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# WIRELESS IN-EAR MONITORING SYSTEMS - AN OVERVIEW

M Noar

Garwood Communications Limited, London, UK

## 1. INTRODUCTION

Historically, musicians have relied upon monitor speakers on the stage to "foldback" the sounds they require in order to aid their performance, whether this be singing in tune or playing in time with the other musicians. The use of a separate sound mixer on stage can allow each musician to construct a mix to their individual requirements. In practice the sound from each speaker spills onto the stage, creating a pool of mixed sound and therefore an increase in the ambient sound level. This leads to each musician wanting their own speaker "just a little louder" to overcome the problem. The result - dangerously high sound levels on stage (which could lead to long term hearing problems), and microphones at the point of feeding back. The microphones will pick up a portion of the sounds from the on stage speakers which are re-amplified and will also appear through the main PA system, causing a degradation in the audio quality that the audience hear. In addition, members of the audience near to the stage area are also subject to the concoction of sound spilling off the stage from the monitor speakers.

## 2. MONITORS AT THE EAR

In ear monitoring was developed to eliminate many of the above problems. It was designed to send the artist a high quality stereo mix of their choice via a wireless link to wherever they are on stage without the consequential disadvantages outlined above. These systems work best when used in conjunction with custom fit earpieces which are cast from an impression of the performer's ears, taken by an audiologist. These allow the performer to hear excellent quality sound at a comfortable volume, without the usual problems associated with conventional monitor speakers.

The most common question asked about in ear monitors is "can they damage your hearing". The fact is, used correctly, in ear monitors can help protect your hearing because in practice the SPL the wearer is subjected to is much lower than the SPL of conventional monitor speakers. The design of in-ear monitors is such that they sit across the entrance to the ear canal and fit comfortably into the ear canal. Inherently, this provides certain rejection of the ambient sound. Because the ambient sound level is reduced, the sound level of the in ear monitors does not need to be as loud as a conventional monitor speaker for the user to hear their monitor mix above the ambient sounds. The user now perceives the same sound volume for a lower SPL at the eardrum. Common symptoms such as tinitus, a ringing in the ears often associated with long exposure to high sound levels, and vocal stress, caused by a vocalist's difficulty hearing themselves sing, can be drastically reduced.

## 3. EAR MOULDS

Custom moulded earpieces offer the ultimate in comfort and audio quality to the wearers. These are manufactured from an impression, taken from the ear by an audiologist. As audiologists take similar impressions from a number of their clients for the fitting of hearing aids, this is a familiar process which takes around 10 minutes. They would usually carry out an audiological screening prior to carrying out the procedure to check and record the existing condition of the ears.

It is advisable to have a mould fitted so the canal is deep enough to reach to the bony part of the canal to reduce an effect known as occlusion. This is the phenomenon which occurs when your ears are blocked, perhaps due to a build up of mucous or wax, giving the impression of the sound resonating around your head causing a perceived increase in low frequencies. The effect reduces as the depth of the mould increases beyond the first and second bends in the ear canal. (This effect can be demonstrated by placing your finger gently in your ears. Begin talking and observe the increase in the lower frequencies and the loss in clarity. Push a little harder and you will notice a reduction in this effect.)

This type of mould can result in up to 26db of isolation and a bass response which can extend as low as 15 Hz. (Assuming the driver could reproduce frequencies that low!) A lower volume at the driver would be required to achieve the same perceived "loudness" due to the superior coupling and isolation obtained using this type of mould. Having a lower SPL at the eardrum offers more protection to the user. Many users are happy with a shallow fitting mould which does not protrude further than the soft tissue in the inner canal. This still offers a comfortable fit and reasonably good coupling to the ear canal, but isolation will only be about 8db and therefore does not offer so much protection to the user.

Generally, the earpiece comprises of a high quality voice coil diaphragm type driver, mounted in a tuned enclosure. This enclosure has an exit port which is acoustically coupled to the ear canal, and a rear port whose size may be varied to adjust the magnitude of the low frequencies. For deep moulds, techniques have been developed whereby the isolation can be controlled via a duct fitted between the mould's canal and the rear port. This duct decreases isolation to only 8db but can be fitted with up to three attenuators, each of which give 6db of attenuation thus allowing customisation. Because of the nature of low frequencies, these will penetrate the earpiece and will be present at the eardrum. For this reason, the attenuators are designed with a highpass characteristic, providing roll off below 500Hz, allowing the user to perceive a flat attenuation.

