Wireless Solutions – The State of the Art and Future of FM Technology for the Hearing Impaired Consumer

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Recently we have seen the introduction of rather complex digital signal processing schemes in hearing instruments. Hearing instruments have turned into “intelligent listening computers” including perception based amplification algorithms, intelligent environment control systems and also different forms of noise reduction systems. Still in a number of environments it remains a difficult task to improve speech intelligibility to a satisfying extent, e.g. highly reverberant environments or communication over larger distances (Crandell and Smaldino 2000). Reverberation and large distance, e.g. in school or while attending a church service or lecture, have a very strong detrimental effect on speech intelligibility especially for hearing impaired adults and children. Furthermore, for a variety of communication conditions there are no fully satisfying solutions when using hearing instruments alone, such as talking over the cell phone. In the past a variety of different wireless communication technologies had been used in order to solve above described problems. Technologies that have been applied in the past, are induction loop systems, communication systems using an infrared link, personal FM systems and sound field FM systems (Crandell and Smaldino 2000), (Lewis 1998).

Over the past years we have seen a significant improvement in miniature wireless communication technologies such as personal FM systems. These wireless communication devices have become very small yet still very efficient. A number of applications have already been introduced in the field of hearing instruments, such as systems applying a remote microphone for improving speech intelligibility or systems that directly connect hearing instruments to a TV or a conventional telephone. However, the application of wireless communication techniques thus far has been limited to BTE instruments by using a separate FM receiver that can be clicked onto the hearing instruments. Wireless communication techniques integrated directly into a BTE have one disadvantage – BTE including FM system may not be upgraded at the same pace as other hearing instrument technology. Wireless communication techniques integrated into BTE or ITE instruments or a direct wireless connection to a cell phone have not yet been introduced into the market.

In this paper, after outlining the state of the art in hearing instrument technology, I will briefly discuss the technological principles as well as advantages and disadvantages of the different technologies. Next I will outline the current state of the technology offering the largest flexibility and range of application which thus, in my opinion, provides the largest potential for future applications. Finally I will compare the personal FM technology with other wireless communication technologies that are currently under development for the consumer electronics market such as Bluetooth or Ultrawide-band.

Hearing Instruments – State of the Art

Today’s digital hearing instruments have become rather complex micro-systems incorporating a lot of sophisticated signal processing technologies. Most of today’s high end digital hearing instrument offer a lot of sophisticated technology for improving the quality of life of hearing impaired people in numerous conditions. The Signal processing schemes applied today can be divided into four broad classes of processing schemes:
- Multi-channel frequency dependent signal processing and amplification schemes for precisely compensating the frequency dependent hearing loss;
- Intelligent Environment Control for automatically adapting the hearing instrument settings to varying acoustic environments;
- Noise Reduction systems applying two technologies for reducing interfering sound sources and background noises
  - Directional microphone arrays / multi-microphone technology
  - Single microphone noise canceller
- Signal processing schemes for reducing feedback

The signal processing applied today applies high resolution spectral filtering in order to split the acoustic signal into a number (at least 10–20) of different frequency bands or channels. This allows a lot of sophisticated signal processing to be performed. First of all, it allows correcting the frequency dependent hearing loss and thus reduced dynamic range (recruitment) precisely to the individual listening needs. Some hearing instruments even apply psychoacoustic models of hearing impaired perception for controlling the gain (Launer and Moore 2003) instead of purely sound pressure level based amplification schemes.

Amplification in hearing instruments requires applying rather high gains up 80 dB between a microphone and a loudspeaker which are very closely spaced together. Such a system is highly prone for feedback squealing which is a major problem in hearing instruments. Digital technology offers several strategies for lessening this problem by applying frequency specific passive gain limitations, adaptive notch filters or even complex feedback cancellers.

Typically hearing instruments apply different signal processing schemes and parameter settings in different acoustic environments. For example, for processing in noisy environments noise reduction algorithms such as directional microphones are being switched on. In order to facilitate the operation of the hearing instrument for the hearing instrument wearer, signal processing algorithms have been developed that allow to automatically identify the acoustic environment based on several different acoustic features such as modulation, level fluctuations, pitch etc. This allows to reliably identifying a number of different broad classes of acoustic environments such as speech in quiet, speech in different types of background noises, noise alone or music. It has been shown in several studies that these systems are very well perceived by the hearing instrument wearer (Büchler 2002). Nevertheless it is important to offer a “brain control” (i.e. either via a switch or a remote control) for this automatic functionality that allows the hearing instrument wearer to make the final decision about which listening program to chose in which environment. Future versions of these intelligent environment control systems will allow identifying a larger set of different acoustic environments and also automatically selecting different input sources such as personal FM systems or T-Coil inputs.

