Testing for Radio-Frequency Common Impedance Coupling (the "Pin 1 Problem") in Microphones and Other Audio Equipment

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ABSTRACT

It has been shown that a primary cause of VHF and UHF interference to professional condenser microphones is inadequate termination within the microphone of the shield of the microphone's output wiring, a fault commonly known as the pin 1 problem. Tests using only audio frequency test signals generally fail to expose susceptibility to radio frequency (RF) interference. Simple RF tests for pin 1 problems in microphones and other audio equipment are described that correlate well with EMI observed in the field.

INTRODUCTION

Brown and Josephson recently studied the susceptibility of capacitor microphones to VHF and UHF fields [1]. A variety of contemporary and vintage microphones were tested, and the results were summarized. They concluded that interfering signals entered the microphones by two principal mechanisms. Those mechanisms were 1) common impedance coupling caused by improper termination of the cable shield within the microphone, a fault that Neil Muncy named "the pin 1 problem;" [2] and 2) inadequate differential mode bandpass filtering and/or decoupling of the balanced signal pair.

Common impedance coupling occurs when currents from two circuits flow through an impedance that is common to both circuits. [3] Good engineering practice calls for the cable shield to have a very low impedance connection to the shielding of the microphone. In a typical microphone, pin 1 of the microphone's internal XL3 connector (the designated shield contact) is connected via a short wire to the connector's retaining screw. A connection is also usually made from pin 1 to circuit common.

At audio frequencies, both connections are electrically short, and very little voltage drop occurs across the short wire connecting pin 1 to the microphone shell. At radio frequencies, however, the same short path between pin 1 and the mic enclosure can have an inductive reactance on the order of 4 ohms at 100 MHz. Current flowing on the cable shield (for example, current resulting from the cable acting as a receiving antenna) produces a voltage drop across this inductance. If pin 1 is also connected to circuit common, that voltage will be coupled into the audio path. The same sort of design error is also common in audio input, signal processing, and power amplifying equipment. Common impedance coupling can be avoided by connecting circuit common to the shielding enclosure, rather than to pin 1.

A more thorough discussion of this issue, complete with photographs of several examples of this defect in microphones is included in [1]. That paper also notes that the conductive path terminating the shield acting as an antenna will radiate RF inside the equipment, where other wiring, also acting as an antenna, will couple it to circuitry that can detect it or amplify it for detection by a subsequent stage. This mechanism is reduced by making the path very short. It is also reduced by making the connection to the outside of the shielding enclosure, because skin effect will confine shield current to the outside surface of the enclosure. [3]

A simple test for pin 1 problems [4] at audio frequencies uses a rectified low-voltage 50 or 60 Hz sine wave produced by a typical "wall-wart" mains power stepdown transformer, current-limited to about 100 ma, to drive between pin 1 and the equipment shield. This test is quite effective where the common impedance is sufficiently large at audio frequencies. It is rarely able to expose common impedance coupling at radio frequencies caused by the small self inductances noted above.

TESTING INPUT AND OUTPUT EQUIPMENT

To diagnose pin 1 problems at radio frequencies, an RF generator is required. If the device under test (DUT) is an input circuit (for example, a microphone preamplifier), the generator is simply connected between pin 1 and the shielding enclosure of the DUT, and the output of the DUT is monitored using headphones or an oscilloscope. Audio equipment is most sensitive to a change in the strength (amplitude modulation) of an RF signal. Thus, to make the RF test most sensitive, an amplitude modulated (AM) generator should be used. Most RF generators are capable of sine wave modulation at 1 kHz. Amplitude modulation can also be simulated by switching the generator on and off, in which case the switching transient will be heard as a click.

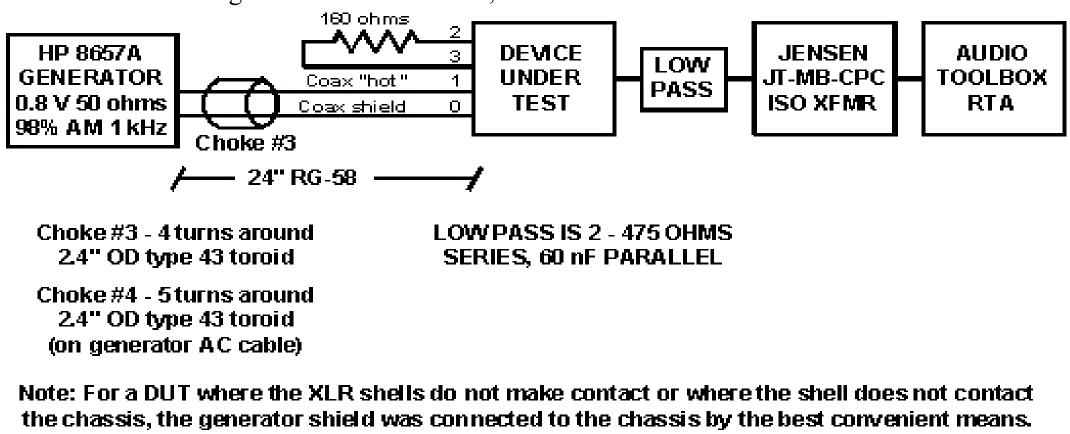

Figure 1 - The test setup for an input circuit

The Hewlett Packard model 8657A used as a signal source is a synthesized generator rated for +13 dBm into 50 ohms between 1 MHz and 1 GHz. Its output is derated by 3 dB between 100 kHz and 1 MHz. It can be amplitude or frequency modulated by its own internal generator at 400 Hz or 1 kHz, or by an external generator. When driving a near short circuit at 1 MHz, it is capable of an unmodulated output of about 50 mA rms. With this load and 100% modulation, the average RF output is about 25 ma. It has been shown that these currents are roughly 6 dB greater than those likely to be induced in exposed audio lines (that is, lines not enclosed by grounded metallic conduit) of comparable length at a distance of 1 mile from an omnidirectional 50 kW AM broadcast transmitting antenna. [2]

The generator, set for 98% amplitude modulation at 1 kHz of an 800 mV carrier, was varied in frequency over the range of 100 kHz to 1 GHz MHz in steps sufficiently small to note variations in susceptibility with frequency. At each frequency, the level of the detected 1 kHz signal, if any, was noted.

TESTING MICROPHONES

If the DUT is a microphone, the RF generator must drive the impedance between pin 1 and the shielding enclosure of the microphone, but the microphone must also be connected to a preamplifier so that interference can be observed. Before using the preamplifier to test microphones, the immunity of the preamplifier must be verified. The microphone test setup is shown in Figure 2.

The Real Time Analyzer function of an Audio Toolbox was used as an audio voltmeter preceded by the built-in one-third octave bandpass filter corresponding to the 1 kHz modulation frequency of the RF generator. This permits accurate measurement of the demodulated interference at levels that are barely audible and very close to the noise floor.

The isolation networks have several purposes. They must 1) allow audio, including detected radio frequency interference, to pass from the microphone to the preamplifier and voltmeter (Audio Toolbox), and allow the preamplifier to provide phantom power to the microphone; 2) prevent the cable shield from being loaded as an antenna by the generator, so they must block shield current; and 3) decouple the signal conductors from the microphone so that any shield current that does flow is not coupled to the signal pair as shield current induced noise. [5]