Techniques under development include controlling the dimensions of the earpiece canal such that this creates an impedance to the mass of air in the ear canal. This arrangement will have a resonant frequency, determined by its dimensions forming a Helmholtz resonator. By controlling the length and diameter of the canal the Helmholtz Resonator can provide a peak at 2.7 kHz to emulate the ear canal's natural response.

## 4. THE WIRELESS LINK

During the last 10 years the use of wireless equipment to release performers from the microphone or guitar cable has grown as rapidly as the use of home computers. As well as the professional touring bands, there are thousands of semi-professional bands, theatres, even churches who use multi-channel radio set-ups for microphones, instruments and in ear monitoring.

RF technology is often considered a "necessary evil" by many users, although most of the operational problems experienced could be avoided by attention to detail and careful planning in the areas of co-channel compatibility with other radio transmission equipment at the venue. Walkie talkies for instance, tend to be reasonably high power devices that can cause all kinds of problems with the sensitive, wideband receivers used on stage. Unfortunately these devices tend to be forgotten about during system planning. Stage clothing is another area which is rarely considered. Many sequinned jackets contain metallic materials which shield the radiating signal from the receiver aerial giving rise to symptoms such as increased noise, an apparent loss in range and a greater number of drop outs around the performance area. The following section will discuss some of the pertinent areas of consideration when planning and using multi-channel radio systems.

4.1 Receiver bandwidth

When putting together multi-channel radio systems it is very important to consider the effects of interaction between the systems. Initially you must consider the receiver RF bandwidth. In a wideband system for example, the input filter bandwidth may be at $\pm$ 100 kHz from the centre frequency. It would be prudent to allow a guard band of, say 50 kHz at each end of its passband. e.g. Centre Frequency = 800 MHz, Passband limits = 799.9 to 800.1 therefore for the upper adjacent channel - (800.1+50kHz guard=800.15). Now add a further channel, 800.15+(50kHz guard+100kHz)=800.3. Our two channels being 800 and 800.3 MHz.

Although this "rule of thumb" method has proved to be a simple and successful method of assigning channels, it is essential to consider intermodulation distortion.

4.2 Intermodulation

The phenomenon of intermodulation distortion is best described as a product or products generated by the interaction of two or more frequencies. A multi-channel system is not necessarily confined to the devices on the stage, it must of course include other RF signals such as local TV, radio or mobile phone transmissions. More frequencies in the equation gives rise to more unwanted products, each of which will intermodulate with each other. The magnitude of these products is a function of the magnitude of the dominant frequencies. There is therefore a trade off between reducing the transmitting RF power to reduce the magnitude of the intermodulation products and therefore the RF noise floor, and maintaining an acceptable signal to noise ratio at the receiver.

Although a comprehensive analysis may be realised through the use of the Fourier transform to derive the spectrum of intermodulation products, the method described below provides a practical solution for the low power devices used by our industry.

A calculation to establish disruptive 3rd order products would necessitate each frequency to be tested with every other frequency and the resulting product to be checked as to whether it is within the passband of the receiver.

i.e. For a wideband receiver typically

$$2 \times f2 - f1 <> f3 \ (\pm 150\ \text{kHz})$$

also

$$2 \times f2 - f1 <> f3 \ (\pm 150\ \text{kHz})$$

where each frequency under test shall have the assignment f1, f2 and f3.

The test should be repeated to check for 5th order intermodulation using the formula:

$$(3 \times f1) - (2 \times f2) <> f3 \ (\pm 150\ \text{kHz})$$

also

$$(3 \times f2) - (2 \times f1) <> f3 \ (\pm 150\ \text{kHz})$$

As can be seen above, the closer the channel spacing, the closer the intermodulation products will be to the fundamentals, and therefore within the passband of the receiver front end filters.

With low power devices such as the units described, the level of any products beyond the 5th order are likely to be at a low enough level so as not to cause any adverse effects.

The importance of intermodulation considerations when choosing frequencies for a multi-channel system cannot be stressed enough.