Finally algorithms have been developed for lessening one of the most severe problems of hearing impaired subjects: speech communication in adverse, difficult listening conditions, e.g. due to a lot interfering sound source and background noise. Digital technology allowed to further improving a very successful approach for reducing background noises by making directional microphones applying multi-microphone beam forming optimally adapt to the respective environment. Today’s multi-microphone systems are capable of adapting their directivity pattern in order to always provide optimal signal to noise ratio and thus optimal speech intelligibility. It has been shown in numerous studies that directional microphones significantly improve speech intelligibility under a variety of very realistic real life conditions including diffuse environments, interfering sources from the side or even moving noise sources (Ricketts and Dittberner 2002). A second strategy for reducing the detrimental effect of background noises is by applying single microphone noise canceling techniques which rely on identifying spectral bands containing only background noise and attenuating those bands. These signal processing schemes have also proven to be beneficial however not in terms of improving speech intelligibility but by improving ease of listening and listening comfort.

However, real life offers an incredible richness in different listening environments in some of which even the most sophisticated hearing instruments show only a limited benefit. In a number of conditions applying other than the above described technologies still can improve performance of hearing instruments significantly. Examples of acoustic environments or listening situations where the performance of conventional hearing instruments can substantially be
improved by applying additional communication devices are the following:

- Reverberant environments such as big churches or lecture halls,
- communication over larger distances e.g. in a lecture or in a classroom,
- communication on the telephone, especially cell phones.

In these environments the application of assistive listening devices (ALD) based on wireless communication technologies offer substantial additional benefits and significantly improve speech intelligibility. However, for a hearing instrument wearer it would be highly desirable to have a single assistive listening device which could be applied in a large variety of conditions and not have to apply different technologies and thus devices for different acoustic environments or communication situations.

Assistive Listening Devices – Wireless Communication Technologies

A variety of different assistive listening devices based on different technologies have been introduced and applied in the past including (see (Crandell and Smaldino 2000), (Lewis 1998), (Lewis 1994) for excellent and more extensive reviews):

- Induction loops / T-Coil,
- Infrared systems,
- Sound Field FM systems,
- Personal FM systems.

Induction Loop

Inductive systems rely on coupling an audio amplifier, e.g. for the microphone of a speaker in a lecture hall or a teacher in a classroom, directly to an induction loop system which basically directly transmits the rather low frequency audio signal as a radiated time varying magnetic field. Induction loop systems use a large coil antenna integrated in the floor of a large room for radiating the magnetic field. Especially in Europe, in most public places, such as lecture halls or churches, induction loops are available. In order to pick the time varying magnetic signal transmitted via an induction loop system, a T-Coil is required in the hearing instrument. In Europe almost every hearing instrument has to have a T-Coil integrated (except the very small CIC type instruments in which T-Coils do not fit in). In the USA induction loop systems as well as T-Coils in hearing instruments are not as widespread as in Europe. It has been estimated that in the USA about 30–40% of the hearing instruments incorporate a T-Coil (Ross 2002). Inductive coupling is a rather simple and cheap approach which could improve speech intelligibility and ease of communication for many hearing instrument users rather easily. However this technology also has some technical drawbacks which limit the range of application of this technology. The physics of inductive coupling requires the receiving coil (T-Coil) to be perpendicularly oriented to the field of the sending coil or induction loop. This is sometimes difficult to achieve because the orientation of the induction loop is fix and the orientation of the T-Coil depends on how it is built into the hearing instrument and the person’s orientation. Furthermore, the inductive transmission strongly depends on the distance between sender and receiver which sometime results in a weak signal. The receiver also always has to remain within the loop in order to receive a signal. External interferences (from power lines or fluorescent lights, computer monitors copiers, fax machines, cell phones etc.) creating background noises or distortions in the hearing instrument, are difficult to remove. Next, in school environments several different systems are required for different classrooms. When applying two different systems in neighboring classrooms it often is difficult to avoid spillover from one induction loop system to the next although recently technological progress has been made for reducing this problem (Ledermann and Hendricks 2003; Yanz and Preves 2003). Furthermore, induction loop systems are not portable and can only be applied where they have been pre-installed.

