Noise Susceptibility in Analog and Digital Signal Processing Systems*

NEIL A. MUNCY, *AES Member*

Neil Muncy Associates, Markham, Ont., Canada, L6C 1R4

A demonstrable cause-and-effect relationship between a popular and widely employed equipment design practice and electrical noise problems in audio systems of all kinds is examined. A means of identifying equipment that may exhibit noise problems due to this design practice is outlined. The relationship between the physical construction of shielded twisted-pair cable and induced noise in a signal circuit due to cable shield current is explored. Established "rules" for equipment installation are reexamined. It is shown that noise problems due to this design practice could be eliminated at the manufacturing level at almost negligible net cost.

0 INTRODUCTION

One of the principal sonic benefits of modern analog signal processing (ASP) and digital signal processing (DSP) equipment is a wider potential dynamic range than ever before available. This is especially true in systems that incorporate multitrack digital recording devices. The consequences of low levels of electrical interference which previously may have been masked by analog tape noise are often now painfully audible. In spite of advertising claims of 16+ bit performance, it is becoming increasing common to encounter *system* noise problems resulting from random combinations of brand-new equipment which turn out to be incompatible with each other, even when all interconnecting circuits are balanced and operating at line level.

An informal survey in several major North American markets suggests that as many as half of all of the audio signal processing systems presently in use exhibit this problem to some degree. The usable dynamic range of these systems is often 10–20 dB (or more) lower than it would be if these interference problems did not exist. Noise problems are especially likely to occur when interconnections are made between line-level input/output (I/O) ports using cables with the shield (screen) connected at both ends. Noise problems have been encountered in systems ranging from the most thoroughly engineered permanent installations incorporating massive (and expensive) technical grounding systems [1, ch. 5], all the way to portable equipment setups which exist for only a few hours before being disassembled. Noise problems are just as likely to occur in fully balanced systems as in hybrid balanced–unbalanced systems, and often appear to be interactive in that a minor reconfiguration of equipment within a system may result in significant and unpredictable changes in system noise levels.

Within buildings the presence of potentially troublesome low-frequency (LF) electromagnetic energy radiated by power wiring and electric equipment has been a fact of life since the dawn of the electric age. Until recently, with the exception of broadcast installations with transmitters located in the same building, most sources of very strong high-frequency (HF) energy were located outside buildings. The recent integration of analog and digital technology into the studio environment has radically changed this situation with the deployment of equipment wherein analog, digital, video, and radio-frequency (RF) signals routinely enter and leave the same device.

Electromagnetic fields generated by such equipment cover the range from below 50 Hz to well above 300 MHz. Devices such as cellular telephones, computers, video displays, switching power supplies, and other high-tech "toys" can easily generate electromagnetic field strengths which considerably exceed those produced by even very high-powered sources located outside and at some distance from the building. The effect of these fields on nearby equipment and systems is known as electromagnetic interference (EMI). Equipment which malfunctions in any manner when under

* Presented at the 97th Convention of the Audio Engineering Society, San Francisco, CA, 1994 November 10–13; revised 1995 April 13.

the influence of electromagnetic energy is said to be susceptible to EMI. Equipment that does not malfunction is said to be immune to EMI.

Notwithstanding the demonstrable noise-rejecting virtues of properly balanced interconnections, a large percentage of equipment with balanced line-level inputs and outputs exhibits considerable sensitivity to electrical noise from external sources. There are more than a few instances where balanced equipment turns out to be more prone to this problem than similar unbalanced equipment. As a consequence, the very concept of balancing (which has been employed very successfully for most of this century in electronic systems of every conceivable kind) is now often in question. This is especially disconcerting to purchasers who have paid a premium for balanced equipment, only to discover that balancing does not guarantee noise-free performance in their systems. Balancing is thus acquiring a tarnished reputation, which it does not deserve.

This is indeed a curious situation. Balanced line-level interconnections are supposed to ensure noise-free system performance, but often they do not. Costly "technical" grounding schemes involving various and often bizarre combinations of massive copper conductors, earth electrodes, and other arcane hardware are installed. When these schemes fail to provide expected results, their proponents are usually at a loss to explain why. Attempts at shielding routinely fail.

Dangerous practices involving violations of both the letter and the intent of municipal and national electrical codes often produce more satisfactory results, even though the resulting systems may constitute a significant shock and fire hazard.

In the last two decades hundreds of thousands of man-days have been spent by countless technicians in search of elusive noise problems in audio systems of all kinds. This repetitive process, which resembles nothing so much as the continuous reinvention of the wheel, represents a great waste of time, talent, and money for all concerned. It should be painfully obvious to anyone who has ever spent seemingly endless time trying to eliminate man-made noise in an audio system, that if properly executed balancing, shielding, and grounding schemes do *not* result in noise-free performance, there must be one or more other unrecognized factors at work. *As it turns out, there are.*

Permanent elimination of EMI problems in both existing and new analog and digital systems depends neither on rocket science nor on the future development of some new, advanced version thereof. Descriptions of completely successful prior work in this area are abundantly available. Readers of this paper who wish to pursue this subject efficiently will find a very useful overview in Gerke and Kimmer [2]. Comprehensive theoretical treatments of EMI are offered by Paul [3], Morrison [4], [5], and Ott [6], to cite only a few.

An overview of grounding, shielding, and electric power distribution in large built-in systems can be found in Fause [7]. A timely treatment of the advantages and limitations of balanced interfaces in audio systems is presented by Whitlock [8]. Facilities grounding is covered in extensive detail by Morrison and Lewis [9]. Technical grounding systems in particular are thoroughly reviewed by Atkinson and Giddings [10]. Testing procedures, which can be implemented to identify the problems described in this paper, are described by Perkins [11] and Windt [12]. An interesting insight into the evolution and consequences of these problems is presented by Macatee [13]. A review of relevant measures in circuit design and hardware layout is given in Harris [14]. Fascinating insight into very early work in these and other related matters will be found in [15]. Further references to literally thousands of previously published works describing prior art, some dating back to the turn of the century, will be found within these publications.

This paper specifically addresses the problem of noise coupling into balanced line-level signal interfaces used in many professional applications, due to the unappreciated consequences of a popular and widespread audio equipment design practice which is virtually without precedent in any other field of electronic systems. Those who are primarily concerned with developing equipment for less demanding applications will see that the principles examined herein are equally applicable in their situations as well.

1 BACKGROUND

There are perhaps no other technical matters in the entire field of audio technology that elicit as much controversy as the subjects of shielding and grounding. The fundamental purposes of shielding and grounding, the correct way to implement these concepts, and the benefits to be realistically expected therefrom are the subject of seemingly endless debate. In this ongoing controversy, the relevant laws of physics are often misinterpreted to the point of absurdity, or ignored altogether. Opinions founded on little more than blind faith have been responsible for countless frustrating attempts to resolve the problems of grounding and shielding. In order to deal with these subjects in a rational manner, the reader is asked to proceed with an open mind and consider the following overview objectively.

All operating electric circuits, devices, and systems generate and make use of electric, magnetic, and electromagnetic fields. These fields may couple into and cause noise or other mysterious and unpredictable malfunctions in nearby equipment. For the purposes of this paper, the term *noise* refers to the consequences of this man-made interference, rather than to the noise of nature (white noise), which is inherent in all operating electric equipment. This man-made phenomenon is known as EMI.

An electronic system is said to exhibit electromagnetic compatibility (EMC) if it satisfies three criteria, as outlined by Paul [3]:

1) It does not cause interference with other systems.

2) It is not susceptible to emissions from other systems.

3) It does not cause interference with itself.

Using the source–path–receptor analogy [6, p. 16], EMI coupling can be envisioned as occurring either through radiation, in which the air is the path, or by conduction, in which the path into and out of the affected device includes one or more interconnecting cables. In practice, both types of coupling are often found to be present. Radiated coupling of EMI can occur despite significant efforts to shield equipment, especially at very high RF. Conductive coupling of EMI can render otherwise perfect shielding essentially ineffective at all frequencies. A particularly bothersome type of conducted EMI can occur when the same conductor is shared by two otherwise unrelated circuits. This phenomenon is known as common impedance coupling [6, ch. 1], [4, ch. 6].

Magnetic fields exist around all current-carrying electrical conductors. Magnetic field coupling between nearby circuits can be described and quantified in terms of their mutual inductance [5, p. 122], [15, p. 122]. All that is required is that each circuit form an electrically conductive loop [9, p. 218]. The magnetic field resulting from current flow in a loop may induce current flow in other nearby loops. Magnetic coupling can be minimized by making the loop area [6, p. 52] of each circuit as small as possible, and keeping high-current circuitry away from low-level circuitry.

Electric fields surround all conductors on which a charge exists, regardless of the presence or absence of current flow. Electric field coupling between nearby circuits can be described and quantified in terms of their mutual capacitance [5, p. 22]. Electric field coupling can be very effectively eliminated by proper shielding and grounding.

Electric and magnetic fields surrounding electric circuitry can be treated as separate phenomena at frequencies up to at least 100 kHz, due to the extremely long wavelengths of radiated field energy at frequencies below this arbitrary limit. Evidence of a comprehensive understanding of this near-field concept as early as 1919 can be found in numerous publications, including [15].

The inevitable electric and magnetic fields produced by the power wiring and electric equipment in buildings are the principal sources of noise in electronic systems of all kinds, including audio. A repeatedly successful means of minimizing system noise cannot be developed without acknowledging the presence of these fields. The following sections of this paper provide a brief review of the basic principles involved in this process, and describe how the noise susceptibility of audio systems can be minimized.

