Hearing Aid devices for Smart Cities: A Survey

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***Abstract*—Hearing loss population has increased in recent years. Hearing aid technology has evolved in the last decade but the percentage of users of such devices remains very low. With the advent of wireless communication protocols such as Bluetooth Low Energy (BLE), along with the exponential growth of smart phone demand, it is expected an increment of the users of hearing aid devices due to the new use cases that BLE will create. In this contribution, we provide a survey of the existing technologies for hearing aid and their use cases. Because one of the key objectives of smart cities is the quality of life of their citizens, we explain how several hearing aid use cases can be applied in these scenarios.**

Keywords— Hearing aid; bluetooth low energy; smart cities

I. Introduction

Hearing loss population has increased in the last decade. Having trouble hearing can make it hard to understand and communicate more meaningfully in daily live. It is being reported an approximate of 35 million persons with some degree of deafness in the United States of America in 2008 and a projected 40 million by 2025 [1]. Worldwide, 360 million people have hearing loss [2]. In the U.S, around 30% of adults with hearing loss have used Hearing Aid (HA) devices –a small quantity despite the amount of people with this condition. There are different reasons reported in the literature for such low usage of HA, but one of the main reasons is the sensed poor benefit from the HA by the user. Users have reported different problems with their HA devices such as background noise, poor sound quality or feedback/whistling. Something important to note is that HA users are usually older adults [3]. Age-related hearing loss (presbycusis) most often occurs in both ears, affecting them equally. Because the loss is gradual, the people with age-related hearing loss may not realize that they have lost some of their ability to hear.

Recent advances in technologies and techniques might be able to reduce the reported annoyances and disadvantages. One of them is digital signal processing (DSP) techniques that have helped HA devices to improve their performance over the last years [4], and the other is bluetooth low energy (BLE) protocol that will soon release a new HA profile that will allow the hearing impaired to use their HA devices in several use modes such as answering a smart phone or connect with different audio sources in an easy way [5]. BLE HA profile will also provide extended battery life which is currently the main problem in the bluetooth classic devices. Hence, BLE will allow in the near future the proliferation of many different use models that can be exploited in a smart city context.

In this paper, the state of the art of HA devices will be presented. These devices are classified as assistive devices or assistive technology because they help people with hearing disorders to communicate. Also, use cases of HA will be shown focusing in the applications for smart cities for users with hearing impairments or disorders that encompass a range of conditions, i.e., from slight hearing loss to deafness.

The paper is organized as follows: The thresholds for different levels of hearing loss are presented in Section II for typical scenarios of sound exposition. In Section III, the main HA technologies are explained. Section IV shows the HA use cases and maps them to smart cities environments. Finally, the conclusions are drawn in Section V.

II. Hearing loss

The frequency range of human hearing includes sound frequencies from 20 to 20000 Hz. Hearing loss is defined as the impairment of the ability to apprehend sound. Human ear is able to pick up a wide range of sounds as shown in Table I [6]. Using the values shown in Table I as a reference, pain and potential hearing damage may happen with a sound intensity above 130 dB. A sound intensity above 140 dB may produce intense pain and hearing loss will happen based on the time of exposure to the sound. A sound intensity above 180 dB will produce hearing loss no matter the time of exposure to the sound source due to the death of hearing tissue [7].

There are four levels of hearing loss as shown in Table II. HA devices are commonly used to mitigate the effects of mild and moderate hearing loss by amplifying the sound.

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TABLE I. MEASURING OF SOUND

Sound type	*Decibel rating*
Total silence	0 dB
Soft whisper	30 dB
Conversational speech	50 dB
Average television volume	60 dB
Heavy city traffic, factory noise	80 dB
Car horn	110 dB
Rock Concert	120 dB
Gunshot	140 dB
Jet Aircraft	150 dB
Rocket launching pad	180 dB

In the next section, the different HA technologies are shown.

