CHAPTER NINE

Flying to the Moon on Radio Waves: Optimizing Outcomes with RF Technologies

Jace Wolfe, Ph.D

Abstract

Given the difficulties that children with hearing loss experience in noisy and reverberant environments, along with the proven benefits of remote microphone radio frequency (RF) technology in improving performance in these situations, pediatric audiologists should strongly consider RF technology for use with all children who use hearing aid or cochlear implant technology. This article highlights several recent advances in digital RF technology and focuses on the potential clinical benefit of these technologies. Specifically, this article addresses the fundamental concepts of digital RF transmission, the potential advantages of adaptive digital RF technology, results of recent studies examining the benefits of adaptive digital RF technologies, as well as the basic characteristics and potential benefits of digital, near-field magnetic induction.

Children with hearing loss often experience substantial difficulty understanding speech in noisy and reverberant conditions (Boothroyd, 1998; Finitzo-Hieber & Tillman, 1978; Wolfe et al., in press). These children also typically encounter greater difficulty than adults with understanding low-level speech (e.g., soft speech or speech spoken from a talker located more than a few feet away) (Nozza, 1998; Scollie et al., 2005). Wireless remote microphone (radio frequency – RF) technology has been shown to be the most effective means to improve speech recognition in these difficult listening situations (Hawkins et al., 1984; Wolfe et al., 2009). Hawkins (1984) evaluated speech recognition in noise for nine children with mild to moderate hearing loss. He reported that performance with a personal remote microphone frequency modulation (FM) technology coupled to the children's hearing aids was significantly better than performance obtained with directional hearing aids alone. More recently, Wolfe et al (in press) studied speech recognition in quiet and in noise for children and adults with normal hearing and 15 children with moderate-to-moderately severe hearing loss. The speech recognition of the children with hearing loss was evaluated while they used only their hearing aids and also while they used personal remote microphone FM systems coupled to their personal hearing aids. When sentence recognition was assessed at a 0 dB signal-to-noise ratio (SNR), the children's performance with use of the personal FM system improved by 50% compared to their performance with their hearing aids alone. Additionally, at a 0 dB SNR, the children's sentence recognition with use of the personal FM system was actually better than that of the adult subjects with normal hearing.

Basic Characteristics of Wireless Radio Frequency Technology

Wireless remote microphone technology for use with hearing aids and cochlear implants has evolved significantly over the past decade. In particular, one significant advance in wireless remote microphone technology was the commercial introduction of Dynamic FM (e.g., adaptive) technology in 2008. Personal, wireless remote microphone systems possess a parameter referred to as receiver gain, which refers to the strength of the signal that is delivered from the receiver to the user's hearing aid or cochlear implant sound processor. With conventional remote microphone systems, the receiver gain is typically set at a fixed level such that 10 dB FM advantage is achieved (ASHA 2002; AAA, 2008). Lewis & Eiten (2004) showed that a fixed receiver advantage of 10 dB was likely too high in quiet environments when speech was not present but it was probably too low for environments with high levels of background noise (e.g.,

restaurants, school cafeteria, a noisy classroom or gymnasium, etc.). In fact, Lewis & Eiten (2004) reported that hearing aid users preferred an FM receiver advantage of 24 dB when listening in high-level noise.

Dynamic FM was developed to meet the wide range of user needs across a variety of listening environments. With Dynamic FM technology, the FM receiver is muted when no speech is present at the microphone of the FM transmitter. When speech is present in a quiet environment, a receiver advantage of 10 dB is provided, and as the noise level at the FM microphone increases above 57 dB SPL, the FM receiver advantage automatically increases from 10 dB to a maximum of 24 dB at an ambient noise level of approximately 80 dB SPL (Figure 1). Previous research has shown that Dynamic FM provides a significant improvement in speech recognition in noise when compared to traditional fixed-advantage FM. Specifically, improvements in speech recognition of up approximately 40% were observed at competing noise levels of 70-75 dB SPL (Thibodeau, 2010; Wolfe et al., 2009).

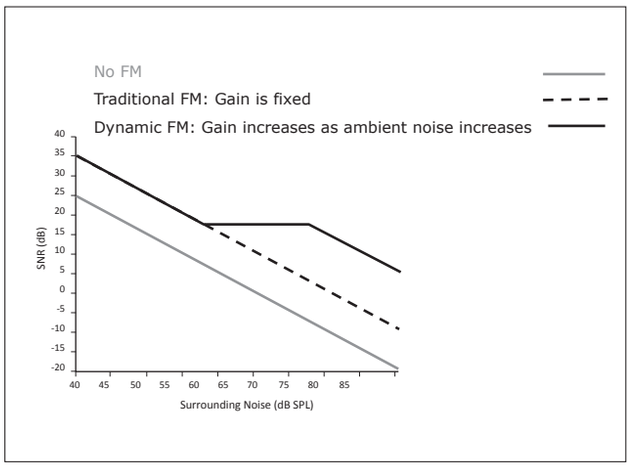


Figure 1. Diagram of SNR as a function of ambient noise level for various remote microphone technology conditions.