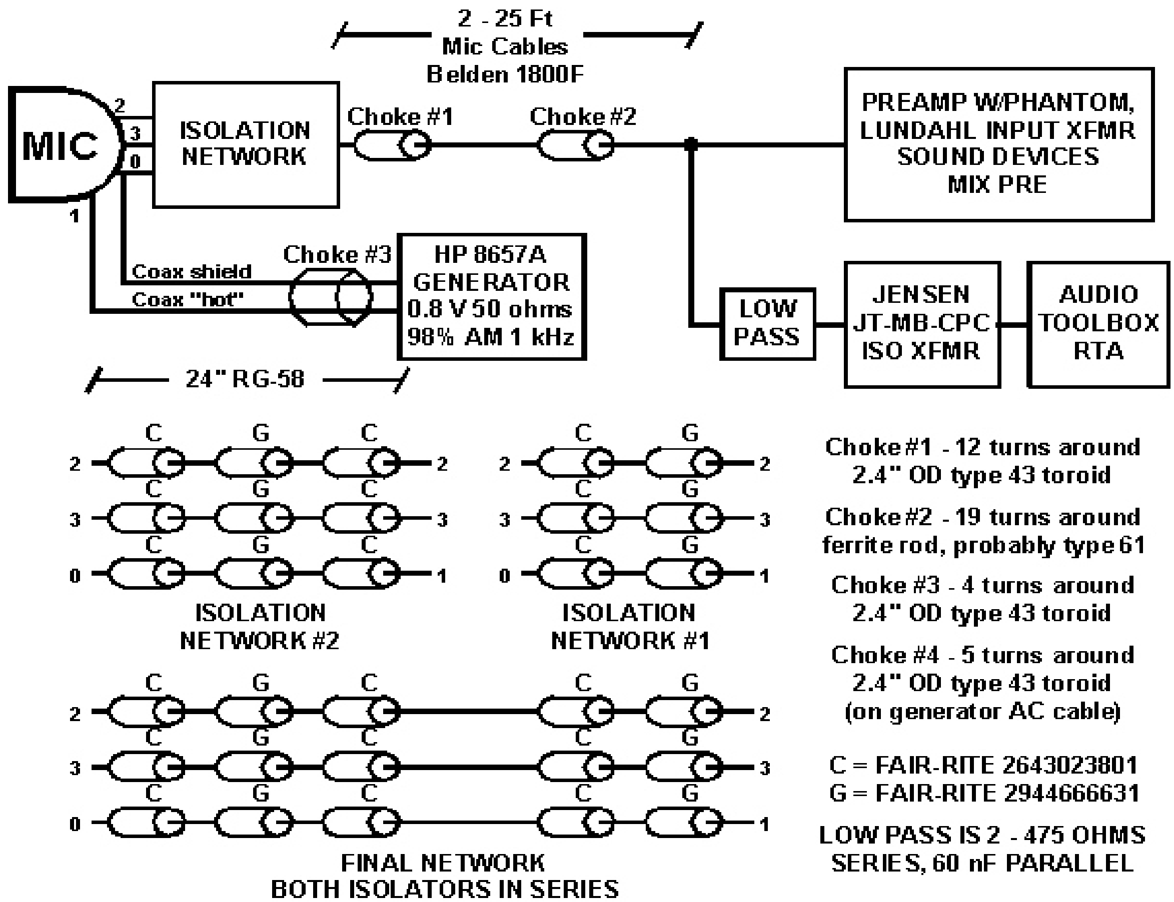

Figure 2 - The microphone test setup

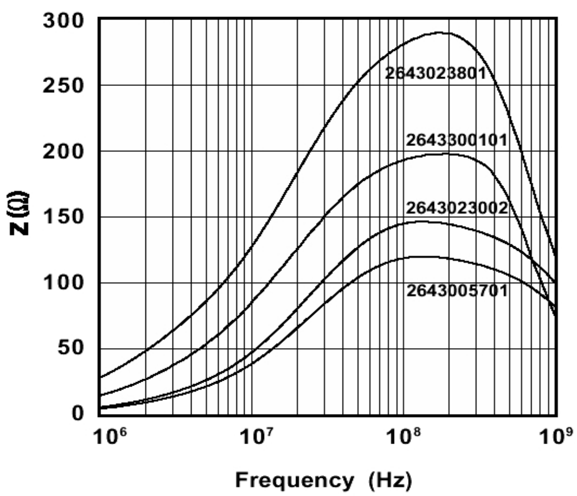

Figure 3 - Impedance of four beads of varying size and shape using type 43 material. The upper curve is for the largest of the group, which is the type C bead used in the isolators.

FERRITE BEADS

The chosen solution for the isolation networks was a brute force filter using multiple NiZn ferrite beads on each conductor. Many variations of ferric compounds are used to make these beads, each optimized for different frequency ranges and uses. When a conductor is passed through one of these very useful components, its inductance is greatly increased over a broad frequency range by the permeability of the ferrite, which, depending on the compound and the frequency, can range between about 20 and 10,000. The permeability and the losses in the ferrite vary with frequency. The approximate equivalent circuit of a wire passed through a bead is series inductance and resistance, both of which vary with frequency. Typical ferrites make the wire strongly inductive at the lower portion of their useful frequency range but, with increasing frequency, the inductive component decreases in magnitude and the ferrite becomes increasingly lossy. In effect, the bead causes the wire passed through it to act as an RF choke at lower frequencies, a resistor at higher frequencies, and a lossy (low Q) choke in the transition region. The responses shown in Fig. 3 and 5 are typical of many beads.

Within the spectrum where these beads have high permeability, magnetic flux is confined to the bead, so physical symmetry has little effect on circuit performance. The resistivity of these materials varies widely. Some have very high resistivities, and can be used with multiple turns of bare wire with no problem. Others have very low resistivity, requiring the use of insulated wire for multi-winding uses. The beads used here were Fair-Rite type 43 and type 44 materials, which have resistivities of $1x10^5$ and $1x10^9$ ohm cm respectively. It was determined experimentally that the beads made of type 44 materials on bare wires on adjacent conductors can be allowed to touch without degrading circuit performance, while those using type 43 materials cannot. The wound bead uses type 44 material.

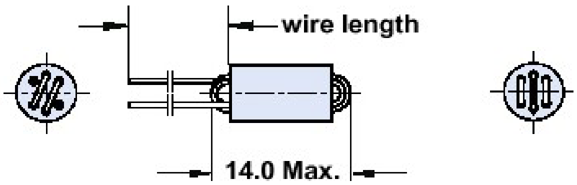

Figure 4 - The wound bead used in the isolators. Dimensions are mm

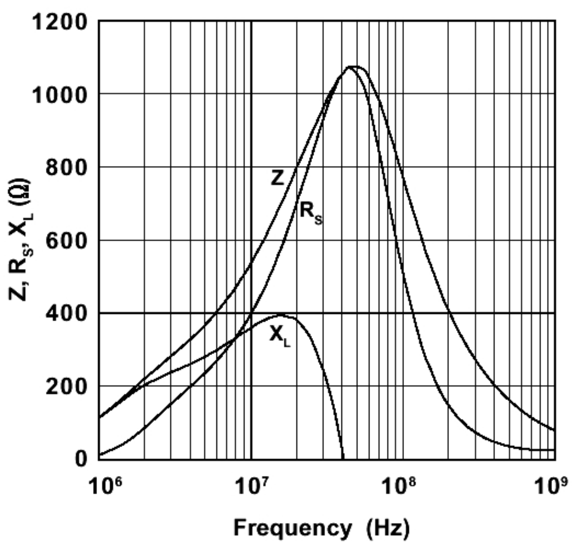

Figure 5 - Impedance of the multi-turn bead used in the isolators, identified as type G in Figure 2.

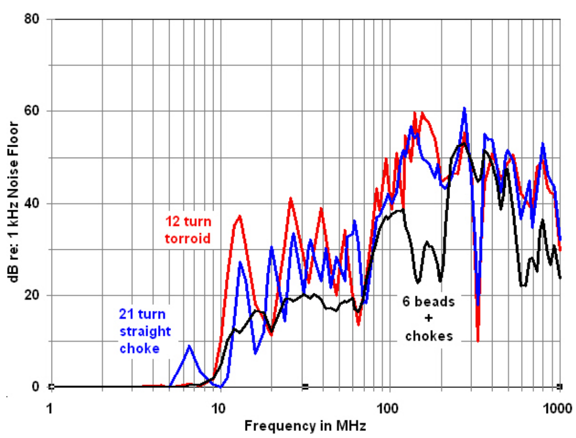

Figure 6 - Pin 1 susceptibility of mic TS-2-15 measured with early test setups

The isolation networks must be taken seriously if good data are to be obtained over a broad range of frequencies. The earliest work on this project was done with no isolation networks at all. Next, the mic cables leading to the preamp were wrapped around ferrite cores to form common mode chokes, with the hope of increasing the impedance and thus reducing current flow on the shield. Next, several generations of isolators were tried, using varying numbers of surplus beads of unknown origin on each conductor (believed to be #43 material). Results as shown in Figure 6 for a typical mic were inconsistent, with many peaks and nulls believed to be the result of inadequate isolation from the cable leading to the preamp, but each time the isolation was increased the data got cleaner. The early bead isolators were abandoned, and a broad variety of bead samples were ordered from a major manufacturer. Both common mode chokes were retained in the final setup.