Infrared Systems

In infrared transmission systems the acoustic signal is converted to infrared light which is then transmitted from an infrared emitter to an infrared receiver containing photo-detector diodes. In the receiver the signal is converter back into an acoustic signal presented via headphones or via the audio boot of a hearing instrument. For optimal transmission, the receiver has to be in a direct line of sight with the emitter which limits the distance or range of
application of such systems. In large theaters or lecture halls, arrays of transmitters have to be installed in order to guarantee good sound quality on each seat. Furthermore, people should not be moving around a lot.

Thus in a home environment, for watching TV this might be a suitable solution while for a child in a classroom setting other solutions probably allow more flexibility and thus should be preferred.

Sound Field FM Systems

A sound field FM system is a small public address system in which speech is picked up by a remote microphone, e.g. worn by a teacher (Crandell and Smaldino 2000). The speech signal is then transmitted via a FM wireless link to a receiver where the signal is presented to the audience via a loudspeaker system. This technology clearly has advantages in environments (classrooms!) with poor acoustics. Applying this technology is beneficial for every child / person, not only those wearing hearing instruments or an assistive listening device. Although there is a lot of evidence supporting the application of these systems in various environments, some limitations, especially for hearing impaired people, must be discussed. For hearing impaired children or adults, the SNR improvement offered by a sound filed FM system is not enough, especially for children with moderate to profound hearing losses. Thus these children/ persons need a personal communication system anyway. Furthermore, when raising the level in a classroom / lecture hall by 8–10 dB, it is conceivable that this might cause discomfort in hearing impaired persons due to loudness recruitment.

Personal FM Systems

Personal FM Systems: Technological Background

Personal FM systems, or simply FM systems, provide a personal communication link between a speaking and a listening person or a group of listening persons. The transmitter can either be a hand held device or body worn hanging around the neck or worn on the belt. A microphone comprised in the transmitter picks up the target speech which is wirelessly transmitted to a receiver applying a similar technology as in standard AM/FM radios. In the receiver, the signal is de-modulated and converted back to an audio signal that can be presented over another body worn device or the receiver can be integrated into a boot style FM device that can be directly clicked onto the hearing instrument. The underlying physical transmission principle is to Frequency-Modulate a low frequency audio signal (100–20,000 Hz) onto high frequency electro-magnetic wave (216–217 MHz or 72–76 MHz) as the carrier. Recently, the 216–217 MHz band has received primary status in the US, i.e. this band is restricted to FM systems for hearing instrument application which reduces interfering senders generating noise and distortions significantly. In order to be applicable for hearing instruments, this FM link needs to work on a very low power budget (roughly 1 mW) limiting the radiated electro-magnetic power to almost negligible values (roughly 1000 times less than the peak power radiated from a cell phone, well below the safety standards set by the government). Today’s latest transmitter and receiver systems are synthesized. This allows frequencies to be changed very easily with the push of a button. This facilitates frequency management significantly, for example in a school, as it allows to operate several personal FM systems in parallel while keeping spill-over or listening-into another channel at a minimum level. Synchronization can be done manually, for example with a button on the transmitter, or automatic, when installing a small unit at the entrance door of a room, which automatically programs the receiver to a selected frequency as a person enters.

Compared to other technologies, personal FM systems clearly outperform above described technologies, due to the mobility they provide, the fact that it works in conjunction and is transparent with a person’s own Hearing Aid, their primary amplification system. The sound quality is superior due to larger signal bandwidth, weaker interferences and a good omni-directional, i.e. direction independent transmission characteristic. Depending on the environment and the system used, the range of signal transmission is roughly between 15–100 ft (i.e. 5–30 m). The transmitted audio signal bandwidth should be roughly 5 kHz in order to also transmit the very important high frequency speech cues required for optimally understanding speech in adverse listening environments or for learning speech sounds. (Boothroyd 1992; Thibodeau 1992; Lewis 1994; Lewis 1998; Crandell and Smaldino 2000) provide good introduction and further information into the under-
lying characteristics and current state of the art of these systems.

Personal FM Systems: Application

Today’s transmitters offer a range of different acoustic characteristic providing the user with a great deal of optimal solutions for different listening environments. The user typically can select between an omni-directional microphone characteristic (applied e.g. in a classroom) and highly directional microphone characteristics allowing to filter out interfering sounds in a noisy environment. The directional microphones typically are achieved by applying microphone arrays, i.e. by adding two or more microphones to form a directional microphone or beam former with a narrow beam of sound pick-up. Additionally, by applying digital signal processing techniques in the transmitter one can further improve the quality and directivity of the beam former. For achieving directional microphones with a high directivity two different approaches can be followed: either to use two microphones and apply signal processing techniques or to use more microphones. The later approach can offer a higher directionality but at the price of some technical drawbacks strongly limiting the performance of the systems: when using more microphones for beam forming, the internal noise floor of the transmitter is strongly increased, the low frequency part of the spectrum rolls off rather strongly and long term reliability of the microphone matching is far more difficult to achieve. Next, it is questionable whether a very narrow beam is practicably desirable because only small body movements of either the target or the user will then lead to losing the target signal. Applying two microphones and sophisticated digital signal processing techniques in the transmitter provides reliable and robust directional systems with a sufficient directionality for real life application.