2 DEFINITIONS

2.1 Definition of Pin 1

The term *pin 1* will appear repeatedly throughout this paper. Pin 1 is defined as the terminal or terminals of any *equipment* input/output (I/O) connector to which a cable shield or shields are connected when a mating cable connector is inserted, regardless of use or connector type. In the case of XLR connectors, the shield terminal usually *is* pin 1. For ¼-in (6.35-mm) connectors, pin 1 is the sleeve; for RCA connectors, pin 1 refers to the shell; and so on.

2.2 Ground

The term *ground* was in widespread use in technical literature by the turn of the century (see references in [15]). Prior to the emergence of electronic equipment, the use of the word ground clearly inferred a deliberate connection to the earth, which was made to minimize the risk of damage from lightning and power surges entering a building on the power lines. Since the dawn of the electronic age, the term ground has taken on a vast number of often confusing, contradictory, or misleading meanings.

The concept of ground can be envisioned in several different contexts. A comprehensive definition is offered by Morrison [4]:

> To the power industry the word ground implies a conductor that eventually connects to earth or soil. In electronics this is not a requirement, although some grounds are eventually tied to earth. A ground is a reference conductor in a circuit. It can be one side of a power supply, a centertap on a transformer, or the frame of a metal cabinet. There can be many grounds or reference conductors in one circuit or facility. Grounds can even float; that is, they can have little or no association with another circuit.

Two definitions in the context of electronic systems are offered by Ott [6, p. 75]:

1) An ideal ground would be ". . . an equipotential point or plane that serves as a reference potential for a circuit or system."

2) In a practical real-world application ground may be thought of as ". . . a low-impedance path for current to return to the source." Each power supply in a system is a distinct source of current which circulates through a particular part of the system in one or more loops. Success in noise-free system design depends on always knowing *where* the current flows.

In terms of electrical safety, the National Electrical Code [16] defines ground as "a conducting connection whether intentional or accidental between an electric circuit or equipment and to earth or some conducting body that serves as earth."

In the context of a complete system, all of these definitions are valid.

2.2.1 Ground Systems

The assertion that massive and complicated connections to earth ground are essential and absolutely required in order to achieve noise-free system performance in an electronic system is not supported by reality. Very complex electronic systems in automobiles and airplanes seem to work quite well without any connection to earth ground at all, as does all other electronic equipment powered by batteries.

An *electronic system* can be loosely defined as interconnected groups of devices (subsystems) which occupy a volume in space. As the entire system is viewed and examined from different perspectives, some subsystems will be more visible than others. One vital subsystem, which is often not seen as a distinct entity, either in hardware or on paper, is the interconnection between devices that forms the *ground system*. This is especially likely if a haphazard approach to system installation has been taken.

Ground systems are required for electrical safety, and are clearly defined and specified by electrical codes. Ground systems ensure safety by:

1) Short-circuiting the stray impedances between system elements, and between the system as a whole and the building, thus minimizing the possibility of electric shock.

2) Providing a low-impedance path for fault currents so that circuit breakers and fuses will operate rapidly in the case of overload or insulation failure.

It is absolutely essential that the safety grounds in a system remain fully functional at all times. The use of "ground lifters" in equipment power cords is illegal in most countries, and creates a potential shock and fire hazard. In a properly configured system, it can be conclusively demonstrated that power-cord ground lifters are completely unnecessary to the elimination of system noise problems.

A properly executed connection between an electronic system and earth ground provides a clearly defined path for stray leakage current (which has coupled into the system from building wiring and other equipment) to return to its source, which is earth grounded to ensure safety, without sharing signal or signal ground conductors.

2.2.2 Ground System Limitations

Ott [6, ch. 3] cautions that the performance of even the best conceivable grounding scheme is ultimately limited by the laws of physics. Regardless of the hardware and techniques used in an installation, "all conductors have a finite impedance, generally consisting of both resistance and inductance. At 11 kHz, a straight length of 22-gauge wire one inch above a ground plane has more inductive reactance than resistance." As a result, even at power-line frequencies, "two physically separated ground points are seldom at the same potential." Another name for a ground conductor is *antenna*. Anyone who has ever been frustrated when attempting to solve RFI problems by using a wire to "ground" things together is at least painfully, if not consciously, aware of this reality.

It should be clearly understood that ground systems are effective in controlling EMI only at low frequencies. The grounding techniques everywhere in use today were developed to deal with power-line frequency problems over a centry ago, when high frequency meant 20 kHz.

2.2.3 Earth Ground Connections

Grounding is a proven means of ensuring electrical safety, as is clearly described and specified in the electrical codes of most developed nations. Since the beginning of electric power distribution to buildings, connections to earth ground have afforded protection against power-line surges and lightning strikes that might enter the building on power lines. A properly implemented single connection between an equipment installation and the grounding electrode conductor at the electric service entrance to a building [9, ch. 2] can be shown not only to meet the letter and intent of relevant electrical codes in many but not all countries, but also to be completely adequate in a properly configured audio system.

In summary, there is a practical limit to the benefits that can be expected from any grounding system, regardless of its configuration. An audio system which exhibits noise problems in spite of heroic efforts to ground everything in sight is clearly suffering from problems in other areas.

A comprehensive review of technical grounding systems is given by Atkinson and Giddings [10]. A thorough treatment of grounding in facilities is presented by Morrison [9].

2.3 Shielding in Electronic Systems

A shield is defined by Ott [6, ch. 6] as ". . . a metallic partition placed between two regions of space. It is used to control the propagation of electric and magnetic fields from one place to another."

2.3.1 Magnetic-Field Shielding

Flexible cable shields provide negligible LF magnetic shielding. Marginal LF magnetic shielding of cables may be provided by rigid electrical conduit if installed properly. At low frequencies (<100 kHz), only highly permeable metallic materials make efficient magnetic shields. Furthermore, the fabrication of effective magnetic shields is difficult and expensive. Magnetic shielding is therefore used only in critical low-level applications such as to surround tape recorder heads.

2.3.2 Electric-Field Shielding

At low frequencies (<100 kHz) the principal use of shielding is to prevent capacitive coupling of electric-field energy from strong (high-level) external sources into sensitive (low-level) circuitry. Shielding against electric fields is provided by surrounding a sensitive circuit with an electrically conductive enclosure, known as a Faraday or electrostatic shield. According to Terman [17], ". . . the exact nature of the shielding material is not important, and the shielding is substantially perfect if the container in which the (circuitry) is located is water-tight or if its joints are lapped." The metal equipment housing surrounding most ASP/DSP devices serves this purpose very effectively if properly implemented. Equipment enclosures made of conductive plastic also provide effective electrostatic shielding if properly fabricated.

2.3.3 Shielding Effectiveness

The effectiveness of an electrostatic shield can be severely degraded by careless interconnections with other equipment. Off [6, ch. 6] observes that "it is of little value to make a shield, no matter how well designed, and then allow electromagnetic energy to enter (or exit) the enclosure by an alternative path such as cable penetrations," and that "cable shields that penetrate a shielded enclosure must be bonded to that enclosure in order to prevent noise coupling across the boundary." These seemingly intuitive observations are routinely ignored in practice.

2.3.4 Shield Connections

Rules for shield connections are stated by Morrison [5, ch. 4]. Rule 1 stipulates that "an electrostatic shield enclosure, to be effective, should be connected to the zero-signal reference potential (ZSRP) of any circuitry contained within the enclosure." This connection effectively short-circuits the mutual capacitance between the enclosure and the circuitry inside, as illustrated in Fig. 1. The maximum potential that can exist between the circuitry and the enclosure is therefore defined by the circuitry itself.

In the case of cable shields, rule 2 stipulates that "the shield conductor should be connected to the zero-signal reference potential (ZSRP) at the signal-earth [ground] connection" (as shown in Fig. 1). "This procedure ensures that parasitic currents will flow in the shield only and not flow in the signal conductors." It should be clearly understood that the term *signal conductors* in this definition includes signal ground conductors. From a systems standpoint, a properly connected cable shield becomes ". . . an extension of the electrostatic enclosure . . ." surrounding a device, and nothing more.

2.3.5 Cable Shielding

There are two primary functions of cable shielding.

1) To eliminate capacitive coupling of nearby electric fields into the circuits surrounded by the shield. At low frequencies, some foil shields provide 100% protection. Braided and spiral wrapped shields are generally not 100% effective, but are usually adequate in most audio system applications.

2) By proper shield grounding, to provide a clearly defined path for the resulting parasitic current [5, ch. 4] to return to its source.

The protection provided by the second function of cable shielding is the same kind of protection that lightning rods impart to a building. The difference between these two examples is merely a matter of scale. Lightning strikes involve millions of volts and thousands of amperes of current flow. Lightning rods on buildings are very carefully connected to earth ground by a system of cables that are *never* permitted to enter the building. Any attempt to utilize existing internal building wiring as a convenient ground path would completely defeat the purpose of lightning rods altogether (to say nothing of the potential for fires and loss of life that could result).

An event similar to a lightning strike, which might occur near a typical audio system, is an electrostatic discharge (ESD) [6, ch. 12], [9, ch. 7], [2] produced by the accumulation of static electricity. ESD events usually involve a minimum of several thousands volts. Given the right current path (through one or more pieces of equipment), an ESD event could totally disable all or part of an audio system, especially those controlled by computers. To provide protection comparable to a lightning rod, audio system cable shields must be able to redirect this type of interference current, as well as the parasitic currents produced by lower voltage coupling from all other nearby electric fields, along a path that permits the return of these currents to their respective sources, without sharing audio signal conductors anywhere in the system, as required by rule 2.