A more recent advance in wireless remote microphone technology is the development of digital radio frequency systems. Digital RF systems differ from FM systems in several respects. In order to adequately describe digital RF transmission, it is helpful to begin with a quick review of analog FM radio technology. Figure 2 provides an illustration of FM radio transmission. In short, FM radio transmission possesses a carrier wave used to deliver information from the transmitter to the receiver (see Figure 2b). The carrier wave is modulated by the speech signal (or some other signal of interest) that is captured by the FM transmitter unit. As shown in Figure 2c, the frequency of the modulated signal changes proportionally with the amplitude of the input signal.

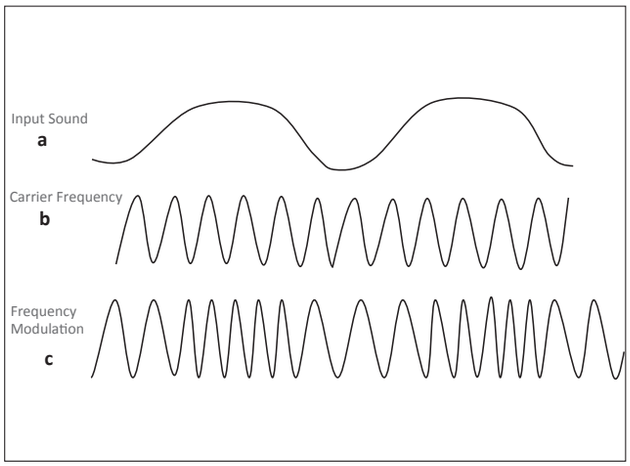


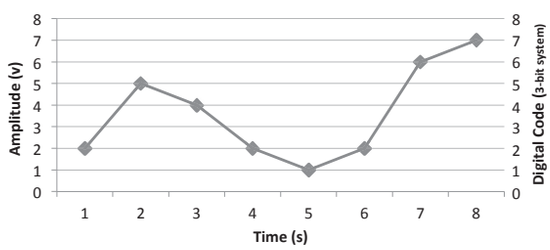
Figure 2. An illustration of two types of radio waves: 2a) the original signal of interest, 2b) the carrier frequency of the radio wave, 2c) an example of an frequency modulated (FM) radio signal (i.e., the frequency of the carrier wave in figure 7b is modulated based on the amplitude of the original signal of interest.

For personal FM systems used with hearing aids and cochlear implants in the United States, the frequency of the carrier wave is within the 216-217 MHz bandwidth (i.e., 216 million cycles per second). With personal FM technology, the transmitter is set to a fixed carrier frequency (e.g., channel). For instance, channel 1 of the Phonak Inspiro FM transmitter corresponds to a carrier frequency of 216.0125, while channel 80 corresponds to a carrier frequency of 216.9875. When two children are using personal FM technology in adjacent classrooms, it is important that channels are selected that are spaced far apart from one another. When children use their personal FM systems in several classrooms within a school building, educational audiologists are often faced with a difficult task of appropriately managing channels of the different FM systems in order to prevent interference across systems in neighboring classrooms.

Digital RF transmission also utilizes a carrier wave to deliver the signal of interest from the transmitter to the receiver. However, this process is quite different from FM transmission. In all digital systems, the input signal to the transmitter is first converted to a digital code of “0s” and “1s.” The basic process of digital coding of the input signal is crudely illustrated in Figure 3.

Although the inherent property of transmitting a digital code is common across all digital RF systems, a variety of specific strategies may be used to transmit the digital information from the transmitter to the receiver. One of these techniques is referred to as amplitude shift keying (ASK) and is depicted in Figure 4. With ASK digital RF transmission, the digital string of "0s" and "1s" is delivered by pulsing the presence and absence of the carrier wave (see Figure 4). A "0" is represented by an absence of the carrier wave, while a "1" is represented by the presence of the carrier wave.

The ASK strategy is a technique that is used with several of the proprietary digital RF "streaming" systems offered by the manufacturers of hearing aid technology.



Time	Digital Code	Fours	Twos	Ones
1	2	0	1	0
2	5	1	0	1
3	4	1	0	0
4	2	0	1	0
5	1	0	0	1
6	2	0	1	0
7	6	1	1	0
8	7	1	1	1

Figure 3. Digital coding in a 3-bit system.