Ironically, intermodulation is an effect required by most receivers in order produce the intermediate frequency from which the audio is extracted. In most receivers, the internally generated frequency is 10.7MHz above or below the wanted incoming frequency. This is designed to mix or "heterodyne" with the incoming signal to produce this 10.7 MHz intermediate frequency, from which the audio signal is recovered. Bearing in mind that a frequency either 10.7 MHz above OR below the incoming frequency will yield an output frequency of 10.7MHz, care must be taken to ensure you do not have a radio system which is distanced such that it may mix down to give a frequency within the 10.7 MHz passband.

4.3 Multipath Dropout

One of the most common problems experienced when using radio systems in a stage environment is that of dropouts around the performance area. In a perfect world, the transmitted signal would radiate from the aerial, across the stage to the receiver aerial. Of course this does happen but, because the antennas used are, on the whole, omnidirectional, the signal will radiate in all directions. At any given frequency, certain materials may absorb the energy whilst others will tend to reflect the signal. This now means that the receiver picks up, not only the main signal but also a multitude of reflected signals. At UHF the time difference between direct and reflected signals can give rise to phase differences. If two signals arrive at the receiver 180° out of phase with each other, cancellation will occur, causing the signal to dropout. This is commonly referred to as multipath dropout. Other phase differences may cause reductions in signal strength at the receiver aerial which may cause other symptoms such as erratic increases in noise.

Desensitisation or receiver saturation can occur when a transmitted RF signal, whose power is of such magnitude , causes the RF amplifier in the receiver to saturate, causing distortion products to appear in the receiver amplifier stages. Where signal amplitudes are high enough, the noise skirt of the signal which may be some distance away from the centre frequency of the receiver could be of sufficient magnitude to also cause saturation of the RF amplifier. It is therefore important when using an in-ear monitor system alongside a body pack transmitter to consider desensitisation to the receiver, and wear transmitter and receiver packs on opposite sides of the body. A common trap is caused through the use of walkie talkie type units during the show, causing sudden pops or whistles in the ears of the artist!

## 5. AERIALS, COMBINERS AND SPLITTERS.

The solution to many of the problems outlined above is to look carefully at the positions of the equipment and their aerials and cables. Avoid placing aerials next to reflective surfaces such as metalwork or sources of potential interference such as digital equipment, other transmitters or other receivers. If you suspect a problem is being caused by multi-path reflection, check the base station aerials are rigged away from metal and other potentially reflective surfaces. Try re-positioning the complete aerial assembly, or if mounted on a mic stand with a boom, try angling the assembly in towards the stage.

It is very important for body pack aerials to be worn correctly. It should be allowed to hang vertically and without direct skin contact, as sweat will significantly degrade its performance. Stage clothing can contain metallic fibres or sequins which may mask the aerial from the signal. It's a tell tale sign when you have a great rehearsal but everything seems to go horribly wrong at showtime! These details should be considered at the planning stage to allow time to investigate and alleviate any potential problems.

5.1 Aerial Splitters

There are many advantages to using a common aerial for a number of receivers and there are a number of commercial units available that perform this task very well. It is of course important to check that the frequency span of the distribution system exceeds the lower and upper frequencies of the receivers. Also, although unlikely, do consider that local oscillators in the receivers can intermodulate with each other and with the wanted signals. It is possible that unwanted product could potentially cause problems.

Check the aerials and cables used are correct for the frequency and impedance of your system. (Most systems are now 50 Ohms, but don't take this for granted). The signal loss down a length of cable tends to be greater at higher frequencies. (See the table below). It is wise not make aerial cables any longer than necessary. If you make your own cables make sure they are assembled in accordance with the manufacturer's instruction. Adapters can be a real lifesaver and it would be wise to keep a selection as part of your tool kit. It should however be noted that adapters can increase the system loss by 1 or 2 dB and so should not be used unnecessarily.

Ground plane or single whip types should be rigged at a height of two to three meters and have line of sight to its respective transmitter or receiver. Rig aerials away from metal structures and, when using multi-channels, away from each other.

Yagi style aerials offer directionality in exchange for some forward gain. It should be noted that gain figures quoted for different aerials are usually referenced to a standard half wave dipole type aerial.

The cable used to connect the aerial to the equipment, being the vital link, should be inspected each time it is used. The connectors should be cleaned with isopropynol or any other de-greasing solvent and the cable should be inspected for lacerations and for shape. The impedance of the cable is a function of the dimensions of the conductors, the coefficient of the dielectric of the insulator and the distance between the inner conductor and the outer screen. Therefore, if a cable is crushed under a flight case it is likely that its impedance has changed from its original value. This mismatch to the transmitter output and aerial could not only have an adverse affect on radiated power but, in some cases, could cause instability and spurious harmonics in the transmitter. Consideration must also be given to losses inherent in RF cables. The amount of loss is dependent upon the dimensions of the conductors, the materials used, the frequency of the transmission signal and the length of the cable.