III. HEARING AID TECHNOLOGIES

HA devices can be digital or analog. Digital HA allows self-adjusting to match a specific pattern of hearing loss. Analog HA are designed based on a specific frequency response based on an audiogram of the patient. In the following sub-sections, different digital HA technologies will be reviewed.

A. *Classical HA technologies*

HA devices are built by: microphone, amplifier, receiver and a battery. They can also have a telecoil, which is a tiny coil of wire around a core that picks up magnetic signals and turns them into sound signals. Telecoil improves signal to noise ratio and helps to reduce acoustic feedback but it is not good for hearing certain types of sound such as music as it can induce distortion and is prone to interference by other digital devices [8].

Cochlear implants (CI) are suited for severe and profound hearing loss. They are electronic devices consisting on an external component placed behind the ear and an internal component into the skin behind the ear. A CI is different from a HA device. HA amplify the sound while a CI converts sound waves to electrical impulses which are transmitted to the inner ear to stimulate the auditory nerve.

B. *DSP Technologies for HA*

DSP algorithms have been used in HA devices for more than 20 years to improve the sound quality of the devices. Signal processing is the method used to modify normal sound waves into amplified sound that is the best possible match to the remaining hearing for a HA user. Since late 90's, HA technology has moved from analog processing to digital processing, as the second one provides better processing capabilities than its analog counterpart [4]. Table III shows a comparison between analog and digital technologies.

TABLE II. LEVELS OF HEARING LOSS

Levels of hearing loss	*Description*
Mild	Difficulty following a conversation. Lowest sound perception is from 25 to 40 dB
Moderate	Difficulty following speech even with HA. Lowest sound perception is from 40 to 70 dB
Severe	People rely on lip reading even with HA. Lowest sound perception is from 71 to 90 dB
Profound	People rely on lip reading or sign language. Lowest sound perception is above 91 dB

HA devices use custom DSP chips which are low power and hence offer reduced computational performance [4]. Custom DSP means that a signal processing scheme is hardcoded into the chip with some parameters that can be adjusted. Different architectures are used across HA industry and so a meaningful comparison cannot be made in terms of performance, measured in million instructions per second (MIPS) [9]. For instance, most of the current HA devices use a 16 bit signal processor, thus not every audio processing algorithm can be used in a HA device. This situation will change in the next years as DSP chips will be manufactured in a 22 or 14 nm process which will allow to integrate more computation capabilities as well as reduce the power consumption. In the meantime, additional effort is required to adapt audio processing algorithms to be used in a HA DSP based solution. Recent commercial HA devices are now integrated into a system on a chip (SoC) which includes a DSP along with a central process unit which handles wireless protocols and provide error correction capabilities [10].

There are several audio processing algorithms for HA. The main purpose of them is to process an incoming sound and remove background noise from the signal. DSP algorithms comprise the following steps: acquire the sound signal by means of an array of microphones, enhance the sound signal and present the enhanced signal to the user [11]. There are several types of DSP algorithms that are used for HA as shown in Fig.1. Many of them require extensive computer processing just to differentiate the signal from noise [12]. Table IV shows the main functions that are present in every HA device, which are implemented using DSP algorithms and technologies. Some of them cannot be implemented by means of analog technologies.

TABLE III. COMPARISON BETWEEN DIGITAL VS ANALOG HA

Digital	*Analog*
DSP implements noise reduction and feedback cancellation algorithms	Amplifies all sounds (speech and noise)
Highly programmable for different listening environments	Basic programming for various listening environments
Error correction capabilities	Not available
Configured by user	Configured by an audiologist
Expensive	Cheap