2.3.6 Cable Shield Terminations

The use of audio cables having the shield connected to pin 1 at both ends is standard practice worldwide.

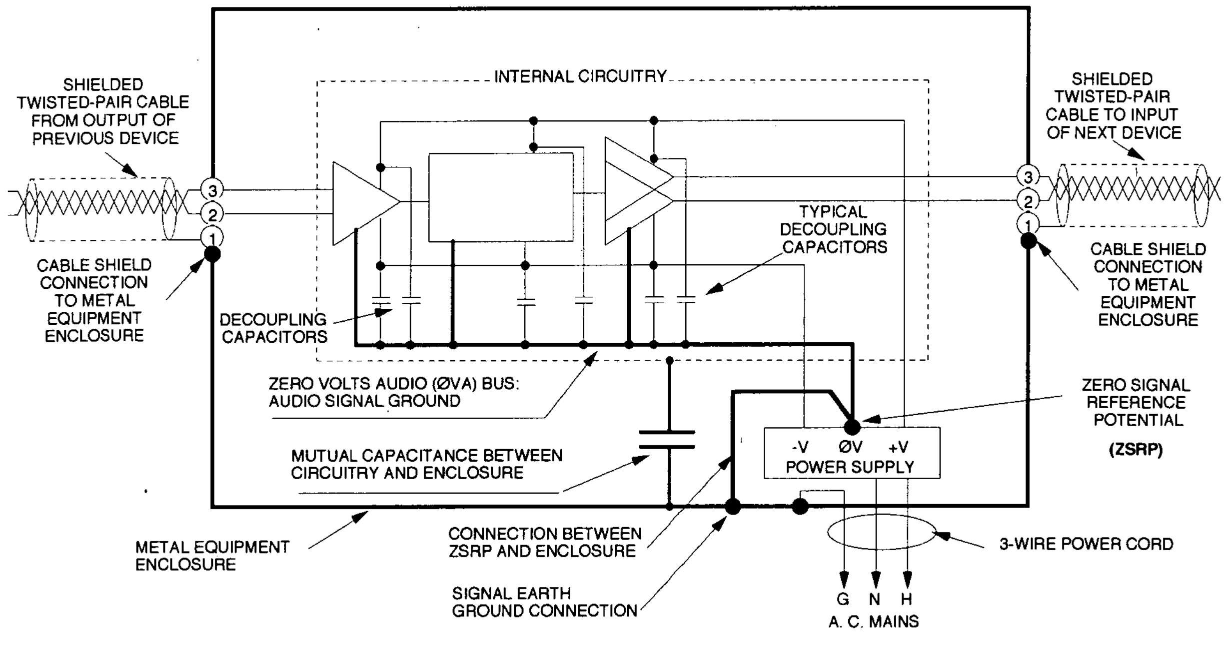


Fig. 1. Generic audio signal processing device.

When such cables are used to interconnect equipment, the cable shields should merely become an extension of the shielding provided by the equipment enclosures. If cable shields are terminated at equipment I/O ports in such a manner that they either directly or inadvertently become connected to internal audio signal ground circuits, coupling of noise energy into the devices from external sources can be expected, regardless of the architecture of the I/O circuitry itself.

2.4 Balanced Circuits

A balanced circuit is defined by Ott [6, pp. 116–122] as "a two-conductor circuit in which both conductors and all circuits connected to them have the same impedance with respect to ground and to all other conductors." An equally important characteristic of a balanced circuit is that the signal amplitudes on each of the two conductors at any given instant must be exactly equal, but of opposite polarity. This condition minimizes capacitive coupling of signal currents into the shield, as described by Whitlock [8] and others.

Balanced circuit connections between devices in a typical audio installation are usually made with two-conductor shielded cable. In this circuit configuration, the cable shield is not required to serve as one member of the circuit pair. In balanced circuits it is therefore essential to realize and understand that cable shields are simply not necessary in oder to transport signal energy from one point to another, as evidenced by the almost universal use of unshielded balanced circuits in the telephone industry.

In balanced systems, with the exception of low-level signal circuits from microphones and other transducers, cable shields may not be required at all in applications where nearby electric- and magnetic-field energy is reasonably low, as suggested by Farr [18] and Morrison [4, ch. 5]. To avoid tempting fate, however, it has become standard practice to shield cables in balanced audio systems, regardless of the likelihood of nearby fields. Cable shielding becomes increasingly important as the required dynamic range of the system increases.

2.5 Unbalanced Circuits

A circuit is said to be unbalanced if the impedance from each side of the circuit pair to ground and all other conductors is unequal. A condition of dynamic unbalance also exists in otherwise balanced circuits if the signal levels on each of the conductors are unequal.

Unbalanced circuit connections between devices in a typical audio installation are usually made with shielded single-conductor cable. In this circuit configuration the cable shield is required to serve as one member of the circuit pair. By making the shield one member of the circuit pair, the second function of cable shielding [see Section 2.3.5, function 2] cannot be realized, and common impedance coupling of EMI is invited. In most cases investigated by the author, this turns out to be a highly overrated factor, which is used as a convenient scapegoat to explain elusive EMI problems. The real problem is almost always to be found within the equipment.

2.6 Line-Level Connections and the One-End-Only Rule

Cables having shields connected at both ends are routinely used for line-level interconnections between equipment, especially in nonpermanent installations. Electrical noise is often encountered in such systems. It is commonly thought that ground-loop [6, ch. 3] currents flowing through one or more cables are responsible for this interference, and that the noise coupling somehow occurs within the cable itself. A popular fix in permanent installations therefore involves the practice of eliminating these nasty ground loops by connecting cable shields at one end only. The decision concerning *which* end to disconnect has been the subject of seemingly endless debate, even though this matter has been thoroughly examined in many widely available publications, including [4]–[6], [8], [9], to cite only a few. If the one-end-only (OEO) rule is followed, it should be applied uniformly throughout the entire installation. Personnel turnover makes this a very difficult policy to maintain in a large plant over a long period of time.

It is often discovered that the degree of noise reduction resulting from adherence to the OEO rule is not completely adequate. While LF noise may be reduced to some extent, interference from nearby RF sources may become worse. It should be apparent in these situations that cable shield current by itself cannot be the only problem, and that other reasons for system noise must exist.

The OEO rule has become a part of the electronic folklore of the audio industry. The origin of this rule can be traced back to much earlier pre-solid-state times, when broadcast ASP systems were designed around vacuum-tube circuitry coupled to balanced impedance-matched transmission lines by transformers. These circuits typically exhibited very low ($<600\ \Omega$) loop impedances, making them particularly susceptible to noise coupling from nearby magnetic fields from all sources. Transformerless electronically balanced circuits exhibit much higher loop impedances ($>20\ k\Omega$), making them much less susceptible to the influence of magnetic fields.

2.7 Applying the OEO Rule

There are several interrelated factors which determine the possible need to continue to observe the OEO rule in system construction.

2.7.1 *Equipment Installation*

The nature of the equipment installation must be taken into account. Not all equipment ends up in racks in large permanent installations. A substantial amount of the same kind of equipment spends its entire service life installed in road cases as part of traveling systems or in rental inventories.

The principal benefit of adopting the OEO rule in large permanent installations is that this can result in substantially lowered circulating currents at power-line frequencies between different points in the plant. In temporary installations, however, there is usually very little opportunity to apply the OEO rule at all due to time constraints. It should be possible to use standard off-the-shelf cables in these applications without adverse consequences.

Other considerations include whether the equipment is all balanced, all unbalanced, or a hybrid combination. The presence of strong RF interference must also be taken into account. The principal determining factor should be the type of installation. In fact it will be found that the circuit architecture of equipment I/O ports is a very important factor. This matter is discussed in Section 5.

2.7.2 Cable Type

The type of cable to be used in a system is dictated by several factors. In permanent installations the principal concern may be cost. In portable systems the principal factor is likely to be durability. The possible influence that the physical construction of the cable may have on the noise level in the system is rarely if ever considered in this section process.

In theory, a shielded twisted-pair cable could be modeled as a transformer with the shield serving as the primary winding, and each conductor in the cable as a secondary winding. In this model, noise current flowing in a cable shield produces a magnetic field that couples into all conductors in the cable. At low frequencies, assuming uniform distribution of the magnetic field around the cable shield and a well-balanced circuit, the magnitude of the resulting common-mode voltage V_{cm} [5, ch. 5], [6, ch. 3] presented to the circuitry at the ends of the cable will be determined by the transfer impedance of the cable, as described by Morrison [9, p. 222].

Theoretically, if the distribution of the magnetic field around the cable shield is not uniform or if the signal circuit is not well balanced (or both), a differential voltage V_{dm} [9, p. 26] will appear across the signal pair and will be amplified by the line receiver just as if it were a signal. This is an example of mode conversion, which is described in principle by Augustadt and Kannenberg [19] and also addressed by Whitlock [8]. It has been suspected for some time by the author and others that cable construction might be a factor in this process. Published studies have not been found.

