing loss, incorporating advanced speech-audio processing techniques in our prototype system, promoting our proposed system by cooperating with local/global organizations serving people with hearing loss, and establishing an effective user feedback mechanism.

REFERENCES


[22] M. S. Lewis, C. C. Crandell, M. Valente, and J. E. Horn, “Speech perception in noise: Directional microphones versus frequency modulation
Fig. 13. Difference of average ratings (SmartHear subtracted by the conventional FM system) in the six dimensions in the user experience survey. Positive values indicate higher satisfaction of SmartHear in the corresponding dimensions.


Yu-Cheng Lin received the B.S. degree in mechanical engineering from National Central University, Chung-Li, Taiwan, in 2010 and the M.S. degree in engineering science and ocean engineering from National Taiwan University, Taipei, Taiwan, in 2013. He is currently a Research Assistant at the Research Center for Information Technology Innovation, Academia Sinica, Taipei, Taiwan. His recent research interests include wireless assistive hearing technology and mobile app development.

Ying-Hui Lai received the B.S. degree in electrical engineering from National Taiwan Normal University, Taipei, Taiwan, in 2005, and the Ph.D. degree in biomedical engineering from National Yang-Ming University, Taipei, Taiwan, in 2013. From 2010 to 2012, he worked on development of hearing aid in Aescu Technologies. Since 2013, he has been a postdoctoral research fellow in the Research Center for Information Technology Innovation, Academia Sinica, Taipei, Taiwan. His research interests focus on hearing aids, cochlear implants, noise reduction, pattern recognition and source separation.
Hsiu-Wen Chang is an assistant professor of Audiology in the Department of Audiology and Speech-Language Pathology, MacKay Medical College in Taiwan. She received her master’s degrees in Linguistics and Audiology, followed by Ph.D. in Biomedical Engineering. She is also a certified audiologist and has extensive clinical experience in adult and pediatric hearing services. She serves as an executive council member of the Taiwan Speech-Language-Hearing Association as well.

Dr. Chang performs research into many aspects of audiology. Most recently, her research has concerned the mobile app development for hearing aids, the electrophysiological evaluation of hearing aid effectiveness in infants and young children and the development of outcome assessment tools in Mandarin Chinese.

Yu Tsao (M’09) received the B.S. and M.S. degrees in Electrical Engineering from National Taiwan University in 1999 and 2001, respectively, and the Ph.D. degree in Electrical and Computer Engineering from Georgia Institute of Technology in 2008. From 2009 to 2011, Dr. Tsao was a researcher at National Institute of Information and Communications Technology (NICT), Japan, where he engaged in research and product development in automatic speech recognition for multilingual speech-to-speech translation. Currently, he is an assistant research fellow at the Research Center for Information Technology Innovation (CITI), Academia Sinica, Taiwan. Dr. Tsao’s research interests include speech and speaker recognition, acoustic and language modeling, multimedia signal and information processing, pattern recognition, and machine learning.

Yi-ping Chang received the B.S. degree in Electrical Engineering from National Tsing Hua University, Hsinchu, Taiwan, in 2000; M.S. degree in Electrical and Control Engineering from National Chiao Tung University, Hsinchu, Taiwan, in 2002; and Ph.D. degree in Biomedical Engineering from the University of Southern California (USC), Los Angeles, CA, USA, in 2009. She also received the Graduate Certificate in Educational Studies with a specialization in Listening and Spoken Language from the University of Newcastle, Australia, in 2014.

From 2009 to 2010, she was a postdoctoral researcher at the House Ear Institute in Los Angeles. Since 2011, she has been with the Children’s Hearing Foundation (CHF), Taipei, Taiwan, where she is currently the director of CHF’s Speech and Hearing Science Research Institute. Her research interests include speech perception in cochlear implants, bimodal hearing, and assessment of listening and spoken language development of children with hearing loss.

Ronald Y. Chang (M’12) received the B.S. degree in electrical engineering from National Tsing Hua University, Hsinchu, Taiwan, in 2000, the M.S. degree in electronics engineering from National Chiao Tung University, Hsinchu, in 2002, and the Ph.D. degree in electrical engineering from the University of Southern California (USC), Los Angeles, CA, USA, in 2008. From 2002 to 2003, he was with the Industrial Technology Research Institute (ITRI), Hsinchu, Taiwan. In 2008, he was a research intern at the Mitsubishi Electric Research Laboratories (MERL), Cambridge, MA, USA. Since 2010, he has been with the Research Center for Information Technology Innovation (CITI), Academia Sinica, Taipei, Taiwan, where he is currently an assistant research fellow. His research interests include wireless communications and networking. He was an Exemplary Reviewer for IEEE Communications Letters in 2012. He received the Best Paper Award from IEEE Wireless Communications and Networking Conference (WCNC) 2012, and the Outstanding Young Scholar Award from the Ministry of Science and Technology, Taiwan, in 2015. He has four awarded U.S. patents.