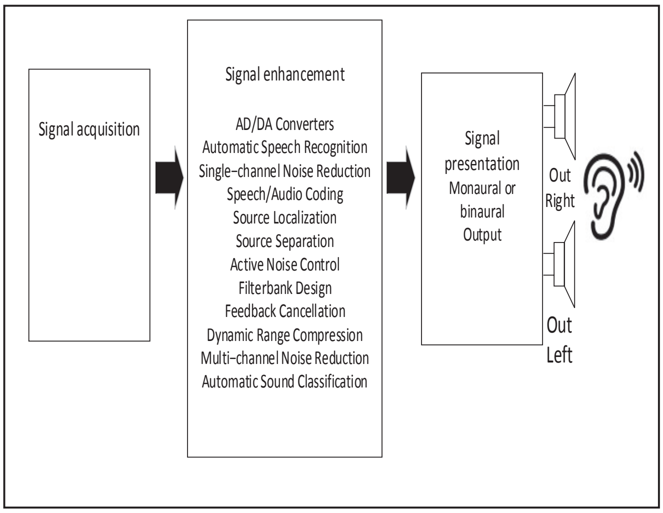

Fig. 1. DSP based hearing aid diagram

C. Internet of Things Protocols and Technologies for HA

Nowadays, there are several wireless communication protocols suited for internet of things (IoT). This means that such protocols allow the interconnection between different devices. In other words, a smart phone is now able to interact with a HA device by means of a wireless communication protocol such as bluetooth. In these days, a lot of different companies –from smart phones to media players- are developing bluetooth technology for audio streaming.

This fact is a great opportunity for HA devices as it allows hearing impaired users to connect to different devices to receive audio streaming. Some examples are: smart phones, radio, television and media players. However, the current problem to use HA devices along with bluetooth technology is the high power consumption. This problem will be reduced in the upcoming years since the bluetooth 4.0 specification introduced the BLE. Although BLE current specification [13] does not support audio streaming due to the limited available bandwidth, the bluetooth special interest group (SIG) has just announced the development of a HA profile that will be released in the next couple of years [5]. This implies that the next major release of the BLE specification will be required to support audio processing while keeping the low power requirements of the protocol. The new BLE HA profile will support several use cases: answering or perform a call from a mobile phone, enjoy audio from music players or TVs, receive broadcast audio from announcement systems and many more that are not yet figured out.

Other existing IoT communication protocols are not suited for audio processing. ZigBee for instance, has a very limited throughput to provide a decent Quality of Service (QoS) for audio streaming. However, ZigBee could be used where a mesh network is needed such as in a smart city for applications ranging from surveillance, emergency and rescue applications [14]. HA users as well as users with no hearing loss could benefit from these applications. In the next section, HA use cases will be presented.

TABLE IV. DSP ALGORITHMS FOR HA

DSP Algorithm	***Description***
Speech recognition	In a HA, speech and noise are amplified at the same time. Based on speech characteristics, the purpose of this algorithm is to distinguish between speech and noise segments and extract the voice signal.
Active noise control	Background noise is the main complaint of a HA user since it reduces speech intelligibility and produces hearing fatigue. The goal of this algorithm is to increase listening comfort in noisy environments
Feedback cancellation	HA present acoustic feedback due to sound leaking from the speaker that is picked up by the microphone. The goal of this algorithm is to reduce the unwanted feedback
Dynamic range compression	HA devices can not apply the same volume to all input signals due to the user may still not be able to hear soft sounds and would find loud sounds uncomfortable. This algorithm is used to control the amplification dynamically

IV. HEARING AID USE CASES FOR SMART CITIES

A smart city is described as one that applies information and communication technologies to create an infrastructure for a sustained development and to improve the quality of life of its citizens. The goal of a smart city is to make its public services more interactive, accessible and efficient [15]. This is achieved through an intelligent management of natural resources, transportation systems, emergency response and public safety, among others.

Quality of life, also known as smart living, refers to the applications available in a smart city to provide services for visitors, promote a cultural agenda, health monitoring and education services [15]. It is in this area that HA devices have a huge market opportunity to use available HA use cases or to create new ones to improve the quality of life of the citizens.

In this section, examples of HA use cases will be presented. It will also be shown that such use cases can be applied in a smart city environment.