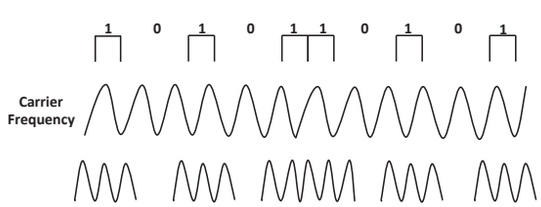


Figure 4. An illustration of Amplitude Shift Keying (ASK) digital radio frequency transmission. The carrier wave is pulsed to deliver the digital code (i.e., a "0" is depicted by a cessation in the carrier wave, and a "1" is depicted by the presence of the carrier wave).

Another technique used in digital RF transmission is Gaussian frequency shift keying (GFSK) which shows for illustration purposes the simpler but similar case of Frequency Shift Keying (FSK). In GFSK, a cycle of the carrier wave is "dropped" to convey a "0," while the cycles are preserved intact to convey a "1." GFSK has been shown to be less susceptible to noise than the ASK technique. The GFSK strategy is commonly used in Bluetooth technology (although other modulation schemes are also used).

Regardless of whether ASK, GFSK, or another strategy (e.g., phase shift keying) is used, digital RF transmission offers several potential advantages relative to analog FM transmission. First, digital RF can remove the need to manage the transmitting channel a wearer uses to avoid interference from proximal RF systems. In short, along with the input signal captured by the RF transmitter, digital RF may also be used to deliver several additional types of information between the transmitter(s) and the receiver(s). This additional information is often referred to as control information, and can include digital passcodes, operation protocols, system optimization, etc. For instance, in a digital RF system, the transmitter and receiver are typically "connected" to one another. The reader may note that the "connecting" process is typically referred to as the "pairing" process when using Bluetooth systems. Pairing implies that two systems are wirelessly coupled to one another (i.e., a pair typically refers to two entities), while "connecting" may refer to multiple entities being wirelessly coupled to one another. In particular, connecting refers to a process in which a digital passcode is established between one or more transmitters and one or more receivers. Once the digital passcode is established between these receivers and transmitter(s), they will only transmit digital RF information within the connected network. In other words, the receivers will not accept RF signals from other transmitters and the system is essentially immune from interference from other transmitters that have not been connected into the network. This feature is one component of a digital RF system that frees the audiologist from having to worry about channel management to avoid interference from neighboring RF systems.

Another feature that contributes to digital RF's resistance to interference is an ability to continuously "channel hop" while delivering the RF signal. Once a digital transmitter is connected to digital receivers, a protocol is established for the channels that will be used to transmit the signal as well as the order in which these channels will be used. As such, the receivers possess a

"knowledge" of the channel on which the transmitter will be delivering from one moment to the next, and the receivers will accept the information delivered on that given channel at that point in time. Additionally, if receivers detect information from several digital RF sources on one particular channel, then the receivers may notify the transmitter to avoid that channel for future correspondence. Most contemporary digital RF systems operate on the 2.4 GHz band (e.g., a carrier wave with a frequency of 2.4 billion cycles per second). The 2.4 GHz band, which is a globally license-free band intended for use with industry, science and medical (ISM) applications, is much wider than the band used for analog FM transmission, and as a result, a much larger number of "transmitting channels" are available.

Digital RF provides additional theoretical advantages over analog FM transmission. For instance, because of FCC regulations, the bandwidth of personal FM technology for use with hearing aids and cochlear implants is approximately 5000 Hz (Platz, 2004). In contrast, digital RF may possess a higher bandwidth (e.g., 7500 Hz). This is likely to be a particularly important advantage for young children, as an abundance of published reports have shown the importance of high-frequency audibility (e.g., beyond 6000 Hz) for speech recognition, speech production, and language development of children with hearing loss (Moeller et al., 2007; Pittman, 2008; Stelmachowicz, Pittman, Hoover & Lewis, 2001). Furthermore, digital RF transmission will most likely provide a more robust signal with better audio quality over a longer transmission range when compared to personal FM systems. Finally, digital transmission of an RF signal potentially allows for a higher precision of control of the signal of interest. This may be beneficial in applications, such as Dynamic (e.g., adaptive) remote microphone technology (described earlier), because it theoretically allows for an improvement in the assignment of receiver gain as a function of the competing noise level.