2.8 Cable Construction versus Shield-Current-Induced Noise

To put this issue into perspective, a survey was conducted using a simple two-device equipment interface arranged to emulate a typical ASP system installation. The test setup, shown in Fig. 2, was modeled after a similar one described by Perkins [20, fig. 18]. The noise current through the shield in all tests was adjusted to approxiamtely 100 mA to simulate worst-case shield currents actually encountered in operating real-world systems. The shield current was provided by a power amplifier driving a 3:1 step-down output transformer with the secondary connected between the powerline equipment ground conductors of the two devices. A 175-ft (53.3 m) length of shielded cable was used between the line driver and line receiver in each experiment. An all-inverting line receiver circuit [9] providing variable CMRR up to >90 dB at 10 kHz was employed. The residual noise in the test setup (with the cable under test removed and the input terminated in 150 Ω) was > -96 dBu, measured in a 30-kHz bandwidth. This level is almost 25 dB below the anticipated thermal noise floor of a typical ASP system with a +22-dBu clip point interfaced to a 16-bit digital recorder. The spectrum of the residual noise was essentially white. Several 175-ft (53.3-m) samples of different types of two-conductor shielded cable were tested. The resulting measurement data are shown in Table 1. The cable samples are ranked in the order of maximum noise-coupling immunity in Table 2.

The premise of the test was that the common-mode rejection ratio (CMRR) of the line receiver and the degree of circuit balance would be found to be the predominant factors. The results of the survey were very surprising.

The first surprise was that the common-mode rejection ability of the line receiver was virtually irrelevant. A change in CMRR of as much as 60 dB produced almost no change in noise coupling at all.

The second surprise was that with only two excep-

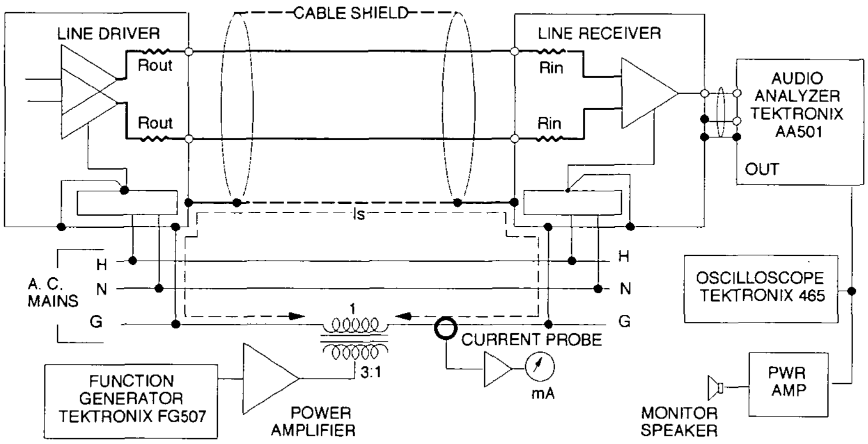


Fig. 2. Test setup used to measure shield-current-induced noise (SCIN).

tions, the amount of noise coupling was considerably below the thermal noise floor of any realistically calibrated 16-bit system. The two exceptions are both representative of older types of cable primarily employed in permanent installations.

Other results of the survey are summarized below.

1) The data suggest that the principal coupling mechanism is magnetic, as the coupling with the shield disconnected at the receive end (and thus no shield current) is negligible compared to the system residual noise. It shows that while noise coupling between the shield and a balanced signal pair is possible, it should not be much more than of academic interest, even in temporary installations when the proper cable is used.

2) Variations in shield-current-induced noise caused by differences in cable construction of more than 20 dB at 60 Hz, and more than 50 dB at 3 kHz, were revealed.

3) For all six cable samples, with the shields connected at both ends, the amount of coupling increases with frequency. This can be explained only partly by the common-mode voltage rejection characteristic of the line receiver, which decreases with increasing frequency.

The survey clearly shows that this matter should be investigated more thoroughly, as corroborating data are not available from any major cable manufacturer. Interested parties are invited to contact the author.

With these matters resolved, the fundamental question that remains to be addressed is: What constitutes proper cable shield termination practice in equipment design, and how is this practice reliably implemented in the real world?

3 CABLE SHIELD TERMINATIONS IN EQUIPMENT

The likelihood that observance of the OEO rule will be required in the design of a system depends on how the I/O connector pin 1s in each piece of system equipment are terminated. To illustrate the system consequences of equipment pin 1 terminations, the generic signal processing device illustrated in Fig. 3 will be used as a model.

3.1 Signal Path

In Fig. 3(a) the balanced input buffer stage A could be either a microphone preamplifier or a balanced line receiver. Any one of a number of circuit configurations can be employed for the balanced output stage B, although some designs are clearly better than others in terms of stability when driving long lines or unbalanced loads. In the middle of the device is some sort of signal processing circuitry C, the exact function of which is unimportant.

3.2 Power Supply

All of the active circuitry in the device in Fig. 3(a) is powered by a bipolar supply D [which could also be located outside of the enclosure, as shown in Fig. 3(b)]. The 0-V output terminal of the power supply is the zero-signal reference potential (ZSRP) for the entire device. All voltage measurements are referenced to this point. The ZSRP is connected to the 0-V audio (∅VA) bus H, making the ∅VA bus the zero-signal reference conductor (ZSRC) for all of the circuitry involved in the device. the ZSRP E is bonded to the chassis signal earth connection J (signal ground) by a dedicated conductor employed for no other purpose. This connection precludes any possible coupling of input and output signals by the mutual capacitance C_m between the circuitry and the metal enclosure [6, ch. 3], [5, ch. 4]. It also makes the entire chassis a perfectly legitimate secondary ZSRC. Cable shield connections to the chassis at any point therefore comply with both rules 1 and 2 [5, ch. 4].

There is a secondary reason for bonding the ZSRP to the chassis by a dedicated conductor. One of the real-world consequences of cost-effective power supply design is that electrostatic shields between the primary and secondary windings of power transformers are the exception rather than the rule. As a result, ac mains leakage current into typical devices via the primary–secondary

Table 2. Ranking in order of shield-current-induced noise immunity versus cable type.

Sample	Description
Cable 1	Twisted trio, two served copper wire shields wrapped in opposition
Cable 2	Twisted pair, braided shield
Cable 3	Star-Quad cable, braided shield
Cable 4	Miniature twisted pair, served copper wire shield, internal drain wire
Cable 5	Twisted pair, foil shield, internal drain wire wound in same direction and with same pitch (twists per unit length) as pair
Cable 6	Shielded two-pair cable, individual foil shields for each pair, conductive side out, external shield drain wire wound in same direction and with same pitch (twists per unit length) as pairs

Table 1. Shield-current-induced noise in dBu for 100-mA test current.

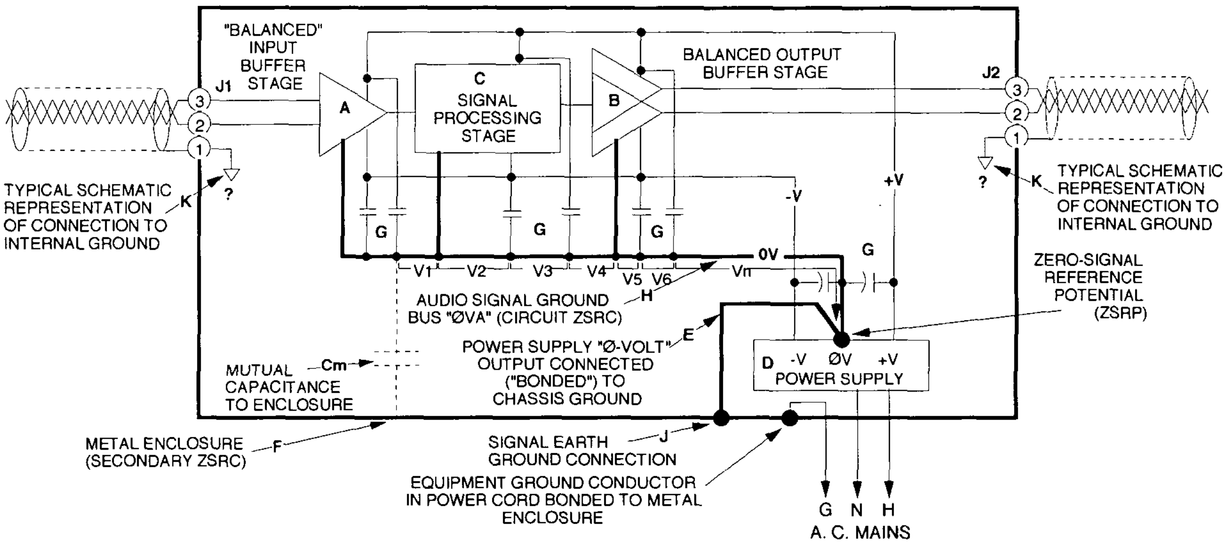
		Test Frequencies and Measured Levels, 30-kHz Bandwidth			
	Test Signal off	60-Hz Square Wave	60-Hz Sine Wave	600-Hz Sine Wave	6-kHz Sine Wave
Equipment residual	−96	−96	−96	−96	−96
Cable 1	−96	−96/−96*	−96/−96	−96/−96	−96/−92
Cable 2	−96	−96/−93	−96/−95	−96/−93	−96/−81
Cable 3	−96	−96/−93	−96/−94	−96/−92	−96/−78
Cable 4	−96	−96/−93	−96/−94	−96/−92	−96/−77
Cable 5	−96	−96/−84	−96/−93	−96/−81	−96/−63
Cable 6	−96	−96/−62	−96/−73	−96/−53	−96/−35

* Shield connected one end/shield connected both ends.