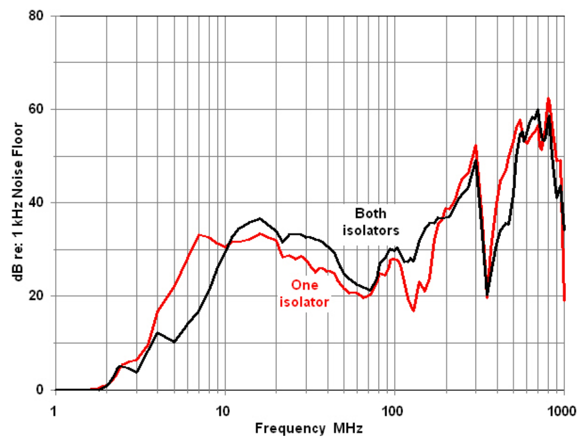

Figure 7 - Pin 1 susceptibility of mic TS-2-15 measured with the final test setup

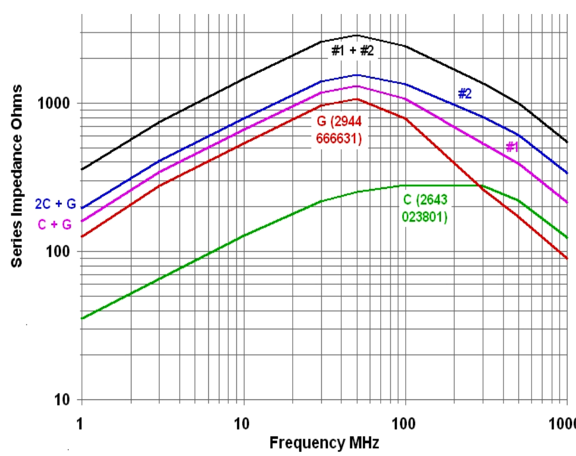

Figure 8 - Impedance of type C and G beads, individually and in various combinations

The manufacturer's impedance vs. frequency data for the most promising beads were transferred to a spreadsheet, labeled A through J, and plotted both individually and in various series combinations. Figure 8 shows the impedance of the chosen beads. The first isolator constructed used one type C bead and one type G bead on each conductor. The total impedance of each conductor is the third curve from the bottom of Figure 8.

Two bead types were selected from more than 50 that were made available to the author as samples. Type G (Fair-Rite 2944666631) is a multi-turn wound bead, whose dimensions and impedance are shown in Figures 4 and 5. The type C bead (Fair-Rite 2643023801) is a 23-mm long cylinder of 5-mm outside diameter and 1.5-mm inside diameter made from type 43 material. When multiple beads are placed in series, their impedance is approximately equal to the sum of their individual impedances (ignoring stray reactances at UHF).

The first isolator resulted in much cleaner data, but it appeared that there was still room for improvement. A second isolator was constructed using two type C beads and one type G bead and placed in series with the first isolator. The top curve in Figure 8 is for the two isolators in series, while the curve below it is for the second isolator alone.

Beads have almost no effect in the audio spectrum -- they introduce no losses at low frequencies and the inductance of the wire passed through them is usually too small to be significant. If the impedance of the "brute force" double isolators shown in Figure 8 were interpolated down in frequency at the same slope as the 1 MHz to 10 MHz decade, it could be expected to be on the order of 80 ohms at 100 kHz and 15 ohms at 10 kHz.

FIELD TESTING

In addition to the laboratory testing, microphones and other equipment were exposed to strong radio frequency fields from nearby transmitters, so that laboratory data could be correlated with practical conditions of use. Two tests were arranged. First, all of the microphones were set up in an open field about 600 m from a 50 kW broadcast station transmitting on 720 kHz with single vertical antenna of 195 electrical degrees height. A second 50 kW transmitter on 780 kHz was at 2 km distance with a comparable antenna. These transmitters are the most powerful used in the United States for standard AM broadcasting (540-1700 kHz). The microphones were set up on stands and connected alternately by 40 m lengths of foil/drain shielded cable and braid/drain shielded cable to the Sound Devices preamp. The cables were suspended approximately 1.5 m above the ground by portable loudspeaker stands. Prior to testing the microphones, the Sound Devices preamp was tested with a dynamic microphone and found to be free of interference. The Audio Toolbox was tested in the same setup. It was found to be free of interference with the braid-shielded cable, but it received significant interference with the foil/drain cable.

In the second series of field tests, the selection of microphones and equipment was set up at an amateur radio "Field Day" site. For this annual 24-hour long event, groups of "ham" radio operators throughout North America set up multiple transmitters, temporary antennas, and emergency power generators in places like public parks, mountain tops, and farms as a test of their preparedness for emergencies.

At the site visited for this round of testing, transmitters were in use at 1.8 MHz, 3.5 MHz, 7 MHz, 14 MHz, and 28 MHz. All operated at radiated power levels on the order of 100 watts using dipole antennas about 8 m above the ground. Microphones were set up on 2-m stands directly under the antennas, and the 24-m long mic cables were run directly under the antennas and approximately parallel to them to the battery powered preamplifier. The mic cables were held about 1.5 m off the ground by portable loudspeaker stands. The presence or absence of interference was observed on headphones connected to the mixers or other DUT. The mics and other equipment were tested separately with both foil/drain and braid/drain shielded cables.

Several conditions were common to all field tests. The cables were wired per AES14 -- that is, the shield was connected only to pin 1. The shielding enclosure of the input equipment was bonded to local ground. For the 720 kHz tests, this was a rod driven about 1 m into relatively moist earth (there had been recent rain). For the "Field Day" tests, it was the system ground established for the transmitters. Providing a ground establishes shield current that would be roughly comparable to the installation of exposed (that is, not in metallic conduit) wiring in a typical church. While the resistive impedance to earth may be higher than in a well grounded building, the inductive component in these tests is much less because the ground cable is only about 2 m in length. Microphones were grounded only via the cable connecting them to the preamp. When the DUT was input equipment (mixers and the DAT machine), it was fed by a dynamic microphone. For all tests, only a single microphone and cable were connected to the input equipment at one time.

Field test results are summarized in Tables 1 and 2 of the companion paper [6]. In the interest of brevity they are not repeated here. For these tests, the level of interference was evaluated by the author on a 12-step subjective scale, ranging from inaudible to extremely severe. Those steps were then converted to whole numbers, with 0 being no interference and 11 being extremely severe. The three highest steps corresponded to interference that was so severe that it shut down a gain stage to the extent that the mic could not be heard and caused circuit instability. All of the amateur radio transmitters used Morse code (the radio signal is switched on and off in temporal patterns that correspond to alphanumeric characters), so the transmission was equivalent to 100% modulation of the signal with a relatively fast switching waveform. For the most part, interference is heard as clicks, but under some conditions, it will be accompanied by hum. Josephson has hypothesized that this hum may be the ripple in the phantom supply due to the stage losing CMRR as a result of RF detection in the input devices. [1] Whitlock has observed that hum will be added to detected RF by modulation of the RF current when it travels through the power supply. [7] He has identified the cause as modulation of the RF impedance of that rectifier diodes by the ac signal. At the highest levels the interference is causing fundamental overload. It is most likely that the transition to instability occurs somewhere above where overload begins.

As previously noted, the Sound Devices preamp responded with a high pitched squeal in the presence of the 3.5 MHz and 7 MHz transmitters, a common symptom of oscillation. The high frequency oscillation observed with a few microphones at 1.8 MHz and 3.5 MHz sounds suspiciously like this squeal. It is possible that the interference noted at 1.8 MHz for microphones TL1-1-10 and TS3-1-10, and the interference noted at 3.5 MHz for TMO7 might be caused by the preamplifier and not the microphones.