Phonak Roger Technology

In 2013, Phonak introduced Roger technology, a proprietary digital RF system developed for use with hearing aids and cochlear implants. The Roger system uses the GFSK technique to deliver a digital RF signal on the 2.4 GHz band. Like other digital RF systems, it also features continuous channel hopping in an effort to avoid interference with neighboring digital RF systems. However, the Roger system possesses several features that are different from other digital RF systems. First, it is the only digital, Dynamic (adaptive) system available for use with hearing aids and cochlear implants. Secondly, the signal of interest is repeatedly broadcast on several channels within the 2.4 GHz band. As such, if one channel is occupied by a neighboring digital RF system, the information on that channel is discarded, but the remaining channels may be used to deliver the signal of interest. This feature reduces the likelihood of signal "drop-out." The transmitter and receivers continually communicate with one another to locate unoccupied channels to provide a clear signal without interference. As a result, the Roger system is essentially interference-free and tap-free. Finally, the end-to-end delay of the signal from the transmitter to the receivers is about 17 milliseconds, which is considerably less than that which is found in other digital RF applications such as Bluetooth (e.g., typical end-to-end delay of approximately 40 milliseconds for Bluetooth audio streaming applications). Long delays can cause the audio signal to be out of synch with visual cues from the talker's mouth.

Research with Adaptive Digital Technology

A number of recent studies have explored the potential of adaptive digital technology to improve speech recognition in noise compared to analog Dynamic FM systems. Wolfe et al. (2013) evaluated sentence recognition in quiet and in the presence of classroom noise (Schafer & Thibodeau, 2006) of 44 older children and adult cochlear implant recipients. Performance was evaluated without the use of wireless remote microphone technology and with three different types of wireless remote microphone technology: 1) conventional fixed-gain personal FM (Phonak MLxS), 2) Dynamic (adaptive) personal FM (Phonak MLxi), and 3) Dynamic (adaptive) personal digital RF (Phonak Roger). The subjects experienced considerable difficulty understanding speech in noise without the use of remote microphone technology. Specifically, sentence recognition decreased by 20% from the quiet condition (95% correct) to the condition with 50 dBA of competing noise (i.e., approximately +15 dB signal-to-noise ratio), and at a SNR of approximately +5 dB, mean performance was about 25% (a 70% reduction from performance in quiet). However, at the +5 dB SNR, use of all three remote microphone technologies resulted in mean sentence recognition scores above 80% correct. Additionally, when the competing noise level was 65 dBA and higher, sentence recognition with the Roger system was significantly better than that which was obtained with

the fixed-gain and Dynamic FM systems. In fact, performance with Roger was 40% better than performance with Dynamic FM at a competing noise level of 75 dBA.

Thibodeau (2012) conducted a similar study with adults and older children who had moderate to moderately severe hearing loss and who wore hearing aids. The test conditions of the Thibodeau (2013) study were very similar to the aforementioned conditions described for the Wolfe et al. (2013) study with cochlear implant users. Thibodeau (2012) also found that performance with Roger technology was significantly better than performance obtained with both fixed-gain and Dynamic FM technology. Specifically, use of Roger technology provided better sentence recognition in noise than fixed-gain and Dynamic gain when the competing noise level was 65 dBA and higher. Furthermore, sentence recognition with use of Roger technology was almost 35% better at the 75 and 80 dBA competing noise levels when compared to performance with Dynamic FM.

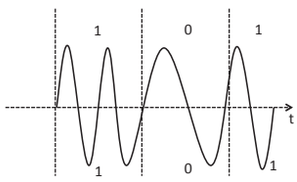


Figure 5. An illustration of Gaussian Frequency Shift Keying (GFSK) digital radio frequency transmission. A positive frequency deviation within the carrier frequency is used to represent a binary one, and a negative frequency deviation within the carrier frequency is used to represent a binary zero.

Wolfe et al. (in press) also evaluated sentence recognition in quiet and in the presence of classroom noise for a group of adults and children with normal hearing and also for a group of school-age children who had moderate hearing loss and who wore hearing aids. Sentence recognition was evaluated for each of these groups without the use of remote microphone technology and also with the use of two different classroom audio distribution systems (CADS): 1) Audio Enhancement Elite II CADS with fixed-gain, infrared transmission and four loudspeakers placed at the quartile locations in a classroom environment, and 2) Phonak DM5000 CADS with Dynamic (adaptive) digital RF from a tower of an array of 12 loudspeakers positioned in the front of the classroom adjacent to the loudspeaker used to present the target sentences. The subjects sat at the back of the classroom approximately 17 feet from the loudspeaker used to present the target sentences. It should also be noted that the subjects were seated approximately 19 feet away from the Phonak DM5000 CADS tower and approximately 7 feet away from the Audio Enhancement Elite II loudspeakers located toward the back of the classroom.

For both the adults and children with normal hearing as well as for the children with hearing loss, the use of the CADS system provided a significant improvement in sentence recognition in noise. Specifically, at a 5 dB SNR, use of the CADS resulted in greater than a 25% improvement in sentence recognition for the children with hearing loss. Additionally, the single-tower, Phonak DM5000 adaptive digital RF system provided significantly better sentence recognition in noise relative to the Audio Enhancement Elite II fixed-gain, multiple-loudspeaker system at the 70 and 75 dBA competing noise levels.