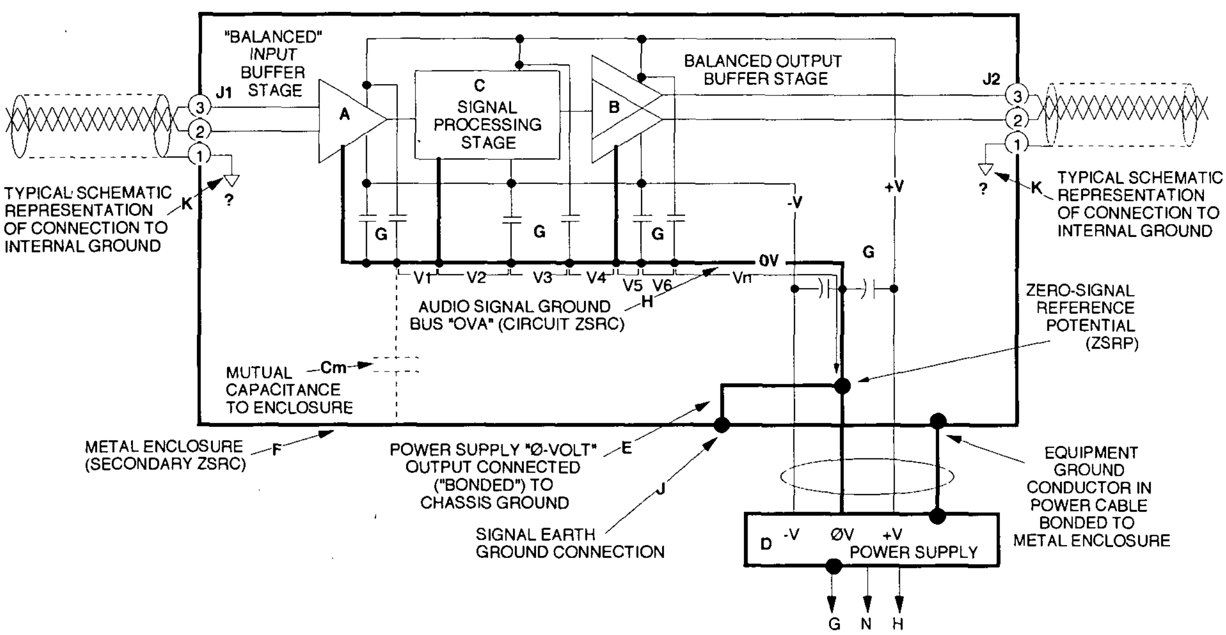
winding capacitance is inevitable. This current must be very carefully directed back to the equipment ground conductor without sharing signal or ∅VA conductors anywhere in the device. A short, robust low-impedance bond connection between the ZSRP and the equipment ground conductor is therefore essential. A conductor of sufficient ampacity to permit the rapid operation of mains fuses in the event of primary-to-secondary insulation breakdown will normally be of sufficiently low impedance that normal leakage currents of a few milliamperes should not cause a potential of any significance to exist between the ZSRP and the chassis.

3.3 Power Distribution

Ott [6, p. 122] defines a power supply as ". . . a zero-impedance source of voltage." In Fig. 3(a) the three power distribution conductors $+V$, $-V$, and $0V$ are common to all internal circuitry. Due to the fact that all conductors exhibit impedance (however small), any current that flows through any combination of these conductors will create small IR (IZ) drops V_1-V_n between connection nodes along each conductor. It is not uncommon to find power distribution conductor dc resistances of several ohms due to the combination of thin circuit-board traces and the overall length of ribbon cables used within such devices, especially in large mixing consoles. At audio frequencies well below the upper limit of audibility, the inductive reactance of even short conductors may easily exceed the dc resistance. The effective impedance of the power supply along the distribution path is therefore nowhere close to zero, and typically rises with frequency. Decoupling and bypass capacitors G may serve to minimize the local consequences of power distribution conductor impedance if properly deployed.



(a)



(b)

Fig. 3. (a) Schematic diagram of generic audio signal processing device. (b) Device with external power supply.

Controlling current paths in equipment is therefore vital to noise-free performance. Connections to power supply conductors must be made only after careful examination of the consequences. In most equipment, access to the $+V$ and $-V$ power distribution conductors is rarely available on I/O connectors. The same cannot be said about access to the ∅VA conductor H, however.

3.4 AC Mains Connections

In Fig. 3(a) the device is shown with a three-wire power cord. Merely plugging into a grounded ac outlet connects the metal enclosure to the building ground system (and ultimately to earth ground). This feature ensures user safety, as required by various safety standards (UL, CSA, VDE, and so on) worldwide, but may be quite unimportant in terms of the operational functionality of the device. A dedicated chassis bonding conductor between the device and its external power supply is shown in Fig. 3(b). To preclude any possibility of the equivalent of a pin 1 problem, this conductor must never be permitted to carry power supply load current.

3.5 Cable Shield Connections to the Hollow Triangle

In Fig. 3(a) pin 1s on the I/O connectors J_1 and J_2 are shown connected to the typical hollow triangle ground symbol K found on many diagrams. This symbol indicates a connection to a ground destination somewhere within the device, as indicated by the question mark. But where, and by what path? While there is no argument that pin 1 must somehow be connected to the metal enclosure in order to extend the electrostatic shielding provided by the enclosure to the I/O cable shields, and also to the ZSRP (as required by rule 2), very few equipment diagrams show where the actual connection to the enclosure is made, or what path these ground conductors actually take to get to their chassis ground destination.

This innocent but dangerous practice in the early development of many new designs may create a false sense of security, as the resulting wishful thinking implies that connecting an I/O cable shield to some convenient nearby point somehow gets rid of unwanted noise. This is an example of the illusory "sump theory of electronics" described by Morrison [9, p. 168], which suggests that any undesirable noise current can somehow be sent to an infinitely large ground sump from which it never emerges. Circuit theory, which requires circuit current to flow in definable loops, clearly shows that ground sumps cannot exist in the real world.

3.6 System Connections

Fig. 4 shows two of these generic devices assembled into a generic signal processing system connected to a source of building power. Off-the-shelf XLR cables with the shields connected at both ends are employed for audio interconnections between devices. Each cable shield is solidly chassis grounded at the point of entry. In the case of cable A from the microphone to device 1, this shield connection serves merely to extend the electrostatic shielding provided by the equipment enclosure to the metal enclosure surrounding the microphone transducer element. The cable shield between device 1 and device 2 ties these two devices together. The entire system is connected to earth ground by the ground conductors in the equipment power cords, thus ensuring electrical safety.

4 POTENTIAL SYSTEM NOISE SOURCES

EMI sources which could influence the operation of such a system are illustrated in Fig. 5.

4.1 RF Fields

In a modern installation it is highly unlikely that significant RF fields will *not* be present, and it must be remembered that Mother Nature does not acknowledge

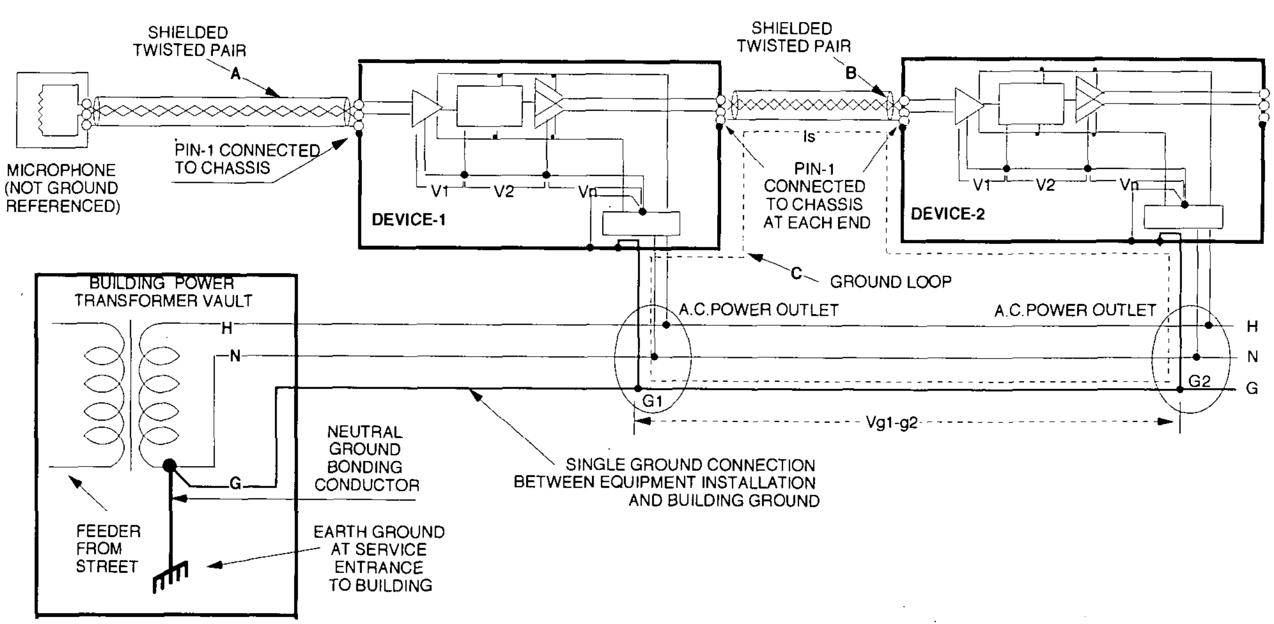


Fig. 4. Schematic diagram of generic ASP system showing interconnections between equipment and building power and ground.

labels. Just because a conductor is labeled "ground wire" or "cable shield" does not preclude the possibility that in the presence of RF it will also behave as an *antenna*. The presence of RF energy at the I/O terminals of all devices in the system should therefore be considered unavoidable. In Fig. 5 sources of RF are shown coupling into the system interconnecting cables.