MICROPHONE RESULTS

A wide variety of microphones was tested, including many of those tested by other means in the lab and in the field for VHF/UHF susceptibility. [1] Designations established for that paper to describe and identify the microphones are used here. Two new microphones were added to the group of test subjects. DS3-2-25 is a small diaphragm cardioid similar in electrical design to DL3-1-10. DS1-2-10 is quite similar to DS1, but optimized for vocal use by reduced input sensitivity and the addition of a windscreen. DS1-2-10 was available for the VHF/UHF tests, but not tested because it was believed then to be identical to DS1. It was subsequently learned that DS1 has a plastic XL shell that makes no contact with the mating connector shell, requiring a unique adapter to include it in this research. Rather than construct another adapter, it was decided to add the vocal mic to the test. Some of the microphones tested for [1] were not available for inclusion in the current work. Others were omitted simply because there wasn't time to include them.

With some microphones, no tone was detected at some test frequencies, but switching transients were heard as the carrier was switched on and off. With mics having the best performance, neither detected 1 kHz modulation nor switching transients were heard over much of the spectrum.

Microphones from manufacturer #1 performed similarly in the field tests (Figure 9). All were free of interference from 720 kHz, 7 MHz, 14 MHz, and 28 MHz transmitters. TL1-1-10, TL1-2-10, DL1-1, and DL1-2-10 received only mild interference at 1.8 MHz and 3.5 MHz. DS1 received extremely strong interference at 1.8 MHz and moderately strong with foil/drain cable and slight interference at 3.5 MHz with braid cable, but none at 3.5 MHz with foil/drain cable and none at 1.8 MHz with braid shielded cable. Its near twin, DS1-2-10, received strong interference at 1.8 MHz and moderately strong interference at 3.5 MHz with foil/drain cable, but none at 1.8 MHz, and very slight interference at 3.5 MHz with braid shielded cable. The fact that interference is much greater with the foil/drain shielded cables suggests that the susceptibility at 1.8 MHz and 3.5 MHz is the result of SCIN, but research reported in [6] suggests otherwise. Instead, Fig 9 suggests that the microphone has a pin 1 problem at these frequencies. This is one of the few instances of questionable correlation of the data.

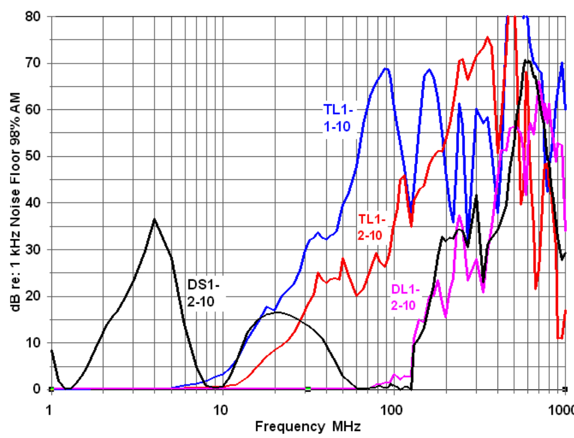

Figure 9 - Pin 1 susceptibility for microphones from manufacturer #1

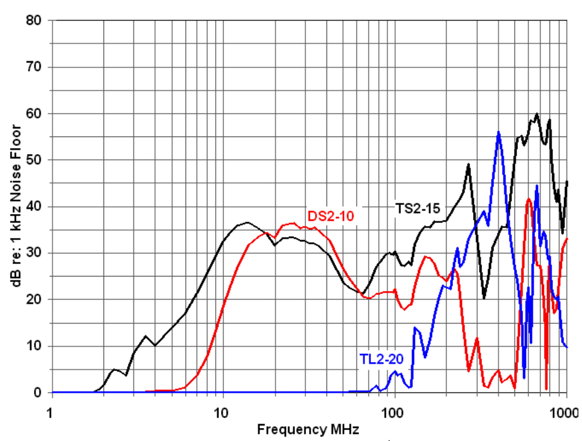

Figure 10 - Pin 1 susceptibility for microphones from manufacturer #2

Microphones from manufacturer #2 (Figure 10) performed quite differently. TL2-20 received no interference in any of the field tests reported on here, but did have some susceptibility at VHF and UHF, as reported in [1]. Figure 10 is consistent with this result. Parallel research [6] suggests that longer mic lines could have put it over its threshold for detection at 720 kHz. On the other hand, DS2-10 received strong to very strong interference at 1.8 MHz, 3.5 MHz, 14 MHz, and 28 MHz, while TS2-15 received strong to extremely strong interference from all the transmitters except the 720 kHz broadcast station.

The interference received by TS2-15 and the lack of interference to TL2-20 are consistent with their pin 1 susceptibility, as shown in Figure 10. The interference received by DS2-10 at 14 and 28 MHz is consistent with both its pin 1 susceptibility and susceptibility on the signal pair as measured in parallel research. [6] But neither pin 1 nor signal pair susceptibility explains the strong interference at 1.8 MHz and 3.5 MHz. Perhaps the cause is the combination of pin 1 and differential mode susceptibility.

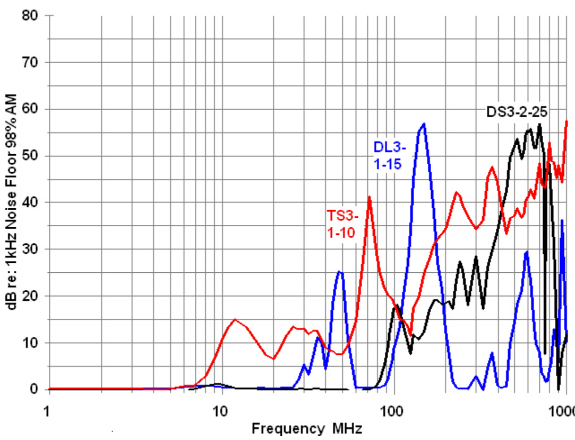

Figure 11 - Pin 1 susceptibility for microphones from manufacturer #3

Two relatively new microphones from manufacturer #3 (Figure 11) measured and performed similarly. The newest model, DS3-2-25, received moderate interference from the 720 kHz and 1.8 MHz transmitters, strong interference at 3.5 MHz, mild interference at 7 MHz, very strong interference at 14 MHz, and none at 28 MHz. Microphone DL3-1-15 received moderate interference at 720 kHz and 1.8 MHz, strong interference at 3.5 MHz, none at 7 MHz, extremely strong interference at 14 MHz, and none at 28 MHz. The data do not show significant pin 1 susceptibility below 30 MHz, and none below 10 MHz.

An older model, TS3-1-10, received mild interference below 10 MHz, but strong interference at 14 MHz and 28 MHz. Parallel research [6] explains why these mics received interference -- their susceptibility to voltage coupled onto the signal pair in the lab tests correlates almost perfectly with the field data. In other words, they provide inadequate filtering of the signal pair.

Both microphones DS4 and DL4-2-10 (Figure 12) received interference only with foil/drain cable, not with braid cable. Microphone DL4-2-10 received moderate interference only from the 720 kHz broadcast transmitter, while DS4 received moderately strong interference at 720 kHz, strong interference at 1.8 MHz, and mild interference at 3.5 MHz, but none at 7, 14, or 28 MHz. Figure 12 does not show significant pin 1 susceptibility. Parallel research reported in another paper [6] explains why these mics received interference -- their susceptibility to voltage coupled onto the signal pair in the lab tests correlates almost perfectly with the field data.