Additional Wireless Technologies

Over the past several years, a number of hearing aid manufacturers have begun to incorporate wireless hearing assistance technology into their products. These wireless accessories are often referred to as digital streaming devices and include numerous modes of application such as wireless streaming of an audio signal from a mobile telephone interface, a remote microphone, or a television interface directly to a user's hearing aids. Wireless streaming may also be used to deliver wideband audio signals from one hearing aid to the hearing aid on the opposite ear. For detailed information related to the various streaming accessories located in the commercial hearing aid market, the interested reader is referred to these sources of information (Crose, Kuk, & Bindeballe , 2011; Groth & Pedersen, 2012; Jespersen & Laureyns, 2013; Kuk, Crose, Korhonen P, et al., 2010; Kuk, Crose, Kyhn, et al. 2011; Stender, 2012).

Wireless streaming devices typically transmit the signal of interest from a source object (e.g., mobile telephone, television, remote microphone, etc.) to the hearing aids via digital RF within the 2.4 GHz band. Some manufacturers have developed their own proprietary systems to transmit the signal of interest via proprietary digital RF within the 2.4 GHz band from a source (e.g., remote microphone, mobile telephone accessory, etc.) to a receiver integrated into the hearing aids as shown in Figure 6 (Crose, Kuk, & Bindeballe , 2011; Groth & Pedersen, 2012; Jespersen & Laureyns, 2013; Kuk,

Figure 6. An example of a digital wireless "streaming" system in which the audio signal of interest is delivered from an external source (e.g., television interface, mobile telephone interface, remote microphone) to a hearing aid (Resound Alera) via proprietary digital RF on the 2.4 GHz bandwidth.

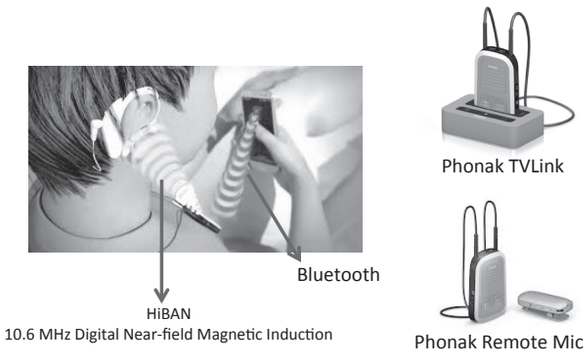


Figure 7. An illustration of a digital wireless "streaming" system in which the audio signal of interest is delivered from an external source (e.g., television interface, mobile telephone interface, remote microphone) to a streaming interface (Phonak ComPilot) via Bluetooth and then to a cochlear implant sound processor (Advanced Bionics Naida CI Q70) via digital near-field magnetic induction.

Crose, Korhonen P, et al., 2010; Kuk, Crose, Kyhn, et al. 2011; Stender, 2012). Other manufacturers have developed audio streaming systems in which the signal of interest is delivered via Bluetooth from the source (e.g., a remote microphone, a television accessory, or a Bluetooth-enabled mobile telephone) to a neck-worn interface, which relays the signal to the user's hearing aids via digital near-field magnetic induction (Figure 7).

Digital Near-Field Magnetic Induction for Audio Streaming

The reader may ask why one system would stream directly to a receiver/antenna integrated into the body of the hearing aid, while another would incorporate a neck-worn interface for streaming applications. As previously mentioned, the system that uses a neck-worn interface delivers the signal to the hearing aids via digital near-field magnetic induction (DNFMI). DNFMI may be used to deliver wideband audio signals in the form of a digital code via magnetic induction over short distances (e.g., less than a meter) with minimal delay and low power requirements, which allows for audio signals, such as speech, to be streamed from one hearing aid to a hearing aid on the opposite ear. This feature, which Phonak commercially refers to as the Hearing Instrument Body Area Network (HIBAN), allows for several advanced forms of signal processing to be provided to assist the wearer in challenging listening situations.

For instance, the beam-forming that occurs at the directional microphone system of each hearing aid may be integrated across hearing aids to provide a higher-order beam-former that provides better performance in noisy environments compared to that which is obtained when the directional systems of two hearing aids work independently of one another (i.e., StereoZoom) (Latzel, 2012). Additionally, DNFMI can allow for signals arriving from one side of the wearer to be streamed to the opposite hearing aid (i.e., ZoomControl). Studies have shown that this application improves speech recognition when the signal of interest arrives from the side of a listener (e.g., in an automobile) (Nyffeler, 2009). Furthermore, the signal at each hearing aid can be compared across hearing aids to offer a significant improvement in speech recognition in wind noise (Latzel, 2012).