At RF it is standard practice to terminate cable shields to the chassis at the point of entry. RF currents I_{RF} will then flow on the outside of the chassis due to skin effect, as indicated by the dashed lines. If RF filters (RFF) are present, residual RF energy that finds its way into the system by way of incomplete cable shielding will be attenuated at each I/O connector, assuming that the filters are properly bonded to the chassis at the point of entry.

4.2 Electric Fields

Fig. 5 also illustrates parasitic current flow in the system due to the coupling of external electric fields via mutual capacitiacnes $C_{m1}-C_{m4}$. In this example I/O cable shields A_1-A_3 are connected to the chassis at the point of entry. Noise currents coupled into the cable shields flow only in the chassis, and not in signal ground conductors.

4.3 Ground Loops

In Fig. 5 the cable shield connection between devices completes a ground loop C [6, ch. 3], which includes the equipment power cord ground conductors and the equipment ground conductors in the building wiring between power outlets. Note that device 1 is connected to building ground at point G_1, and device 2 is connected at point G_2. If these points are located at any significant distance from each other, potential differences V_{g1-g2} resulting from the operation of all devices connected to this building ground conductor will cause current flow I_s in the ground loop. This is an example of conductive coupling of EMI from one circuit (equipment ground) to another (cable shield).

Stray magnetic-field energy which couples into the loop via mutual inductances L_{m1} and L_{m2} will also cause current flow in the loop. The larger the loop area, the more likely the interference.

In both examples cable shields are connected to the chassis at the point of entry. Noise currents coupled into the cable shields flow only in the chassis, and not in signal ground conductors, as indicated by the dashed lines.

4.4 Common-Mode Coupling to Cables

All of these noise-coupling mechanisms produce common-mode voltages on the cable signal conductors. The ultimate degree of common-mode rejection provided by a balanced circuit is totally dependent on the degree of balance achieved by both line driver and line receiver circuitry. Even in perfect designs, the CMRR of an electronically balanced circuit usually falls off linearly with

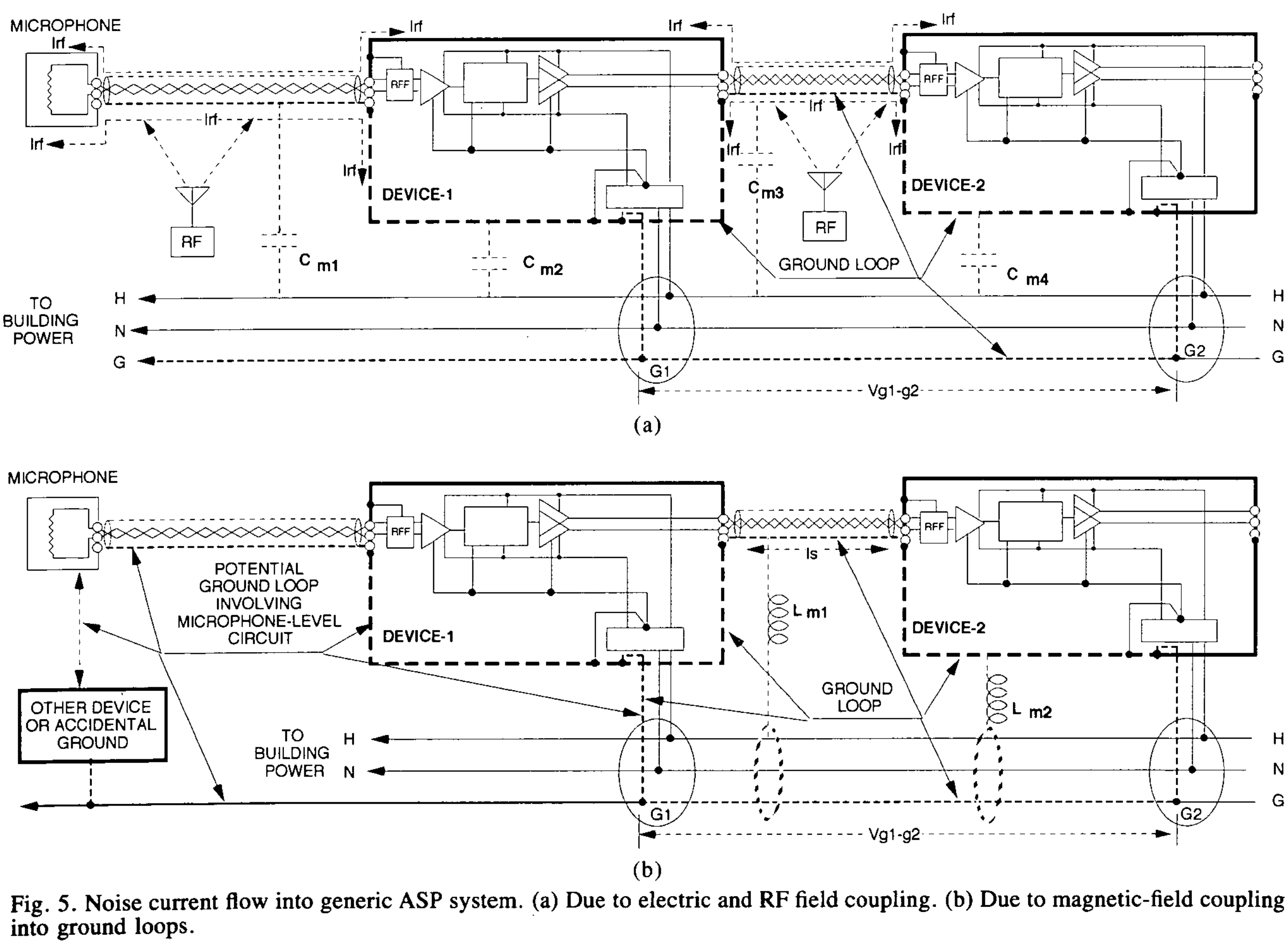


Fig. 5. Noise current flow into generic ASP system. (a) Due to electric and RF field coupling. (b) Due to magnetic-field coupling into ground loops.

frequency [4, ch. 5]. In a system that consists entirely of equipment with I/O connector pin 1s terminated as shown in Fig. 5, noise coupling will usually be noticeable in extreme cases only. A large percentage of all equipment presently in use, however, is not so configured.

5 PIN 1 PROBLEMS IN CONTEMPORARY EQUIPMENT

Very effective EMI immunity in analog and digital systems can be achieved by proper implementation of shielding, grounding, and the use of balanced signal transmission lines. The best conceivable shielding, grounding, and circuit balancing designs will be of negligible help in preventing EMI problems, however, if they are effectively bypassed. This is the essence of the pin 1 problem.

5.1 Pin 1 Connections

Fig. 6 illustrates the pin 1 circuit configuration found in a large percentage of both existing and new equipment. Instead of bonding I/O connector pin 1s to the chassis at the point of entry, as shown in Fig. 5, it has become common practice to connect pin 1 terminals to the audio signal ground ∅VA bus within a shielded device. In both examples, cable shields are connected to the ∅VA bus. Noise currents coupled into the cable shields therefore flow in signal ground conductors, rather than only in the chassis, as indicated by the dashed lines.

5.2 Conductive EMI Coupling

In Fig. 6 the I/O connector pin 1s are connected to the ∅VA bus in each device. Internal circuitry in each device is also connected (referenced) to the ∅VA bus at various points. The impedance of the ∅VA bus is therefore in series with both cable shield ground paths and signal ground paths. The degree of noise coupling is directly proportional to the magnitude of this common impedance. At low frequencies, coupling is determined by the ∅VA bus resistance. Before the upper limit of audibility is reached, the inductive reactance of the bus predominates.

5.3 Noise Due to Electric and RF Fields

In Fig. 6(a) nearby LF electric fields and RF energy are shown coupling into the shields of the microphone cable and the cable between devices 1 and 2. At low frequencies, the coupling impedance is mainly determined by mutual capacitance C_m and will normally be very high. The resulting current will therefore by very low, producing only very small voltage drops $V_1 - V_n$ along the ∅VA bus in each device.