A. Smart HA devices

As discussed in previous section, the essential function of HA devices is to amplify the sound for people with hearing loss. However with the rise of new technologies for HA and the advent of the IoT (with new communication protocols such as BLE), use cases for these devices can be extended. Nowadays HA can be paired with a smart phone to place and receive calls as well as to listen music or a television show. Also, wearable technology is growing very fast. It can be found these days in the form of smart glasses or recently as a smart watch. Both devices are able to process sound which allows a

HA to be used along with such new technology. Currently, wearable devices are being used in many applications for healthcare and fitness.

Modern HA devices can use an application to calibrate the HA device for its own range of hearing frequencies. Thus calibrating the HA can be done by the user who can have or not hearing loss. This means that modern HA devices are not just meant for people with hearing disorders but also for general users. It is expected that the rise of BLE HA in the near future will reduce the cost of these devices.

B. *Use cases for HA*

1) *Audio Noise cancellation*

Audio noise cancellation (ANC) capabilities of a HA device along with its self-configuring capability regarding frequencies that can be suppressed can be used in hazardous noisy environments such as heavy traffic, construction noise, train stations, etc.

2) *Personal sound zones*

Sound streaming within a designated region has led to a concept named personal sound zone [16] which allows different people to hear their own sound. For example, as shown in Fig. 2, one person is watching a TV show in the living room (personal sound 1) while another person is listening to the radio (personal sound zone 2) and a third one is listening to music (personal sound zone 3) without interfering to each other.

Personalized audio broadcast within an area can be exploited in a museum or in a touristic area of the city. Tourists can listen relevant information of an art work or the history explanation of a monument without the required effort to listen a tourist guide in a crowded area, thus reducing the listening fatigue.

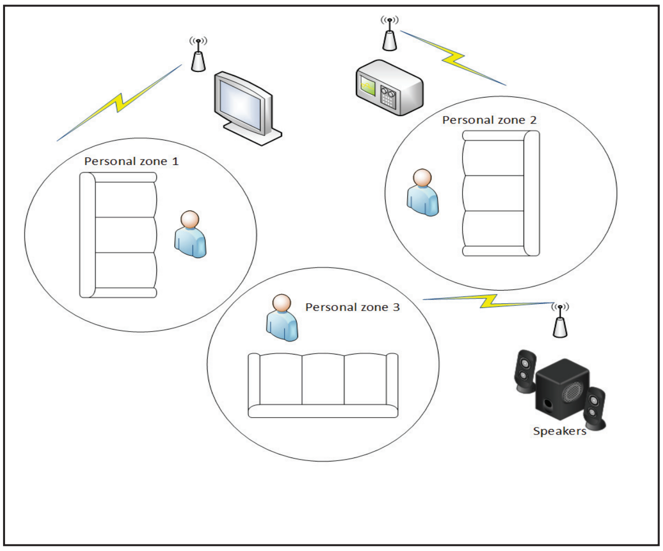

Fig. 2. Audio broadcast

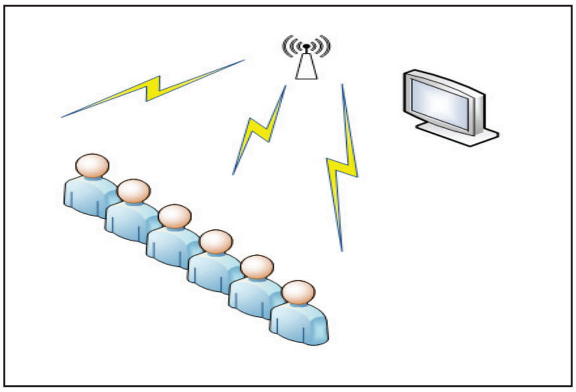

Fig. 3. Audio broadcast

3) *Audio broadcast*

A group of people can be connected to a single audio source such as a television, as shown in Fig. 3. As an example: it is common to find televisions in a gym right in front of the walking machines. Usually each television is tuned to a different channel. In this case, users can pair their HA to a specific television and start listening.

