APPLICATION NOTE AN-3

# The Measurement and Suppression of RF Interference from TDMA Phones

## Introduction

While the recent explosion of mobile telephone usage has improved the quality of life for many in this fast paced world, it has reduced the quality of life for some hearing aid users. People who attempt to operate certain mobile phones which use digital transmission in close proximity to their hearing aids can experience a disruptive "buzzing" sound due to electromagnetic interference.

Wireless technologies such as GSM (Global Systems for Mobile), PCS (Personal Communication System), DECT (Digital European Cordless Telephones) all use TDMA (Time Division Multiplex Access) as their multiplexing scheme. This RF signal can be demodulated by a hearing aid and result in an unwanted "buzz". Some products are now emerging which use a spread spectrum transmission mode called CDMA (Code Division Multiplex Access). Power densities at any particular frequency are very low and rectification is less of a problem. It is fortunate that the world seems to be embracing CDMA and other spread spectrum technologies for the next generation of wireless products.

A brief discussion and comparison of the various systems will help explain why some systems can be more problematic than others.

## GSM Cellular

Digital systems seem to have a greater potential for interference because the rectification and demodulation of the RF amplitude-varying waveform leaves products in the audio range. The actual envelope variations of the signal are too high in frequency to be of concern if demodulated. However, because the data is transmitted in "frames" by the mobile phone, the signal appears as bursts of high speed pulses.

The actual data rate of GSM is 270.833kbps which, by itself, is too high a frequency to cause any demodulation problems. Each GSM frame lasts 4.615ms and consists of eight (8) time slots of 576.92µs. The mobile phone only transmits the 270.833kbps pulses during these time slots. Since these time slots repeat every 4.615ms, they have a spectral component at 216.68Hz, clearly within the audible frequency range. There are other less critical low frequency spectral components caused by multiframing (a GSM multiframe consists of 26 frames of 120ms duration each for a spectral component of 8.3Hz, obviously unaudible).

To exaggerate this problem, GSM has one of the highest portable transmit output powers at 1W maximum/125mW average.

## USDC (US Digital Cellular)

In contrast to GSM, the USDC IS-54 specification operates at a data rate of 48.6kbps. The frame duration is 40ms (25Hz) consisting of six (6) time slots of 6.66ms each (150Hz). Harmonics of this may still present potential demodulation problems.

USDC mobile phones operate at 600mW maximum and 200mW average output power which tends to further reduce the interference potential as compared to GSM.

## DECT (Europe), PHS (Japan), PACS (US) Digital Cordless Phones

Of the three other major mobile protocols, DECT (10ms frame for 100Hz spectral rate, 250mW power), PHS (5ms frame for 200Hz spectral rate, 80mW power), and PACS (2.0ms to 2.5ms frame for 400-500Hz spectral rate, 100mW power), PACS phones would seem to be a likely problem except for the fortunately low power level.

While there are many "standards" wireless communication protocols, GSM would be the transmission methods most likely to cause problems in today's hearing aids.

## Technical Background to RF Interference

The interference of certain TDMA mobile phone transmissions on hearing aid circuitry is a particularly difficult problem for several reasons. The very close proximity of the radiating antenna to the high gain hearing aid circuitry is an unusual situation which can place large RF electric field gradients over the sensitive aid circuitry. The hearing aid also functions in the near field of the antenna so that no *a priori* assumptions can be made about the orientation of the electric (E) and magnetic (H) fields. If such assumptions were possible to make, then a mechanical redesign which guaranteed positioning of the pick up points in the field null areas would be sufficient.

RF energy can enter a hearing aid via any one of the five (5) basic elements of the aid- the microphone, volume controls/trimmer, integrated circuits, wiring, or the receiver.

RF energy can affect hearing aid circuitry in two different ways depending on its strength and location in the hearing aid system. If the RF signal has significant amplitude, it may reduce the headroom for the intended audio signal within the circuit itself. This would show up as appreciable distortion or clipping of the audio signal at a level far short of the normal clipping amplitude. This can happen at any point in the circuit but would be most likely in the output stages where the intended signal is at the greatest amplitude.

This type of interference can theoretically be caused by any type of cellular phone, either analog or digital. Testing has shown that this is currently not a cause of significant interference from analog or digital phones. However, this potential source of interference must be continually recognized and monitored to ensure that it does not become problematic.