In the UK, the frequencies available for in ear monitoring and radio mics centre around 858MHz. The table below shows approximate cable losses per 10 metres of cable, assuming the connectors are fitted correctly!

| Type | Description | Loss at 550 MHz | Loss at 858 MHz |
|---|---|---|---|
| RG58 | standard 5mm diameter, 50 ohm co-ax | 5db | 7db |
| RG213 | low loss 10mm diameter, 50 ohm co-ax | 1db | 2db |

As you can see, using a 15 meter RG58 type cable to allow you to place a transmitter aerial closer to the action can cause serious loss problems resulting in poor operating range!

5.2 Aerial Combiners

Aerial combiners to allow a single transmission aerial to serve multiple receivers, offer an attractive alternative to having to rig say, 8 cables and 8 aerials, correctly spaced, night after night. A practical solution requires careful design to prevent the combiner causing more problems than it solves. In transmission systems, poor isolation will allow the signals generated by the other transmitters to intermodulate with each other which will lead to a broad spectrum of both wanted and unwanted signals being radiated by the aerials. Apart from intermodulation, one has to consider isolation between the transmitter outputs and insertion loss of any isolators used. For example, consider a four transmitter system whose outputs are coupled to a single aerial. Say the output of each transmitter is 50mW or 17dbm/50ohm. Each pair of transmitters would be coupled, the output of each coupling to be coupled together to drive the aerial. Even assuming a 2db loss at each couple, the output of each transmitter will be 4db down on the input, now 13dbm/50ohm or 20mW. The solution is of course to incorporate amplifiers to restore the loss. Because there will be low level intermodulation products generated by the coupling process it is necessary to place an amplifier for each input, prior to the coupling system as opposed to a final output amplifier which will tend to amplify the wanted and unwanted signals.

## 6. RADIO SYSTEMS AND THE LAW

The radio spectrum represents a commodity in great demand by a wide variety of users. Unfortunately the amount of usable frequencies available for applications are limited by two main factors. The first being that of the length of aerial required to transmit and receive at a given frequency - The lower the frequency, the longer the aerial. The second and perhaps the most important is that at frequencies much above 1GHz, propagation becomes less efficient, the RF energy being easily absorbed by objects such as trees, buildings and living beings. At microwave frequencies above 10GHz, the earth's atmosphere can absorb significant amounts of the radiated energy whilst raindrops can represent a ¼ wave reflector, causing multipath ! To help overcome this problem at these high frequencies, transmission aerials tend to be very directional thus concentrating the radiated signal via a narrow path to its receiver.

For mobile applications neither very low nor very high frequencies are particularly practical. We are therefore left with a chunk of spectrum, primarily between 20MHz and 1000MHz to accommodate commercial radio, television, mobile phone, emergency services, aircraft radio, CB, Amateur ,radio microphones and of course garage door openers - to name but a few!

It is for this reason of demand that governments all around the world "police "the airways. In most countries the Governments insist that all equipment goes through the process of Type Approval, a standard to ensure the equipment does not upset other users on nearby frequencies or indeed interfere with other equipment sensitive to electromagnetic energy. There are many Type Approval standards covering the wide variety of radio transmission equipment available and once the equipment meets the standard, the user must purchase a license to then use this equipment. There is a "Deregulated" category designed for low power equipment (garage door openers, wireless telephones etc.) which may be used without a license.

During the past few years, especially with the vast increase in mobile phone users, Type Approval specifications have been revised/ amended to cater for new technologies. Many areas have been made more stringent so as to maximise the usable spectrum. The penalties for using equipment not type approved for use in the UK are confiscation with a fine of up to £5000 and/or six months imprisonment! At this point in time, each country has its own Type Approval process and its own pre-assigned frequencies for radio equipment. This makes it virtually impossible for a touring band to perform shows around Europe whilst adhering to local legislation! Although within the next few months it is hoped a pan European specification will be adopted, making Type Approval a one time process, we will still have to address frequency allocation for each country. - At least things are moving in the right direction.