4) *Audio alerts*

Users of public transportation or people walking in the street can listen to relevant information such as a train approaching a station or a pedestrian can listen when is approaching to a point of interest in the city. Also, people can just listen to audio alerts in case of an emergency in a specific area such as a fire in a building or a riot in the street.

As can be seen in Fig. 4, people walking in the street or driving a car can hear any audio alert such as approaching to an intersection or getting traffic alerts as the EAR-IT project envisions: an on-demand acoustic data streaming for surveillance and emergency management [17].

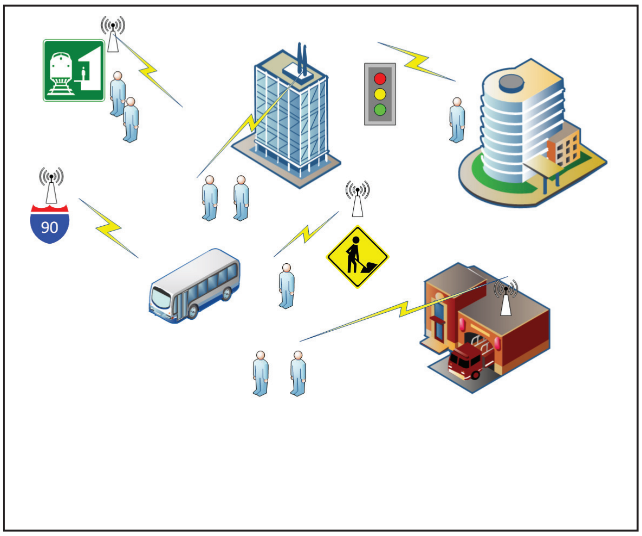

Fig. 4. Audio alerts for smart cities

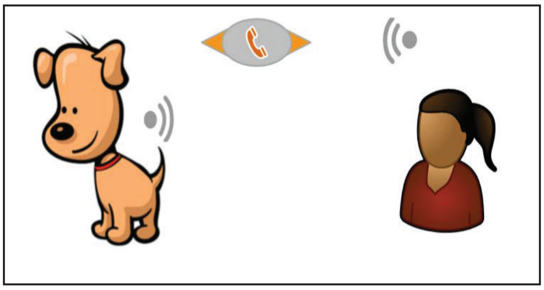

Fig. 5. Owner calling a dog via wireless

5) Sound streaming

In general, any use case for sound streaming can be applied to a hearing device to become smart. All that is required is a BLE HA device along with an application in a smart phone to configure the device. For example, a person can call to a dog which is walking unleashed in the park to bring it back to the owner. Or just call the pet in order to feed it. If there is a BLE hearing device placed in the collar, the owner could use the smart phone to call the pet as shown in Fig. 5

V. CONCLUSIONS

The purpose of this survey is to provide a sight of the market opportunities for the companies developing HA devices.

The internet of things is changing the way we live. Because of it, now everything can be connected and become smart. This will allow to create an unlimited number of use cases and applications to increase the quality of life of the people. HA devices will benefit from this new paradigm. As we have presented in this work, a HA user will be able to answer a call from a smart phone, listen audio from a television or a media player easier than with previous HA generations. This will allow to revert the statistics of low HA usage and will help people with hearing loss to better adapt to a HA device.

We have highlighted in section IV that the HA use cases can be extended for general users and into a smart cities scenarios. However, there is still a lot of work to do. Audio processing requires high computation performance and HA devices require low power consumption, therefore there is a need to find better audio processing algorithms to comply with low power requirements. BLE operates in the industrial, scientific and medical (ISM) frequency band which is getting very crowded due to the amount of new devices using it to interconnect. Therefore, there is a need to find solutions to reduce the interference in the ISM band. Additionally, audio streaming requires a determined QoS to transmit high definition audio -a service which has bandwidth requirements. Thus, research is required to provide new models of QoS for audio applications despite the current hardware limitations in terms of computational performance and power consumption of BLE devices.

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