The second mechanism involves reception and rectification of the RF energy in the semiconductor circuits. The TDMA digital modulation scheme is especially problematic in this way because the RF carrier is pulsed on and off. The dominant TDMA modulation scheme (GSM) uses a pulse rate of 217Hz as discussed above. This gives a demodulation interference spectrum of 217Hz and all of its harmonics. These frequencies are quite audible over much of the audio frequency and result in an audible "buzz" from the hearing aid.

Suppression of this type of interference requires that that RF energy be kept away from any nonlinear circuit element which could provide the demodulation. This includes the hearing aid circuit as well as the microphone preamplifier. The interference is most problematic in the low level input stages due to the gain that is applied to the signals from this point onward in the system.

The balance of this application note will deal specifically with issues related to eliminating the interference from the output of the microphone buffer circuit although much of this discussion also applies to hearing aid circuits in general.

## General Approaches to Isolation

The RF energy radiated into the hearing aid is coupled into the electrical circuits through inductive (or possibly capacitive) coupling. This coupling can be reduced by shielding the discrete wires and conductors on hybrid circuits within the hearing aid. It is not practical to use shielded wires within the aid, but twisting the lead pairs where possible can achieve a considerable degree of reduced inductive coupling.

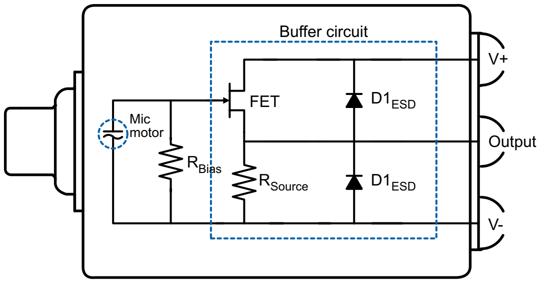



Figure 1: High level RF can enter the circuit through the leads and be rectified in the ESD protection diodes or the FET buffer

The stainless steel case of the microphone provides a great deal of shielding to the sensitive components within the case. Some radiative coupling is possible through openings in the case, but the dominant point of entry for RF energy is likely to be the electrical leads to the battery and the signal output lead. In some microphones, each of these three leads provides an immediate path to a nonlinear semiconductor junction which is capable of RF demodulation if the leads are unprotected. The FET itself, and any ESD diodes, represent such nonlinear devices and are all capable of demodulating the signal (see Figure 1, above).

A general strategy for EMI protection is to provide a filter which shunts the RF energy to ground before it has the opportunity to encounter a demodulating nonlinear circuit element. Fundamental to this strategy is a good grounding point on the microphone case with good, low RF connections to ground. The simplest form of decoupling filter is a simple shunt capacitor to ground on the power supply lead and the signal output lead. This provides a low impedance path to ground inside the microphone and forms a voltage divider with the RF source impedance in the external circuitry. This may work quite well at some frequencies although it relies on the impedance outside the microphone, which is beyond the control of the microphone designer.

A more reliable approach is to include a moderate value resistor in series with the electrical leads to guarantee a minimum impedance value in the voltage divider of the filter. Filters of this kind implemented on the IC or hybrid circuit in the microphone can provide significant reduction of RF interference (see Figure 2, below).

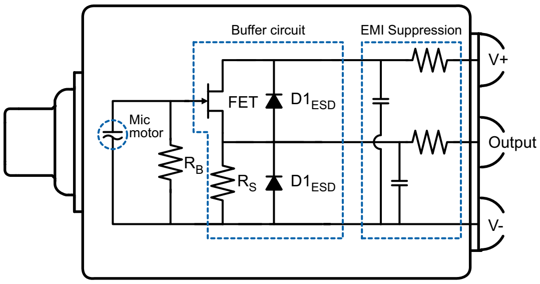



Figure 2: Microphone with EMI suppression circuitry to protect nonlinear semiconductor junctions

A challenge in all of the above approaches is the small inductance which can often accompany any capacitor. At increasingly higher RF frequencies, this inductance can often give a significant impedance in series with ground connections and decrease the level of RF suppression. Special care in circuit design and layout and careful experimental investigation is necessary to verify that the intended solution actually provides the necessary degree of suppression.