RFI filters (RFF), if any, in devices with pin 1 problems are usually found to be connected to the ∅VA bus rather than to the chassis. RF energy is thus distributed to every stage that is referenced to the ∅VA bus, rather

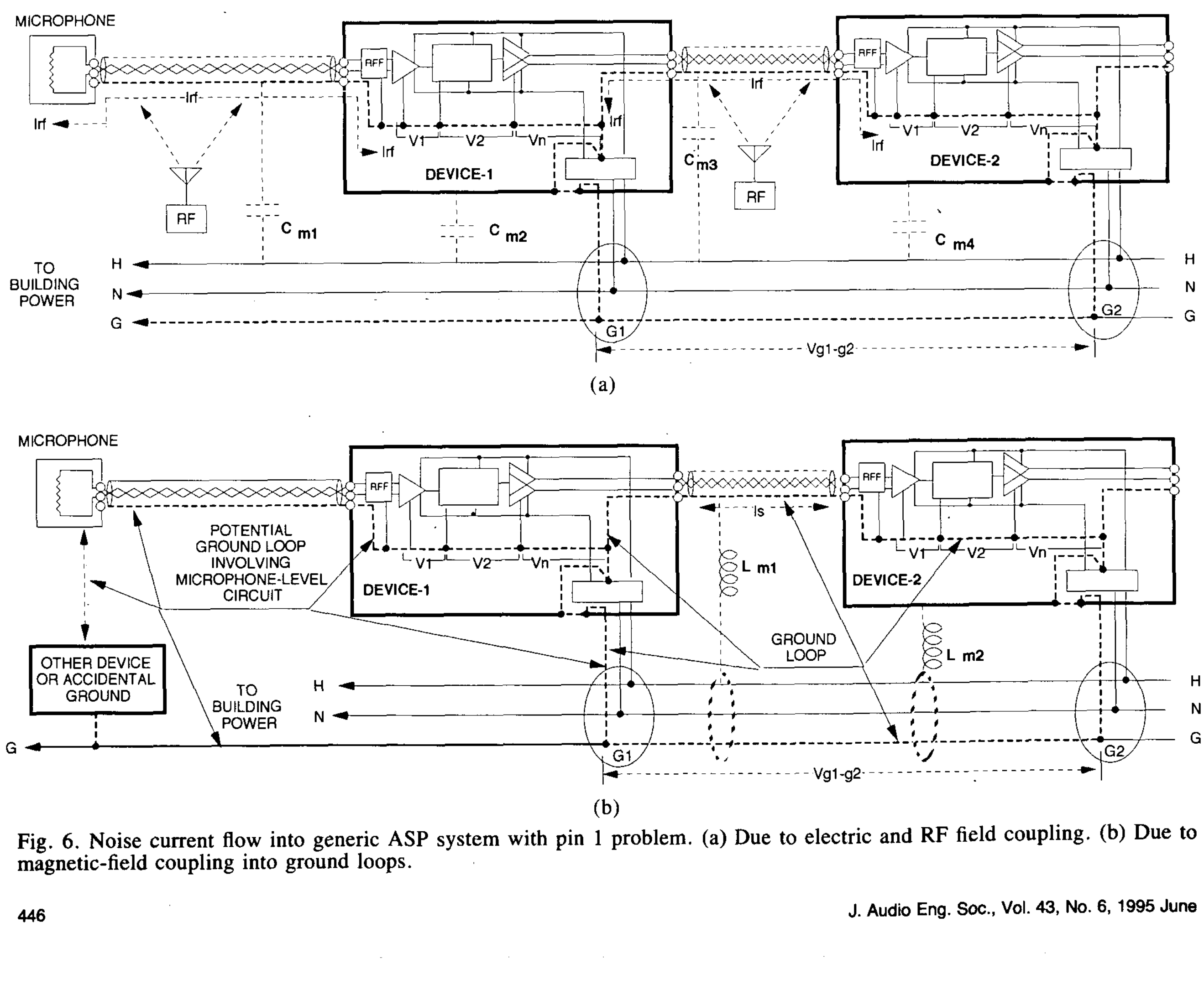


Fig. 6. Noise current flow into generic ASP system with pin 1 problem. (a) Due to electric and RF field coupling. (b) Due to magnetic-field coupling into ground loops.

than to the chassis at the point of cable entry. The value of the filter is therefore effectively neutralized. At RF, substantial voltages can appear between connection nodes along the ∅VA bus due to its series inductance, where they may be strong enough to overwhelm low-level stages. Dc components of rectified RF energy can interfere with the bias of sensitive stages, often resulting in changes in the sonic performance of the device. Demodulated carrier signals may appear as garbled noise at the output of the device.

5.4 Noise Due to Magnetic Fields and Ground Loops

Fig. 6(b) illustrates the path of LF noise current in the device 1–device 2 ground loop. Loop current will result from coupling between any nearby magnetic-field source and the loop via any mutual inductance, including L_{m1} or L_{m2}. As the resistance of typical ∅VA buses rarely exceeds more than a few ohms, the current resulting from even a moderate nearby LF magnetic field can be substantial, producing corresponding voltage drops between connection nodes along the ∅VA bus.

In device 1 the ground loop includes the ∅VA conductor between all internal circuitry and the chassis. All internal circuitry in the device is therefore elevated with respect to the chassis by voltage drop V_n.

In device 2, voltage drops V_1-V_n between connection nodes along the ∅VA bus will be amplified by any stage whose signal input loop includes any portions of the ∅VA bus.

Ground reference voltage differences V_{g1-g2} between power outlets along the equipment ground conductor in the building wiring will also produce noise currents in the ground loop, as described.

5.5 System Noise Due to Pin 1 Noise Current

Noise current flow into a pin 1 terminal may seem at first glance to be inconsequential, as it is widely thought that merely connecting a shield to a convenient nearby ground conductor is somehow supposed to get rid of unwanted noise (see sump theory [9, p. 168]). In practice, however, the author and others have found numerous examples wherein LF noise current flow of as little as 1 mA into a single pin 1 terminal of a device resulted in noise levels within 20 dB of the normal signal output level itself. In real-world systems, LF cable shield currents of as much as 100 mA have been routinely encountered. Peak shield currents in excess of 1 A have occasionally been observed.

5.6 EMI Coupling into Devices with Multiple I/O Ports

LF noise contributions from multiple I/O cable connections to a device are usually cumulative, as the wavelengths of LF electromagnetic fields are very long compared to the lengths of typical audio cables. LF noise signals, which on any individual I/O cable may be almost impossible to measure accurately, can add up to significant noise levels at the output of a device with multiple I/O ports. Mixers and consoles of all sizes are particularly sensitive to this phenomenon. At RF, the wavelengths of interfering signals may be shorter than the audio cables involved. In this instance, physically moving cables may make the interference worse or better, as the phase of interfering signals arriving via different paths changes with cable orientation.

5.7 Side Effects of Common Impedance Coupling

Any current flowing in the ∅VA bus, regardless of source, will produce voltage drops V_1-V_n between connection nodes along the ∅VA bus. If these voltage drops are the result of noise current flow from sources external to the device, the noise will be amplified and will appear along with the signal at the output of the devices, as described.

If these voltage drops are the result of signal current flow, the consequences may range from being difficult to detect at all to subtile changes in sound quality, all the way to outright instability and oscillation. This problem is particularly likely in mixing consoles with many possible combinations of signal paths, and it often shows up as crosstalk between various combinations of outputs.

A different type of crosstalk often referred to as "fader leakage" is often found in systems in which the OEO rule has been applied. In cases where the shields of cables connected to unbalanced sources are lifted at the source end, signal current coupled into the shield by the capacitance of the cable is forced to return to its source via a path that includes the ∅VA bus in the following device. The signal will be heard at the output of the device at a low level, even with the input fader closed.

5.8 EMI Coupling in Unbalanced Systems

EMI coupling into unbalanced systems is routinely thought to be the result of unbalanced connections to such equipment. A much more likely cause is the pin 1 problem. For reasons that can be traced back to the birth of the consumer audio equipment, it has been standard practice to insulate I/O connector pin 1s from the chassis at the point of entry, and connect them internally to signal ground, as shown in Fig. 7(a). This practice was found to be necessary to eliminate internal ground loops, as early amplifier input architectures were inherently unbalanced. Why the resulting systems were never completely hum-free was a great mystery.

Modern operational amplifier technology is now almost universally employed in both balanced and unbalanced audio equipment. Differential line receivers involving one operational amplifier are found in almost all devices that are equipped with "balanced" line inputs, even though differential line receivers are not balanced, as shown by Bohn [21] and Jung and Garcia [22].

In many unbalanced designs, an operational amplifier is used as an unbalanced unity-gain input buffer connected to a single-circuit I/O connector. Pin 1 in this scheme is connected to audio signal ground, as shown in Fig. 7(b). Equipment so configured will be susceptible to EMI for the reasons described previously. By merely reconfiguring the input stage into the form of a differential amplifier as described by Hay [23] and shown in

Fig. 7(c), an unbalanced input connector can be chassis grounded at the point of entry, thereby precluding a pin 1 problem. The unbalanced output connectors can also be safely chassis ground referenced if the connection between the ZSRP and the chassis is moved to a point near these connectors.

In equipment which incorporates ¼-in (63.5-mm) input connectors, the utility of this design can be enhanced by using a tip-ring-sleeve connector, as shown in Fig. 7(d). If a shielded two-conductor cable from a balanced device is inserted, the full benefit of a differential line receiver is realized. If an unbalanced ¼-in (6.35-mm) connector is inserted, the ring contact will be connected to chassis ground, resulting in the input configuration shown in Fig. 7(c). The same technique can be applied to the output connectors as shown. This configuration makes the unit completely interchangeable with older versions of the same model.

6 DEMONSTRATING PIN 1 PROBLEMS

6.1 Test Setup

The relationship between the pin 1 problem and EMI coupling can be demonstrated using almost any device that is known to exhibit a pin 1 problem. The device is modified by installing a second set of I/O connectors with all pin 1s connected to the chassis at the point of entry. The audio signal contacts on these connectors are wired in parallel with corresponding contacts on the original connectors. Such a modified device is shown in Fig. 8 as device 2.