Another feature made possible by DNFMI is commercially referred to as the DuoPhone and involves the wireless delivery of the telephone signal captured at one hearing aid to the opposite hearing aid to allow for binaural hearing on the telephone. Picou & Ricketts (2011, 2013) have recently shown that binaural hearing on the telephone results in a 20-30% improvement in speech recognition on the telephone compared to performance in the monaural listening condition. Wolfe and colleagues (in press) also compared speech recognition over the telephone for a group of young children, who were assessed in the monaural condition and also in the binaural condition (e.g., DuoPhone). They found that

speech recognition on the telephone with the DuoPhone feature was almost 30% better than performance in the monaural condition.

Case Study

The benefits and limitations of the aforementioned technologies are nicely exemplified in the following case study. A 48 year-old Advanced Bionics cochlear implant recipient has participated in a number of clinical studies evaluating wireless RF technology at our center. She served as a subject in a study evaluating sentence recognition in quiet and in noise without the use of wireless remote microphone technology and with a fixed-advantage FM personal FM system (Phonak MLxS), a Dynamic (adaptive) personal FM system (Phonak MLxi), and a Dynamic (adaptive) digital RF system (Phonak Roger). Her sentence recognition results are provided in Figure 8. As shown in Figure 8, she performed quite well without wireless remote microphone technology in quiet (95% correct), but in a noisy condition similar to what might be encountered in the real world (classroom noise at 60 dBA/5 dB SNR), she struggled substantially (23% correct). However, with use of remote microphone technology, she scored over 90% correct in the same noise condition, and her performance with Roger at higher noise levels was significantly better than what she obtained with Dynamic (adaptive) FM or fixed-advantage technology.

She has also participated in a study in which performance was assessed with use of a digital RF streaming system similar to what is available from many manufacturers for use with hearing aids or cochlear implant sound processors. Sentence recognition in noise was evaluated using a Phonak Roger personal RF system and also with the Phonak RemoteMic and ComPilot streaming system (Figure 9). The Phonak RemoteMic is a fixed-gain wireless transmitter that uses Bluetooth to deliver the signal of interest to the ComPilot interface. The Phonak RemoteMic possesses an omni-directional microphone similar to what is found in the streaming systems of other hearing technology manufacturers. Additionally, it is not a Dynamic (adaptive) system. The ComPilot interface is worn around the neck of the user, and it captures the signal from the RemoteMic and delivers it to the wearer's hearing aids via digital near-field magnetic induction. The subject's sentence recognition results with each system are provided in Figure 9. Use of the Phonak RemoteMic/ComPilot system is clearly beneficial as evidenced by the fact that sentence recognition in noise is greatly improved compared to the condition in which no remote microphone technology was used. However, use of the Phonak Roger Dynamic (adaptive) digital system provided significantly better sentence recognition in noise when compared to the RemoteMic/ComPilot system. The better performance obtained with the Phonak Roger systems can most likely be attributed to several reasons: 1) the Roger system provides adaptive increases in receiver gain with increases in the competing noise,

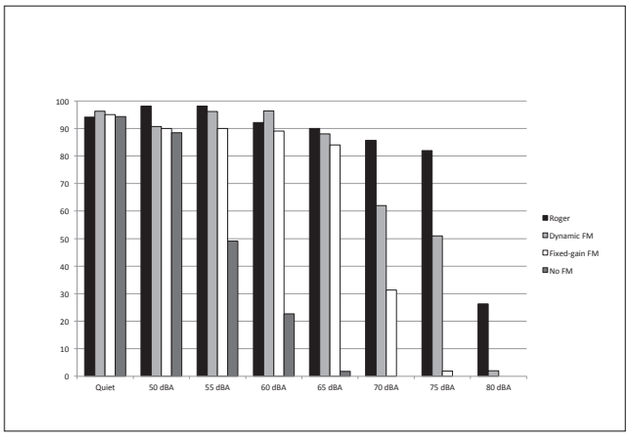


Figure 8. Sentence recognition in quiet and at seven different competing noise levels for a bilateral Advanced Bionics cochlear implant recipient using different wireless remote microphone technologies.

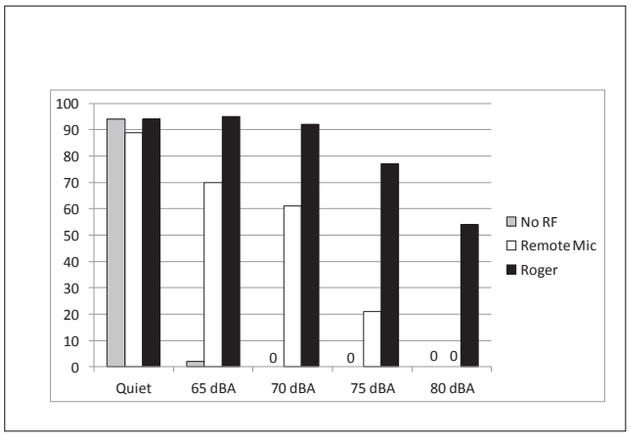


Figure 9. Sentence recognition in noise for a bilateral Advanced Bionics cochlear implant recipient using a digital wireless "streaming" system and a digital adaptive personal RF system (e.g., Phonak Roger).