A microphone's RF immunity is determined by the amount of RF energy that reaches the internal nonlinear devices and the "efficiency" with which these devices demodulate the RF energy. These facts suggest two approaches to improve RF immunity in the microphone. First, incorporate additional circuitry into the microphone hybrid, external to the IC, to prevent RF energy from reaching the IC device. Second, modify the IC design either to better filter out incoming RF signals or to provide poorer demodulation of said signals.

## Hybrid Approach to Microphone RF Immunity

The first approach is the most direct: Adding internal shunt capacitors between the terminal pads of the microphone. Measurement of the high frequency impedance (0.1 to 1.8GHz) between the pairs of microphone terminal pads without capacitors demonstrated impedance levels of 30Ω to 100Ω in the frequency band 0.5 to 2.0GHz. By adding shunt capacitors, this impedance could be significantly lowered, attenuating the RF signal passing to the semiconductor. (Caution must be exercised when taking this approach to ensure that the integrity and pull-strength of the terminal pads is maintained.)

A good quality capacitor for RF will have low inductance and low ESR (equivalent series resistance). The inductance is determined mainly by the capacitor geometry, a square shape being ideal. ESR is affected by a number of factors including the dielectric material and the material used for the electrodes.

The dielectric material selected was characterized at high frequencies. For the electrodes, a low-frit gold conductor material was experimentally proven superior over more conventional types for providing a low inductance. This enabled fewer dielectric layers providing higher capacitance per unit area without metal migration problems as well as providing a more optimum ESR.

Due to the small working space, some compromises from the ideal were required. In practice, impedance was reduced from 90Ω down to 1.5Ω at 900MHz using a 33pF capacitor. With this particular capacitor construction and value, the parasitic inductance produced resonance at too low a frequency with a resultant impedance level reduction from 30Ω down to only 12Ω at 1.8GHz. A smaller capacitor of 15pF reduced the impedance to 1.6Ω at 1.8GHz but increased the impedance at 900MHz; this appears to represent the best overall performance across the entire frequency range.

In order to provide adequate RF immunity in the 1.8 to 2.0GHz region and for the future in the 2.4 to 2.6GHz range, various approaches have been considered and have been the subject of a number of experiments. Among these are lowering the parasitic inductance of the capacitor by varying geometry, use of multi-layer capacitors to increase capacitance and enable placement of electrodes to shield the signal carrying leads, electrical placement of the common electrode at the common (V-) terminal of the microphone, and use of more complex filter types. The most effective placement and quality of grounding was also investigated.

Again, size limitation preclude extremely complex filter arrangements, but the addition of small value series resistors prior to the bypass capacitors has experimentally proven effective in enhancing RF immunity as has more optimal construction of the capacitors and more effective construction of grounds. These specific items are the subject of continued experimentation.

## Integrated Circuit Solutions to RF Immunity

Any rectifying junction within an integrated circuit can demodulate RF energy from a TDMA phone and produce an audible baseband signal. It is imperative that the RF energy be prevented from entering the IC or be sufficiently attenuated on the IC before reaching a rectifying junction. RF signals can be conducted into the IC either differentially between leads or as a common mode signal present on all leads. In the latter case, asymmetry of the impedances between the various terminals causes inadequate common mode rejection.

Regardless of how the RF energy enters the IC, the solution is to reduce the shunt impedance between the terminals (at the carrier frequency) and to raise the series impedance of each terminal. The best way to implement this is by adding capacitance between the terminals and adding a small resistance in series with each terminal. The capacitors must be well designed to have low resistance and low inductance in order to maintain a low impedance value throughout the carrier frequency range. Integrated capacitors, due to their smaller size, generally have lower parasitic inductance that discrete components and therefore perform better at very high frequencies. The resistance in series with each terminal should be on the order of a few hundred ohms so as not to impact the baseband operation of the audio circuit. Polysilicon resistors are preferable over diffused resistors to avoid creating yet another junction where RF demodulation can take place. This series resistance establishes a critically needed minimum source impedance regardless of the external circuit impedance.

Device design and layout of an effective solution to EMI must work in concert with any ESD protection of the circuit. In fact, they share several common goals in that both must dissipate energy and shunt it around the IC without letting it enter the core of the IC. As a solution on the IC, EMI cannot be completely suppressed. There is always a level at which an external RF signal will be strong enough to overwhelm the circuit and be perceptible. Also, the level of EMI attenuation achieved is inversely proportional to the shunt impedance and is highly dependent on how much IC area is available. Therefore, the best result is an optimum level of EMI suppression for the given available area on the IC. ESD protection is similar and competes with EMI attenuation for IC space.