Personal FM systems offer the largest flexibility and the highest quality in most environments compared to other technologies described above. Personal FM systems are applicable everywhere, not limited to rooms with pre-installed devices. By picking up the microphone signal either very close to the mouth of the speaker or by applying directional microphone technology the Signal to Noise Ratio in a noisy environment, in a highly reverberant environment or over a large distance is significantly improved (Pittman, Lewis et al. 1999; Crandell and Smaldino 2000; Lewis, Crandell et al. 2003; Lewis, Crandell et al. 2003). Using an additional transmitter device allows the FM system also to be easily coupled to the TV or the phone at home. In children with hearing impairment, FM systems can be applied at home or in schools or while playing outdoors in combination with hearing instruments. FM systems have also been successfully applied for other types of disabilities such as Auditory Processing Disorders (Rosenberg 2002).

Personal FM Systems: Future Prospects

It is comparatively simple to integrate a Digital Signal Processor (DSP) into a FM transmitter system allowing to apply sophisticated audio signal processing techniques, e.g. for beam forming or automatic beam steering and localization, adaptive two microphone noise canceling, blind source separation algorithms or de-reverberation algorithms directly in the FM transmitter. This would significantly increase the overall performance of the overall system hearing instrument and FM. Furthermore, one could apply algorithms for sound classification, i.e. for automatic identification of the acoustic environment, directly in the FM system in order to analyze the content of the acoustic environment and automatically activate or de-activate the FM link based on an intelligent decision.

FM technology can also be applied for connecting the hearing instrument wirelessly to other audio sources or communication devices such as telephones (fix net or cell phones), TVs or public information systems e.g. in museums. FM could provide a hassle free, high quality and robust wireless connection to those external devices. Here a promising approach is to apply standard, widely available wireless communication standards such as Bluetooth (Haartsen 1998; Schulte 1998) for connecting different devices directly to hearing instruments. The link would comprise a Bluetooth link between external devices, e.g. cell phone, which connects the external device to the FM system which then transmits the audio signal to the hearing instrument. The immediate reaction to this approach is the question “why not integrate the Bluetooth link directly into the hearing instrument?”. Even today the Bluetooth technology is not fulfilling the technically very challenging requirements for hearing instrument application in terms of size and power consumption. Thus, today and within the next years, we need to take a detour for wirelessly connecting hearing instruments to external communication.
devices. Another approach is to integrate a FM receiver into every hearing instrument (and not only the 675 battery type instruments) which remains to be a technical challenge but not an unsolvable one. The issue to be solved here is the size requirements of today’s FM systems (antenna and receiver volume). However, integrating FM into every hearing instrument would really make sense if the frequencies used for large area sound distribution systems are standardized and the availability of FM transmitters integrated in public places (in lecture halls, theaters, etc. similarly to induction loops) is sufficiently high in order to generate a higher market demand and much broader acceptance for FM systems.

Currently a lot of technological development in low power wireless communication technologies is going on and in mid term future also hearing instruments will benefit significantly from those technological developments. New communication concept such as Bluetooth, Ultra-Wide Band technologies or “Body Links” (i.e. communication technologies for wirelessly connecting different devices using the human body as the transmission channel) are discussed in the scientific literature and presented in the press. However, those technologies are far from meeting either the size or the power consumption constraints required for application in hearing instruments.

Summary

This paper argues that personal FM is a robust, high quality technology for wirelessly connecting hearing instruments to numerous external devices such as a remote microphones, cell phones, or public information systems for improving communication in a large variety of acoustic environments and listening conditions. Furthermore, compared to other technologies discussed and presented here, FM offers a lot of flexibility for application in everyday life as well as a large potential for future developments. In the context of this paper FM had been discussed from the perspective of application in people with sensorineural hearing impairment. However, as some interesting papers in this volume show, application in other fields such as Auditory Processing Disorders also is conceivable. The technology has come to a point where integration into BTE hearing instruments is technically easily feasible. Thus hopefully we will see a larger range of application of FM systems in the adult as well as in the paediatric hearing instrument segment.

References