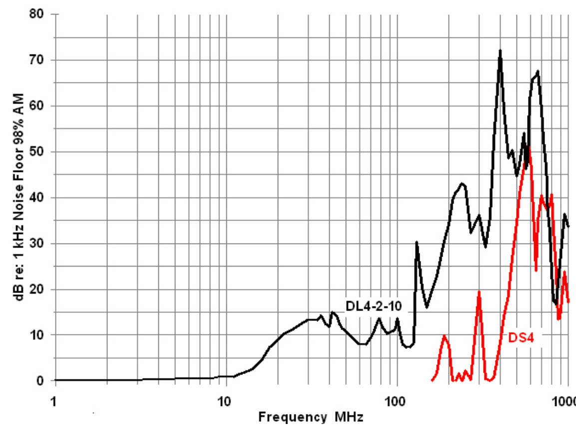

Figure 12 - Pin 1 susceptibility for microphones from manufacturer #4

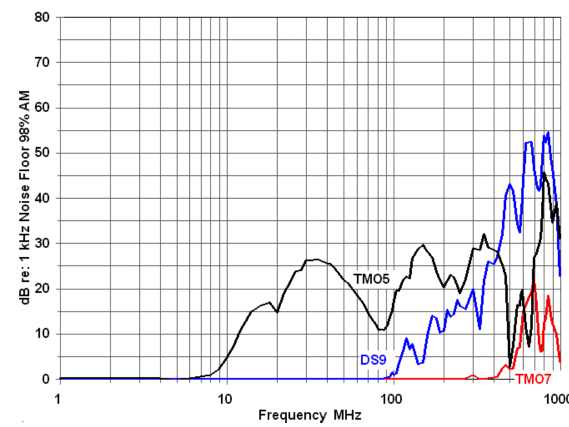

Figure 13 - Pin 1 susceptibility for microphones from manufacturer #5, 7, and 9

Microphone TMO5 was free of interference below 10 MHz, but received moderately strong interference at 14 MHz and 28 MHz. Figure 13 and parallel research [6] suggest that susceptibility is probably due to a combination of a pin 1 problem with inadequate filtering of the signal pair. Microphones TMO7 and DS9 encountered no interference in any of the field tests. This result is consistent with Figure 13.

Interface of a microphone or other equipment to the outside world is only part of the susceptibility problem. Once inside the enclosure, RF must be coupled to some piece of active circuitry where it is converted to audio by detection (demodulation). Detection and coupling mechanisms are discussed at length in [1].

The coupling path will have some complex response based on a set of circuit parameters relating to circuit layouts and component stray reactances that are unique to each product. Small changes inside a product can significant affect immunity. Figure 14 shows the difference in susceptibility between the omni and cardioid pattern settings of two switchable pattern microphones.

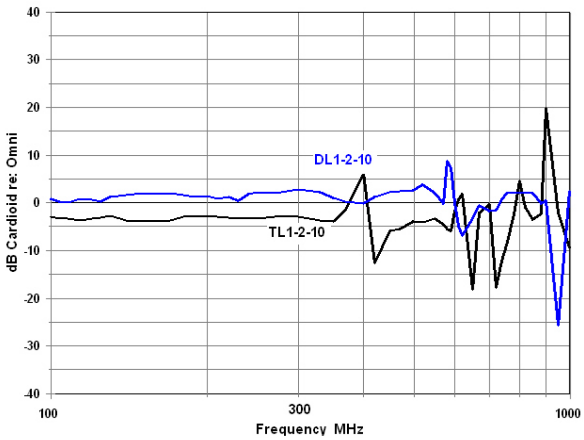

Figure 14 - Difference in Pin 1 susceptibility between omni and cardioid patterns of two switchable pattern microphones

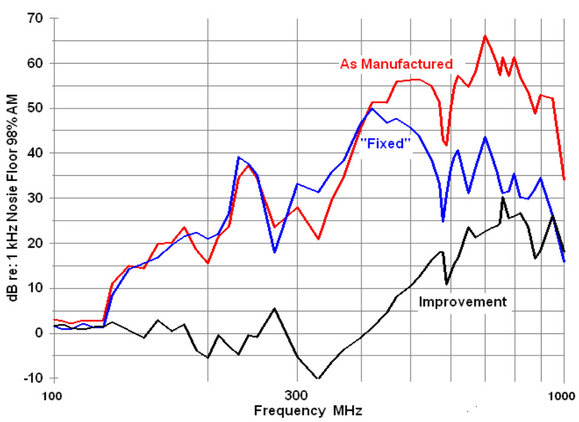

Figure 15- Result of moving one wire on microphone DL1-2-10

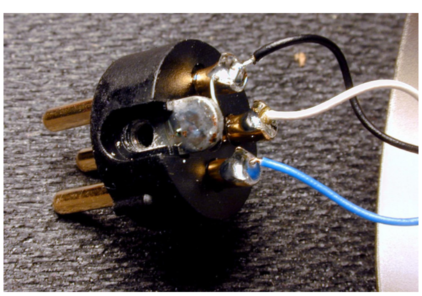

Figure 16 - Pin 1 termination in DL1-2-10 as manufactured

Figure 15 shows how one microphone with a pin 1 problem at VHF and UHF can be improved simply by moving the wire connecting the circuit board to pin 1. As shown in Figure 16, pin 1 is connected to the shielded enclosure by the tiny wire to the connector retaining screw, and via the black wire to the circuit board. An ohmmeter also reveals that there is at least one other connection between the black wire and the enclosure. For the earlier research, the black wire was removed from pin 1 and connected to the enclosure, as shown in Figure 17. A more serious engineering effort (for example, choosing the optimum point on the circuit board to connect to the enclosure and where on the enclosure to connect it, and improving the bond between pin 1 and the enclosure) could undoubtedly make much greater improvements. Whitlock has recommended making the circuit board connection to the shielding enclosure at a point very close to the capsule. Other problems associated with connector wiring in this microphone are noted in [6].

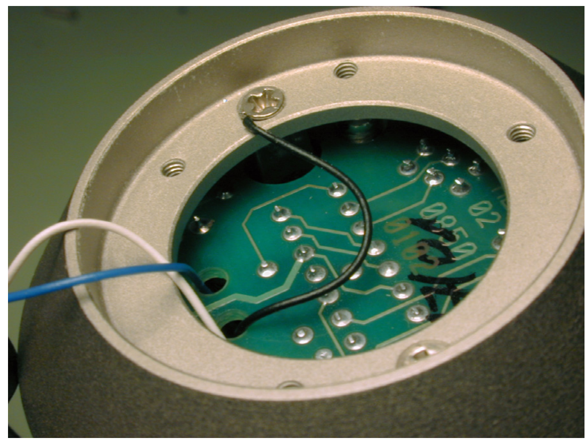

Figure 17 - New location for the black wire that was connected to pin 1 in microphone DL1-2-10

EQUIPMENT TEST RESULTS

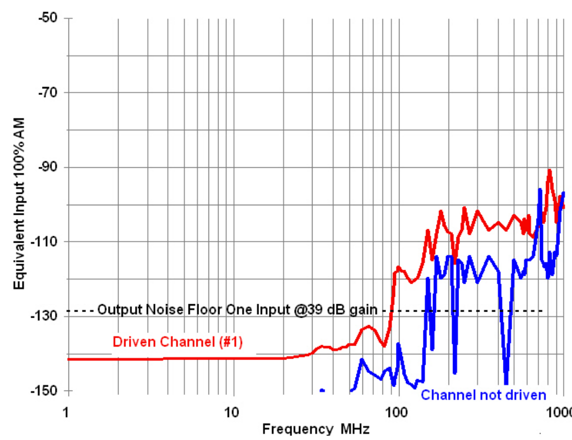

Figure 18 - Pin 1 susceptibility of the Sound Devices Mix Pre used for microphone testing. Pin 1 of channel 1 was driven and delegated to channel 1 out, channel 2 was delegated to channel 2 out, and both channels were set for 39 dB gain

Susceptibility of the Sound Devices Mix Pre is shown in Figure 18. When exposed to the transmitters, the unit performed well. The only interference noted was some audible squealing in response to the 3.5 MHz and 7 MHz transmitters. A few of the microphones tested responded with similar squealing at 1.8 MHz and 3.5 MHz, as did some of the input equipment at some frequencies. [In the field tests, the input equipment was tested only with dynamic microphones to insure that microphone susceptibility would not cloud the result.]

In addition to the Sound Devices and Audio Toolbox units used in the test setup, four small mixers, a portable DAT recorder, and a 2-channel compressor/limiter were tested. All mixers were from the same manufacturer, but were manufactured over a period of about five years during which the manufacturer was struggling to solve serious problems with susceptibility in this series of mixers, especially to AM broadcast stations around 1.5 MHz. The mixer shown in Figure 19 is from the problematic group. The mixer shown in Figure 20, introduced about three years ago, significantly reduced the number of complaints. The mixers of Figures 21 and 22 were introduced about a year later.