## Measurement of RF Immunity of Microphones to Mobile Phone Transmissions

Although the basic concept of measuring the RF immunity of microphones is simple, the actual application is quite complex. The basic concept is to place a microphone in a controlled RF field of defined modulation characteristic and use the measure of audio frequency perturbations in the microphone output to quantify RF immunity.

If measurements are to be meaningful, the RF field must be reasonably comparable to that generated by a typical mobile phone designed for the frequency and modulation characteristics of interest. Initially interest was in the 900MHz range but now also includes the 1.8 to 2.0GHz range popular with GSM phones. Future TDMA protocols make the 2.4 to 2.6GHz range the next frequency range of interest.

Open field sites, screen rooms, TEM cells, and RF anechoic chambers are all environments commonly used to measure RF immunity. The RF anechoic chamber provides the best characteristics for maintaining a reliable, uniform RF field capable of being accurately calibrated and provides consistently repeatable RF fields for experimental measurements (see Figure 3, below).

The RF field within the shielded anechoic chamber is generated with a frequency synthesizer, power amplifier, and antenna

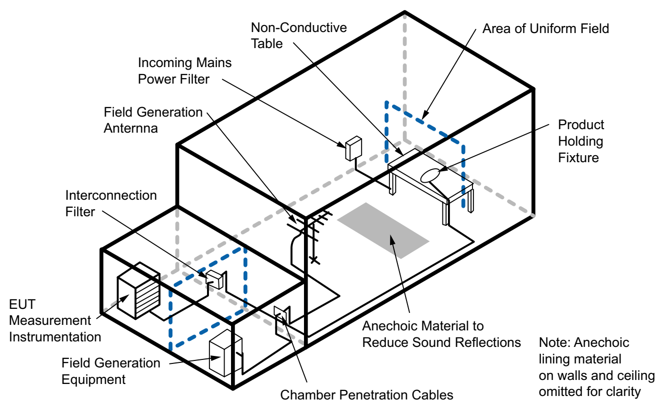



**Figure 3:** Example of a suitable test facility

appropriate to the frequency band. A log periodic antenna is used for frequencies below 1.0GHz and a horn antenna is used for frequencies above 1.0GHz.

A typical mobile phone operating in the 1.8 to 2.0GHz region (PCS) was characterized in the anechoic chamber using a probe and spectrum analyzer. The phone was placed near the probe with the audio receiver of the phone 1 to 2cm from the probe element in an effort to simulate positioning of the phone receiver close to the ear. The electric field strength was 15V/m (RMS) and varied from 9V/m to 19V/m for various positions of the phones while maintaining the 1 to 2cm distance. Since the modulation was pulsed (100%) with a 10% duty cycle, the effective peak field strength was greater than 100V/m.

For measurement purposes, a peak field strength of 60V/m was selected as this provided useable data from various microphones with varying degrees of RF immunity prior to field generation amplifier clipping. Modulation used was 50% with a 1kHz sine wave. A sine wave was used rather than a pulse (square wave) to avoid measurement errors due to signal distortion in the filters and measurement equipment.