2) the Phonak Roger system possesses beam-forming at the microphone of the transmitter, and 3) the Phonak Roger system possesses digital noise reduction at the transmitter.

Finally, this subject also participated in a study examining recorded word recognition over the telephone. As shown in Figure 10, she experienced great difficulty understanding monosyllabic words in the monaural condition. However, her speech recognition improved significantly when she was able to receive the signal bilaterally with use of the DuoPhone feature. Furthermore, significant improvement in word recognition in noise over the telephone was observed in the DuoPhone feature when the telecoil was used to capture the telephone signal and the processor microphones were attenuated by 10 dB.

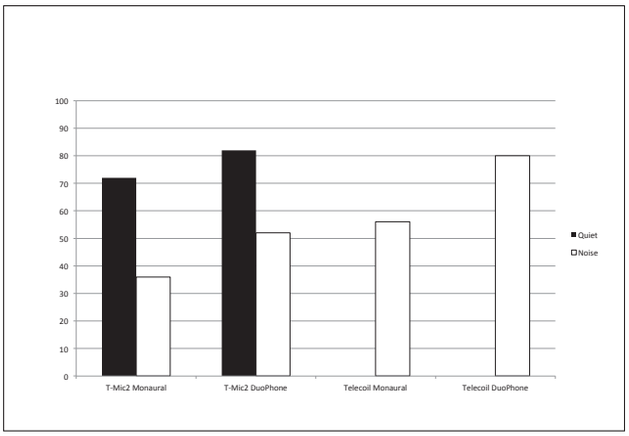


Figure 10. Word recognition scores for recorded monosyllabic words presented over the telephone to a bilateral Advanced Bionics cochlear implant recipient.

Children (and adults for that matter) frequently experience difficulty understanding speech in noisy and reverberant environments. They also often experience difficulty with understanding low-level speech (e.g., soft-spoken speech or speech that originates from more than a few feet away from the child) and speech that originates from a telephone. Use of digital, Dynamic (adaptive) RF technology (e.g., Phonak Roger) provides significant improvement in these difficult listening situations. Additionally, the binaural listening via the DuoPhone feature has the potential to substantially improve speech recognition over the telephone. Pediatric audiologists should consider digital, Dynamic (adaptive) RF technology, such as Roger, as imperative for use by all children with hearing loss, regardless of their age or the type of personal hearing technology (e.g., hearing aids or cochlear implants) they are using. Finally, pediatric audiologists should always strive to ensure that children with hearing loss are able to access important speech and environmental sounds with both ears.

Acknowledgement

This research was partially funded by a grant from Phonak AG.

References

American Academy of Audiology. (2008). *Remote microphone hearing assistance technologies for children and youth.* Reston, VA.

American Speech-Language-Hearing Association. (2002). *Guidelines for fitting and evaluation of FM systems.* Rockville, MD.

Crose, B., Kuk, F., Bindeballe, H. (2011). Digital wireless hearing aids, part 4: Interference. *Hearing Review,* 18(13), 30-39.

Finitzo-Hieber, T. & Tillman, T. (1978). Room acoustics effects on monosyllabic word discrimination ability for normal and hearing impaired children. *Journal of Speech and Hearing Research,* 21, 440-458.

Groth, J. & Pedersen, B.D. (2012). How user requirements affect technology choice for wireless hearing instruments. *ReSound White Paper.* Retrieved on January 28, 2014 at http://www.gnresound.com/~/media/DownloadLibrary/ReSound/White%20papers/user-requirements-affects-choices-wireless-white-paper.pdf

Hawkins, D.B. (1984). Comparisons of speech recognition in noise by mildly-to-moderately hearing-impaired children using hearing aids and FM systems. *Journal of Speech and Hearing Disorders,* 49, 409-418.

Jespersen, C.T. & Laureyns, L. (2013). ReSound Unite Mini Microphone for maximum understanding. *ReSound White Paper.* Retrieved on January 28, 2014 at http://www.gnresound.com/~/media/DownloadLibrary/ReSound/White%20papers/verso/ReSound%20unite%20Mini%20MIcrophone.pdf

Kuk, F., Crose, B., Korhonen, P., et al. (2010). Digital wireless hearing aids: Part 1: A primer. *Hearing Review,* 17(3), 54-67.

Kuk, F., Crose, B., Kyhn, T., et al. (2011). Digital wireless hearing aids: Part 3: Audiological benefits. *Hearing Review,* 18(8), 48-56.