An examination of Figures 19-22 shows that manufacturer #10 has made significant progress in reducing its pin 1 problems. Figure 20 shows good performance below 7 MHz, an improvement of about 30 dB over Figure 19. But things are much worse between 10 MHz and 150 MHz. The mixer shown in Figure 20 received so much interference in downtown Chicago from broadcast transmitters of only moderately high power in this spectrum (TV channels 2 and 5 and FM broadcast) that it was unusable for the VHF/UHF tests described by [1].

Unfortunately pin 1 immunity alone is not sufficient to prevent interference, and all of these mixers received serious interference in the field tests. Parallel research shows why - all of the units have very poor rejection of RF on the signal pair. [6]

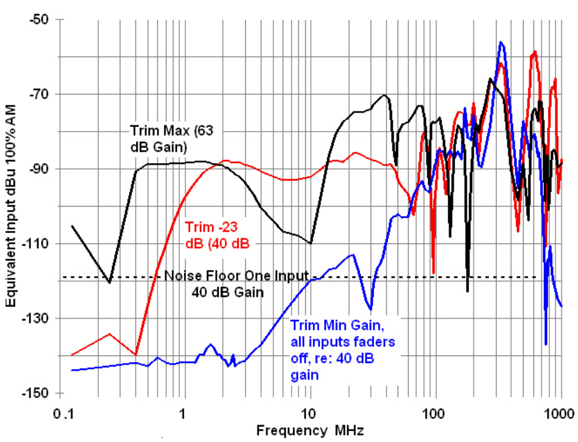

Figure 19 - Pin 1 susceptibility of 4-input mixer from manufacturer #10. Only pin 1 of channel 1 was driven for all tests.

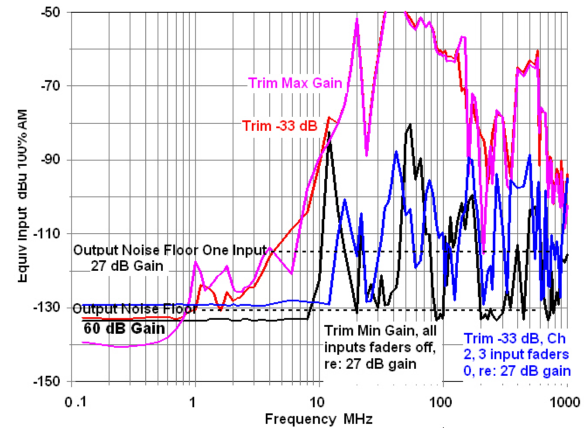

Figure 20 - Pin 1 susceptibility of 16-input mixer from manufacturer #10. Only pin 1 of channel 1 is driven for all tests.

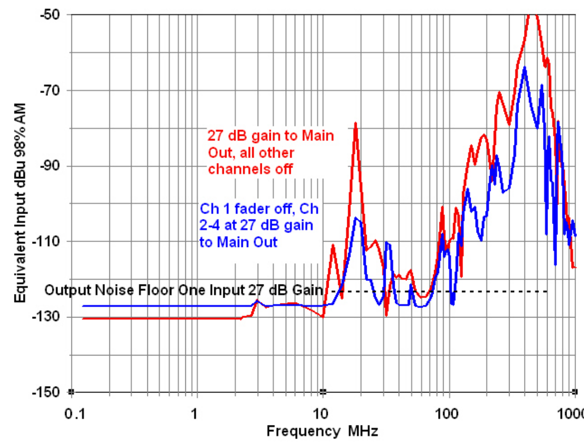

Figure 21 - Pin 1 susceptibility of a newer 4-input mixer from manufacturer #10. Only pin 1 of channel 1 is driven for all tests.

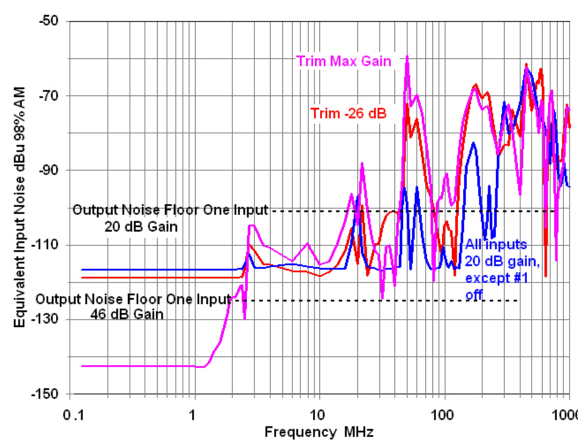

Figure 22 - Pin 1 susceptibility of an 8-input mixer from manufacturer #10

Figure 21 shows further improvement below about 110 MHz in the newer 4-channel mixer, but there is still considerable coupling into the circuit board above about 200 MHz. Figure 22 seems to show a step backwards (or may be an earlier design). Here, susceptibility begins rising at 20 MHz and approaches the levels of the first 4-channel mixer. One piece of good news is that the unit has good pin 1 immunity in the AM broadcast band.

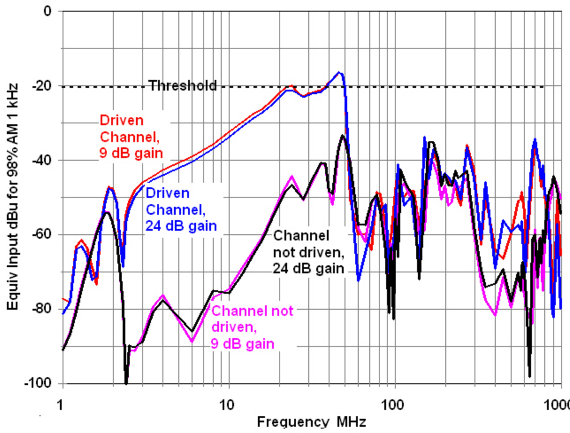

Figure 23 - Pin 1 susceptibility of a two-channel compressor/limiter from manufacturer #11. Pin 1 of only one channel is driven, and gains are equal.

The 2-channel rack mount compressor/limiter shown in Figure 23 has a classic pin 1 problem. The input and outputs are via 1/4-inch connectors with plastic shells that insulate them from the chassis. The cable shield terminals (the sleeve of the connectors) go to the circuit board. This line level product has so much pin 1 susceptibility that the generator hit the threshold of compression between 20 and 50 MHz -- just right if you want to listen to citizens band radio in your audio system! This product was recently discontinued by its manufacturer.

This rack mount unit is powered by a "wall wart" style stepdown transformer with a two-prong plug. Some might argue that the 2-prong power plug prevents the flow of current on the shield since there is no ground path. The author fails to see the logic in this argument -- the product is intended to be rack mounted (which requires that it be grounded), there will be current flow through the unit to other wiring, and there will almost certainly be capacitive coupling between the unit and the power system via the capacitance of the power transformer.

Figure 24 illustrates a common characteristic of pin 1 problems. Not only is the interference present in the channel whose wiring carries the shield current, but it is also very strongly present in other channels.

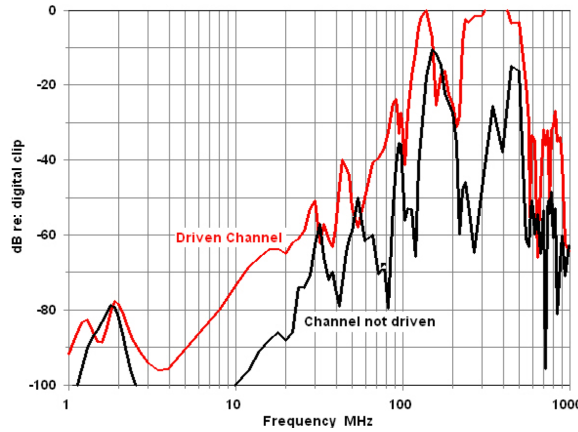

Figure 24 - Pin 1 susceptibility of a portable DAT recorder from manufacturer #12. Pin 1 of channel two is driven, gains of both channels are set for mic level at 35 dB below their maximum. At this gain setting, the input stage clips at -15 dBu and digital clip (to tape) is reached at -19 dBu..