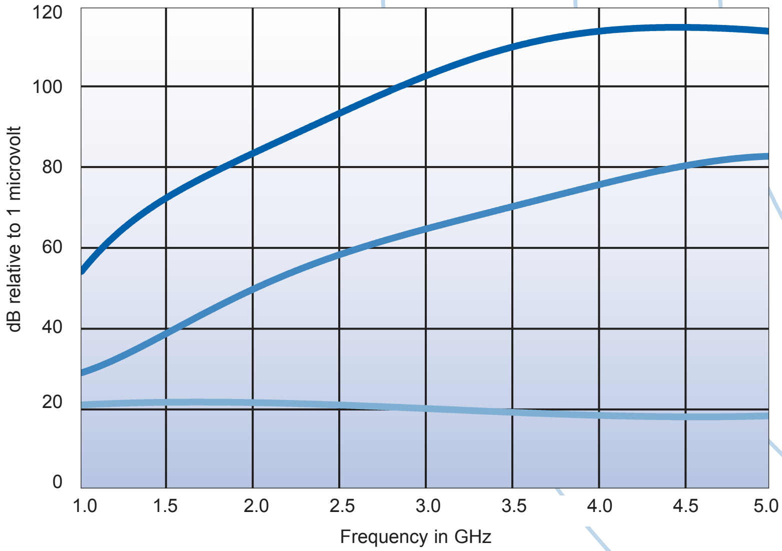
As in any RF measurement, fixturing of the device under test and interconnection to the measuring equipment is critical. The microphone by itself has little pickup of RF energy since it is contained in a metal case. Only the exposed terminals can actually pick up the unwanted RF signal. The RF energy is in practice picked up by wires (acting as antenna) connected to the terminal pads. For testing, the microphone was mounted to a circuit board which plugged into a fixture. This provided consistent measurement between devices. The fixture was a die cast metal box, which, in addition to being a connector for the circuit board, contained a battery to power the microphone. A doubly shielded cable was run from the fixture to outside the chamber and connected by way of a third-octave filter to a spectrum analyzer. A 10Hz bandwidth was selected on the analyzer. Ferrite beads were used liberally on the cable and inside the fixture to help suppress any RF pickup by the cable. The microphone was connected to the circuit board by 0.5cm long #36 AWG lead wires.

A "dummy" microphone consisting of an Improved EM microphone with the transistor replaced by 10kΩ resistors between the terminal pads was constructed. Without a nonlinear device in this microphone, any recovered 1kHz on the analyzer would be from RF pickup that was demodulated in the filter or measuring equipment. This proved an excellent tool for determining that the minimum detection level of the measurement system was low enough to result in meaningful measurements.

Orientation of the microphone under test with respect to the antenna will affect the amount of RF pickup and thus affect the measurements. The proper orientation, i.e., the orientation that maximizes the pickup, must be determined experimentally. This will vary with different microphone designs. For a given microphone design, such as the EM series microphone, once a particular optimum position is determined, it can be used regardless of internal microphone variations.

Figure 4 shows the typical data for the minimum detection level, a Standard EM series microphone with integral capacitor, and an EM microphone with modifications to optimize EMI suppression across the frequency range of interest.

For additional details on the methodology for testing RF immunity, please refer to IEC 118-13, Hearing Aids- Electromagnetic Compatibility and to IEC 1000-4-3, Testing and Measurement Techniques for Electromagnetic Field Immunity Testing.




EM microphone with integral capacitor dark blue line),
EM microphone with modifications to improve RFI suppression (blue line), and
Sensitivity curve for the minimum detection level (light blue line)

## Conclusion

The hearing aid industry is faced with new challenges due to the explosion of mobile phone transmission systems and the subsequent ingress of modulated digital signals. Any small wire or circuit board trace inside the hearing aid can act as an antenna to pick up unwanted RF signals. Care should be taken to keep all leads twisted and as short as practical. The entire hearing aid housing should be completely shielded if at all possible. As any interfering signal is most intrusive if injected at the input stage before system amplification, special consideration is necessary to suppress signals at the microphone preamplifier stage.

Knowles Electronics has investigated various alternatives for the suppression of EMI in microphones. After testing and evaluation, several solutions have been combined into Knowles products resulting in a wide degree of of suppression across the spectrum from 100MHz to 6GHz. Additional research is underway to improve RFI suppression for the current frequency bands and anticipated higher frequency bands of tomorrow's mobile phones.

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Knowles Electronics, Inc.
1151 Maplewood Drive
Itasca, Illinois 60143
Phone: (630) 250-5100
Fax: (630) 250-0575
www.knowles.com

Knowles Europe
York Road, Burgess Hill
West Sussex, RH15 9TT, England
Phone: (44) 1444 235432
Fax: (44) 1444 248724

Knowles Electronics Taiwan, Ltd.
53 Pao Hsing Road
Hsin Tien City, Taipei, Taiwan
Republic of China
Phone: (886) 2 2911 4931
Fax: (886) 2 2918 6868

Knowles Electronics Japan KK
Kyodo Bloom Building
19-1 Miyasaka 2-Chome
Setagaya-Ku, Tokyo 156-0051, Japan
Phone: (81) 3 3439 1151
Fax: (81) 3 3439 8822

Micromax Pty. Ltd.
P.O. Box 1238
Wollongong N.S.W.
2500, Australia
Phone: (61) 2 4226 6777
Fax: (61) 2 4226 6602