Kuk, F., Korhonen, P., Crose, B., et al. (2011). Digital wireless hearing aids: Part 2: Considerations in developing a new wireless platform. *Hearing Review,* 18(6), 46-53.

Latzel, M. (2012). Binaural VoiceStream Technology™ - Intelligent binaural algorithms to improve speech understanding. *Phonak Insight.* Staefa, Switzerland: Phonak AG. Retrieved on January 28, 2014 at http://www.phonakpro.com/us/b2b/en/evidence/topics/auto-stereozoom.html

Lewis, D., & Eiten, L. (2004). Assessment of advanced hearing instrument and FM technology. In D.A. Fabry and C. DeConde Johnson (Eds.), *ACCESS: Achieving Clear Communication Employing Sound Solutions-2003. Proceedings of the First International FM Conference.* (pp. 167–174). Staefa, Switzerland: Phonak AG.

Moeller, M.P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., et al. (2007). Vocalizations of infants with hearing loss compared with infants with normal hearing: Part I - phonetic development. *Ear and Hearing,* 28(5), 605-627.

Nozza, R.J. (1988). Auditory deficit in infants with otitis media: More than a "mild" hearing loss. In D. Lim, C. Bluestone, J. Klein, and J. Nelson (eds.), *Recent Advances in Otitis Media: Proceedings of the Fourth International Symposium* (pp 376-379). Toronto: BC Decker.

Nyffeler, M. (2010). Binaural directionality wireless communication opens the door to a completely new approach in directional multi-microphone systems. *Phonak Insight.* Phonak AG: 2010. Retrieved on January 28, 2014 at http://www.phonakpro.com/us/b2b/en/evidence/topics/auto-stereozoom.html

Picou, E.M. & Ricketts, T.A. (2011). Comparison of wireless and acoustic hearing aid-based telephone listening strategies. *Ear and Hearing,* 32(2), 209-220.

Picou, E. & Ricketts, T. (2013). Efficacy of hearing-aid based telephone strategies for listeners with moderate-to-severe hearing loss. *Journal of the American Academy of Audiology,* 24, 59-70.

Platz, R. (2004). SNR advantage, FM advantage, and FM fitting. In D.A. Fabry and C. DeConde Johnson (Eds.), *ACCESS: Achieving Clear Communication Employing Sound Solutions-2003. Proceedings of the First International FM Conference.* (pp. 147–154). Staefa, Switzerland: Phonak AG.

Schafer, E.C. & Thibodeau, L.M. (2006). Speech recognition in noise in children with cochlear implants while listening in bilateral, bimodal, and FM system arrangements. *American Journal of Audiology,* 15(2), 114-126.

Scollie, S., Seewald, R., Cornelisse, L., Moodie, S., Bagatto, M., et al. (2005). The Desired Sensation Level Multistage Input/Output Algorithm. *Trends in Amplification,* 9, 159-197.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., & Lewis, D. E. (2001). Effect of stimulus bandwidth on the perception of /s/ in normal- and hearing-impaired children and adults. *Journal of the Acoustical Society of America,* 110, 2183–2190.

Stender, T. (2012). ReSound Alera and the Unite wireless accessories – Connecting the hearing instrument user to the world. *ReSound White Paper.* Retrieved on January 28, 2014 at http://www.gnresound.com/~/media/DownloadLibrary/ReSound/00-local-downloads/US/Global-Audiology-white papers/RESOUND%20ALERA%20AND%20THE%20UNITE%20WIRELESS%20ACCESSORIES.pdf

Thibodeau, L. (2010). Benefits of adaptive FM systems on speech recognition in noise for listeners who use hearing aids. *American Journal of Audiology,* 19(1), 36-45.

Thibodeau, L. (2012). Results with devices that utilize DM technology. Oral Presentation at the *Phonak Advances in Audiology Conference.* December 4, 2012, Las Vegas, NV.

Wolfe, J., Morais, M., Neumann, S., Schafer, E., Wells, N., et al. (in press, 2014). Evaluation of speech recognition with personal FM and classroom audio distribution systems. *Journal of Educational Audiology Association.*

Wolfe, J., Morais, M., Schafer, E., Mills, E., Mülder, H.E., et al., (2013). Evaluation of speech recognition of cochlear implant recipients using a personal digital adaptive radio frequency system. *Journal of the American Academy of Audiology,* 24(8), 714-724.

Wolfe, J., Schafer, E. C., Heldner, B., Mulder, H., Ward, E., and Vincent, B. (2009). Evaluation of speech recognition in noise with cochlear implants and dynamic FM. *Journal of the American Academy of Audiology,* 20(7), 409-421.

Wolfe, J., Schafer, E., Mills, E., J. A., Hudson, M., Anderson, S. (submitted 2014). Evaluation of the benefits of binaural hearing on the telephone for children with hearing loss. *Journal of American Academy of Audiology.*