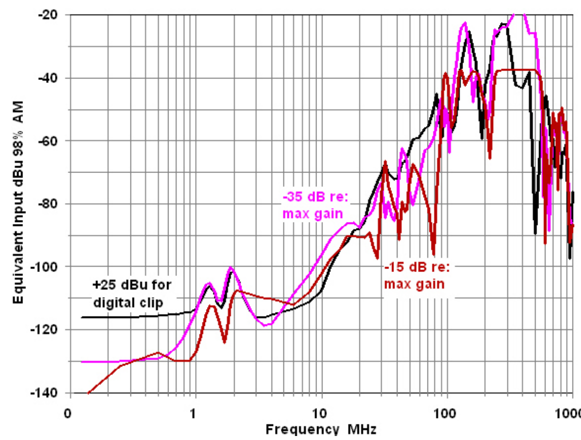

Figure 25 - Pin 1 susceptibility of the same portable DAT recorder for the driven channel expressed as equivalent input noise. The flat-topping of the highest gain curve is the input stage clipping.

The portable DAT recorder shown in Figures 24 and 25 has acceptable pin 1 immunity below about 5 MHz, but immunity degrades severely above 20 MHz. It performed very poorly in field tests, and parallel research [6] shows that the cause is poor differential mode low pass filtering on the signal pair. At full input sensitivity it displayed very severe fundamental overload with the foil/drain shielded cables at all frequencies below 14 MHz, and very strong interference at 14 and 28 MHz. Reducing its input trim by 20 dB got it out of overload at some frequencies, but the interference was still extremely strong. Switching to the braid shielded cable helped some, but at only two of the test frequencies was the unit useable -- at 1.8 MHz with the braid/drain cable and at 28 MHz with the foil/drain cable.

ANALYSIS AND DISCUSSION

ACOUSTIC CONDITIONS

The acoustic conditions for the laboratory and field tests were not ideal. The grassy field where the 720 kHz tests were performed is less than 200 m from a major freeway and a busy local road. Typical levels were measured at 53 dBA and RC47. A church could be expected to be more than 10 dB quieter; a recording studio at least 20 dB quieter. The Field Day site was much better, at 37 dBA and RC30 during quieter hours when most of the measurements were done.

The noise level in the author's laboratory was 47 dBA, RC 42. The background noise level in the 1 kHz one-third octave band was about 35.5 dBSPL. The limiting factor was the RF generator's fan (which needed to be close to the microphone so that its output cable could be very short to minimize the effects of standing waves). There are also computers and support equipment.

Most detection below the point of fundamental overload has a square law response. Thus a 20 dB increase in the acoustic noise floor could be viewed as equivalent to a 10 dB reduction in sensitivity to the level of the RF signal, which in turn is equivalent to being 3.16X more distant from the transmitter. In other words, taking the acoustic noise floor into account, the test conditions are equivalent to being in a recording studio 1.9 km from the 720 kHz transmitter, or in a church at a distance of 1 km. Much less adjustment is needed for the acoustic conditions at the Field Day site, which was quieter than many churches, but noisier than most recording studios.

COHERENT SUMMING

Coherent addition of the detected signal can also significantly increase the severity of RF interference. Coherent addition occurs several ways. It can result from the detection of the same signal at multiple points in the equipment (for example, at multiple inputs of a mixer or at more than one stage in a signal chain). Detected RF (that is, audio) that is detected at multiple points within the same product is usually in phase. If detected at comparable points within a product (for example, in the input stages of multiple channels), it will also be in polarity. Detection can occur at multiple points within a signal chain that are out of polarity with each other, resulting in partial cancellation of the two detected signals. The relative magnitudes of the two signals will generally not maintain the same relative level over a broad range of frequencies, due to the frequency response between stages.

Addition can also occur at RF. The lower curve in Fig 26 shows pin 1 susceptibility in a mixer with 8 mic inputs and 4 line inputs with all the inputs at their nominal gain setting except the driven channel (channel 1), which is set for minimum gain and muted (that is, switched off of the buss). Here, the RF driven into pin 1 of channel 1 is coupling into the circuit board and showing up at the output buss.

In the tests reported here, only one channel was driven. Typical systems will have at least half as many microphones connected as there are input channels. If the microphone cables are run exposed (that is, not within grounded conduit), follow different paths, and are of approximately equal length, it is likely that equal levels of RF will be induced in each. To the extent that the induced signal is in phase at RF, it will add coherently. The lower the radio frequency of the interfering signal, the more likely the induced signal is to be in phase at the mixer. Thus, the 8-input mixer could see the coherent addition of RF currents from 4-8 microphones.

When signals sum coherently, they will add by 6 dB for each doubling of the number of signals of equal strength. When they add non-coherently, they add by 3 dB per doubling. Program audio received by multiple microphones will be non-coherent. Thus the ratio of received interference to program audio can increase by as much as 3 dB for each doubling of the number of inputs receiving interference and detection mechanisms.

The summing of RF paths to a common detection point is probably responsible for most of the narrowband peaks and nulls in the curves at VHF and UHF. Some of these peaks and nulls can also be part of the test setup. Because the short coaxial cable running from the generator to the DUT is driving a mismatched load, there will be strong standing waves on that transmission line, establishing peaks and nulls at various frequencies that may be shifted slightly up or down in frequency by the interaction of that transmission line with its termination at the DUT. This effect can be minimized by placing a resistive attenuator (pad) at the end of that line adjacent to the DUT. The pad terminates the line, reducing any standing waves to a much lower value, but with the obvious effect of reducing the current into pin 1. This option was not tried, since it was originally believed that it was necessary to have the greatest practical level of excitation to expose pin 1 problems.

The higher level of excitation may not be necessary. In fact, the data suggest that, especially at VHF and UHF, the test setup may be more sensitive to pin 1 susceptibility than is required. Future refinements of the test method suggest that an attenuator designed for a matched attenuation on the order of 6 dB could be used with good results. While the attenuation in the test would be significantly greater than the matched attenuation because the load (pin 1) approaches a short circuit, the peaks and nulls would be greatly reduced in magnitude.

SHELL CONTACT ISSUES

Several of the products tested made no contact with the shells of mating XL connectors or made erratic contact. Among those making erratic contact were microphones DS4, DL4-2-10, DS1-2-10, the Sound Devices preamplifier, and the DAT machine. To test these products, it was necessary to insert a small piece of wire between the two connector shells to force them to make contact.

The poor contact in microphones DL4-2-10 and DS4 was due to spray paint having been applied to the inside of the connector shell. Scraping the paint allowed the shells to make contact. To be effective, the EMC connector described in [1] must make good shell contact with a mating shell that is bonded to the shielding enclosure.

The shell contact failure in the MixPre is particularly troubling. Both the connectors integral to the unit and the mating connectors that failed to make contact are from the same major manufacturer.

All of the mix consoles from manufacturer #10 purposely made no contact with the connector shell. To drive pin 1, it was necessary to connect the generator shield to a 1/4-inch connector whose shell was mounted to the chassis.

The compressor/limiter from manufacturer #11 used plastic body 1/4-inch connectors as inputs and outputs, insulating the mating shield contact from the enclosure. To drive the shield contact the generator shield was returned to the chassis.

In field tests, the DAT machine received very strong interference from VHF television and FM broadcast stations at a distance of one mile from 20 kW transmitters. The special EMC connector was tried with this unit and was quite effective at reducing the interference -- <u>if</u> the shells were forced by hand pressure to make contact. If the hand pressure was released, the interference returned.

Some users, including those in the European broadcast and EMC community, have urged the use of XL connectors that make a DC connection of the shield to the shell of cable-mounted connectors, and some choose to make a connection only to the shell (as opposed to the designated shield contact, pin 1). Both practices are foolhardy. They are in conflict with IEC and AES standards, which are specifically written to prevent ground loops in the shields of audio wiring. In addition, the products that fail to provide shell to shell contact for mating connectors won't provide a termination for the shield that is the objective of these schemes. The microphone test circuit purposely used the shell contact for phantom power to minimize the influence of the cable to the preamp on the measurement. At least five of the microphones tested for this research simply did not operate in our tests because they failed to conduct phantom power through the connector shells.

DETECTION

For there to be an observable pin 1 problem, there must be a sufficiently strong source of interference, some means of detection, and some path between pin 1 and the means of detection at the frequency of the interference. The resulting interference can be reduced or eliminated by reducing the magnitude of any one or a combination of these factors. For example, it is possible to minimize detection by placing a suitable bypass capacitor across a semiconductor junction that would otherwise detect the interference. Detection can also be minimized by running cables in grounded conduit in installations where interference is strong enough to induce significant currents. Detection mechanisms are discussed at length in [1].

It was also noted in [1] that interference from FM signals is generally demodulated by slope detection -- that is, the FM signal is converted to AM when the gain (loss) within the signal path varies with frequency. Some have questioned how the gain can change enough to cause sufficient conversion in the relatively narrow bandwidth of a broadcast FM signal to cause detection. An examination of any of the susceptibility data shows strong slopes of gain vs. frequency. Even more pronounced slopes commonly result from the narrowband peaks and nulls caused by multipath (reflections) reception of signals.

CABLE-RELATED DIFFERENCES

In the field tests, significant susceptibility differences between foil/drain cable and braid cable are strong indications of inadequate filtering of the signal pair, and negative indicators of pin 1 problems as the cause of the susceptibility. The two cables used for all of the field tests were run in close proximity to each other and were essentially the same length, so the induced currents should be reasonably close to equal and the current flowing into pin 1 should be nearly the same for both cable types.

There are significant differences in SCIN performance between the two cable types up to at least 4 MHz, and those differences correlated with field test results for most of the microphones and input equipment tested. SCIN performance is discussed in depth in [5] and [6].

After studying the results of these measurements, it appears that the test setup might be improved to further remove differential mode susceptibility from the measurement at the highest frequencies by placing a capacitor across the signal pair at the microphone. It is likely that the inherent imbalance of an XL connector with respect to the coupling, both capacitive and inductive, would couple signal unequally from pin 1 to the two signal contacts. This effect may be responsible for some of the susceptibility measured in the UHF range.

PREVENTING SHIELD CURRENT FLOW

Interference coupled by pin 1 problems can generally be eliminated by reducing or eliminating current flow on the shield. A sufficiently large RF choke in series with the shield at the input of the victim electronics (that is, the device receiving the interference) will accomplish this result. At MF and HF frequencies this is readily accomplished by winding the signal cable around a toroidal or cylindrical ferrite core. At the 720 kHz test site, current flow was eliminated by adding the 25 ft microphone cable wound around the ferrite core to form choke #1 (see Figure 2) in series with the input of the device under test. This significantly reduced the strength of interference in most of the equipment tested. The author's improvised solution to his first encounter with VHF-TV interference to condenser microphones (around 1980) was to wrap the microphone cable several turns around the steel microphone stand adjacent to the microphone. This improvised choke was sufficient to reduce the interference below the level of audibility.

Passing a conductor through a cylindrical ferrite core forms a single turn choke. The effect provided by multiple ferrite cores along the same conductor is approximately additive, and the inductance is essentially proportional to the length of the core. The inductance of a multi-turn toroidal coil is proportional to the square of the number of turns, so when practical, a multi-turn coil is generally the easiest and most cost effective solution. Where the cable diameter is so great that it is not practical to wind it around a toroidal core (for example, a multi-pair cable) it may be practical to sufficiently reduce current to the level needed to eliminate the interference by passing the cable through multiple large toroidal cores of sufficient diameter to fit over the entire multi-cable.

Pin 1 problems on output wiring are also capable of coupling RF interference into audio equipment. The author has successfully eliminated moderately strong interference to consumer stereo equipment from his 100 watt ham transmitter operating on 3.5 MHz, 7 MHz, 10 MHz, 14 MHz, 21 MHz, and 28 MHz by the simple expedient of wrapping each of the loudspeaker cables three turns around a 1.4-inch OD, 0.9 inch ID toroidal ferrite core of #43 material. A separate core was used for each cable.

The 1.4-inch core is likely to be quite effective for a microphone input. It is possible to improvise such a 4-turn choke by passing a miniature mic cable (for example, one pair of a typical multi-pair cable) with a male XL connector attached without removing the connector. A greater number of turns could be wound by removing the XL connector and replacing it. The 12-turn choke with the full-size microphone cable was easily wound on the 2.4 inch core without removing the connector.

CORRELATION WITH VHF/UHF TESTS

To perform the correlation and understand the results of [1], it is important to understand the RF spectrum in the test environment. Thus, as part of that research, it was learned through spectrum analysis measurements that the predominant energy in that area is from television channels 2 and 5 (54-82 MHz) and from FM broadcast transmitters (88-108 MHz). The reason this is true is interesting. Television transmitting antennas must have a flat response over the entire bandwidth of their assigned channel (6 MHz in North America) to maintain good video quality. For television channels 2-6, that is, approximately 10% of the transmitting frequency. It is difficult to accomplish a sufficiently flat response over that high percentage bandwidth if the antenna has appreciable vertical directivity. The FM transmitters also use low gain antennas, but for a different reason. They are concerned with good building penetration to reach listeners in interior offices in downtown buildings, and they also need to avoid multipath distortion. Directional antennas are subject to the same grating lobes common to line arrays of loudspeakers, and these lobes tend to increase multipath problems.

While stations operating on higher frequencies utilize much higher transmitter powers, their assigned channel is a much smaller percentage bandwidth, so they can utilize antennas with much greater directivity in the vertical plane. Antennas for television channels 7-13 (174-216 MHz) typically use 4-6 elements, while UHF stations (470-810 MHz) may use 12-16 elements in a vertical array. In Chicago, where these tests were performed, all of these transmitting antennas are at an elevation of 400-600 meters. As a result, the main lobe of antennas transmitting television channels 7-69 passes high over even the tallest buildings in their immediate vicinity. In fact, a receiving antenna doesn't appear within the main lobe of the UHF antennas, which is typically only about 8 degrees wide in the vertical plane, until the receiving antenna is 10-20 miles from the transmitter. At that distance inverse square law has reduced the field sufficiently that detection is far less likely (although it can occur with really problematic microphones and equipment).

A comparison of the current work with the VHF/UHF susceptibility tests reported in [1] shows a very strong correlation. For example, microphone TL1-1-10 received very strong interference from broadcast TV and FM stations, the handheld transmitters, and the cell phone. Figure 9 is consistent with those results, showing very high susceptibility to pin 1 current for this microphone beginning about 30 MHz with strong peaks around 90 MHz and 170 MHz and strong susceptibility to 1 GHz.

Microphones TMO7 and DS9 received mild 150 MHz interference and strong cell phone interference, all of which was eliminated when the experimental EMC connector was used to bypass the pin 1 problem. Microphone TMO5 received strong cell phone interference and mild VHF-TV interference; the VHF TV interference was eliminated and the cell phone interference reduced to slight by the experimental connector. The laboratory data for these microphones shown in Figure 13 are consistent with that result. Similar comparisons of the other microphones tested in both studies also show good correlation.

CONCLUSIONS

1. Terminations for the shield that depend solely upon contact between connector shells are likely to fail in a large number of products to which they must mate.
2. Below 30 MHz, immunity failures (that is, interference from radio transmitters) are more likely to be the result of inadequate filtering on the signal pair than a pin 1 problem.
3. Pin 1 problems couple interference into equipment in ways that bypass the channel to which the cable receiving the interference is connected. That is, interference entering equipment on a cable connected to channel 1 may be heard even though channel 1 is turned all the way down! This is clearly shown in Figures 18, 19, 20, and 23, where interference coupled to pin 1 of channel 1 shows up on channel 2, even though input 1 is not routed to channel 2. It also was apparent in all of the small mixers. This can complicate the diagnosis of how the interference is entering the system.
4. Interference caused by pin 1 problems can generally be eliminated by preventing current flow on the shield at the frequency or frequencies of the interference. This can often be accomplished by the use of an RF choke improvised by winding multiple turns of the cable around a suitable ferrite rod or toroidal ferrite core.
5. In the VHF/UHF susceptibility tests reported in [1], the authors blamed pin 1 problems within microphones for much of the interference received, but also pointed out the contribution of susceptibility to differential voltage coupled to the signal pair. The current work supports that assessment.

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