The test setup shown in Fig. 8 is then used to demon-

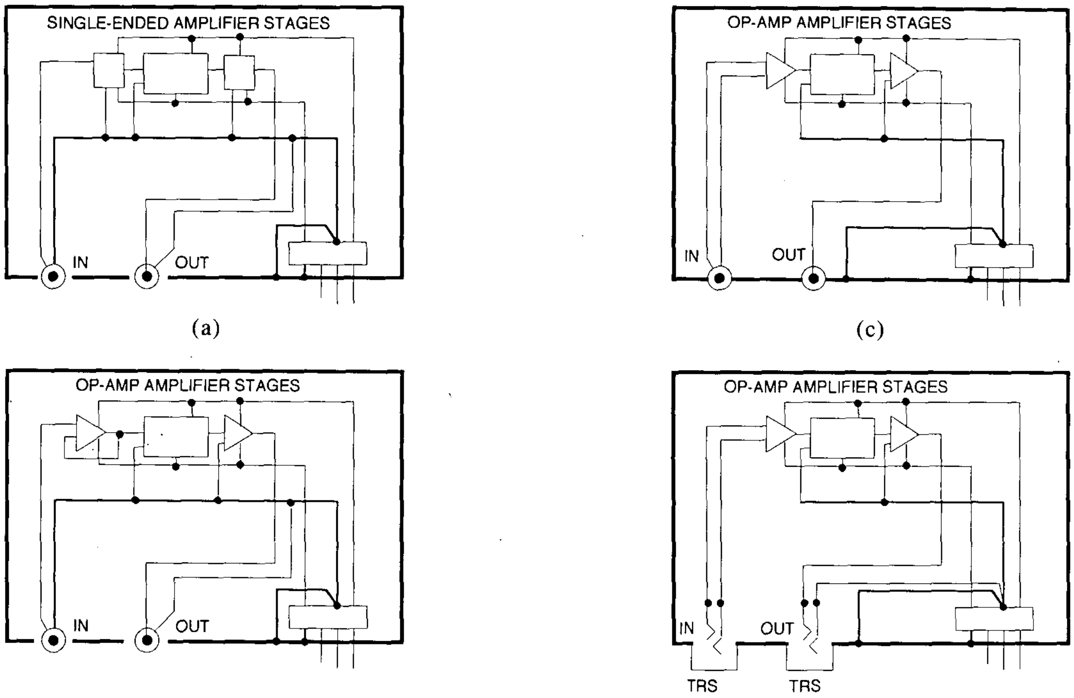


Fig. 7. Unbalanced devices. (a) Older device; I/O connector pin 1s connected to audio signal ground. (b) Modern device with unity-gain noninverting input; I/O connector pin 1s connected to audio signal ground. (c) Device with differential input referenced to device chassis; I/O connector pin 1s connected to chassis ground. (d) Device with differential input "forward referenced" to source device; I/O connector pin 1s connected to chassis ground.

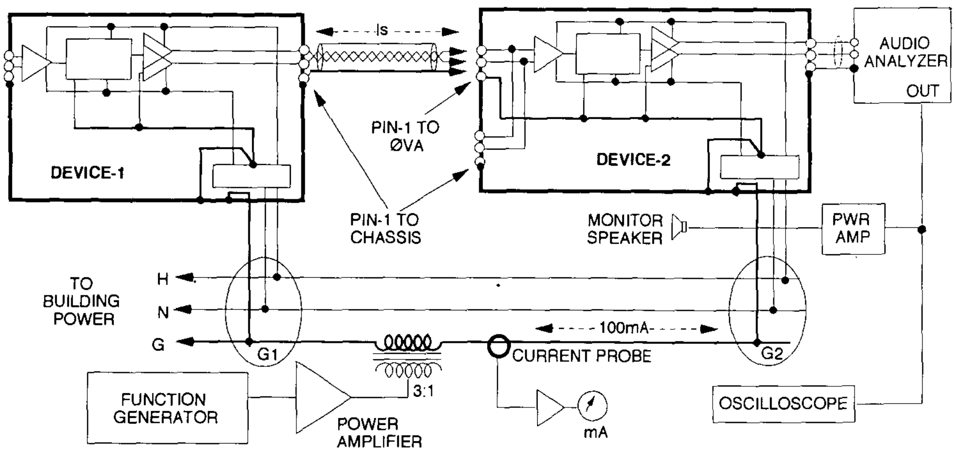


Fig. 8. Pin 1 problem demonstration test setup.

strate the pin 1 problem. The cable between devices 1 and 2 is connected to the new device 2 input connectors, forming a ground loop that does not include the ∅VA bus in either device. A measured current at several frequencies is induced into the ground loop, and the resulting levels at the output of device 2 are noted. The level of interference found in this example will be negligible compared to the residual thermal noise in the system, as long as the interconnecting cable does not exhibit a demonstrable shield-current-induced noise problem.

The test is then repeated with the cable connected to the original device 2 input. A second set of measurements is then taken. Any increase in interference indicates the presence and severity of the pin 1 problem in device 2.

6.2 Generic Noise Coupling Model

In the research for this paper a generic mixer with 16 input positions and one output channel was constructed as a model. To eliminate the signature of any one particular equipment manufacturer, the device incorporates several typical pin 1 problems which have been encountered in equipment installed in existing systems. Two sets of I/O connectors are provided, as in the previous example.

An abbreviated circuit diagram of this generic mixer is shown in Fig. 9. Input 1 is configured for use with a low-impedance microphone. Inputs 2–16 are configured for use with line-level sources. For the sake of clarity, input positions 3–15 are omitted from the drawing. All inputs and outputs are balanced.

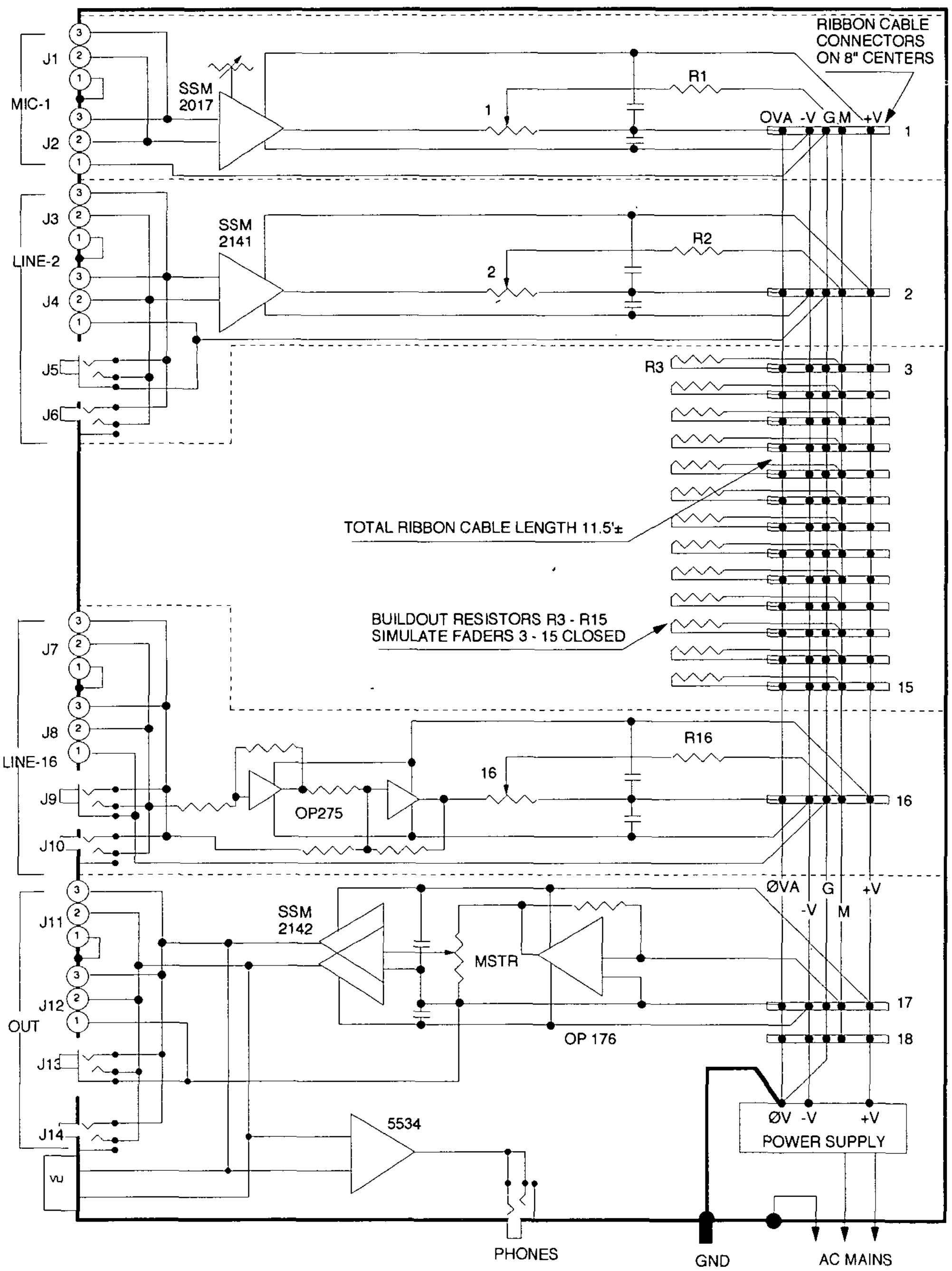


Fig. 9. Generic 16 × 1 mixer v2.0.

6.3 System Test 1: I/O Shields Terminated at Chassis Entrance Point

The generic mixer shown in Fig. 9 was installed as device 2 in the test system shown in Fig. 8. Using the procedure outlined in Section 6.1, a 60-Hz square-wave test current of approximately 100 mA was injected into the ground loop. In the first test, all I/O cable shields were terminated directly to chassis ground at the point of entry, as shown in Fig. 8. The noise current flowing in the resulting ground loop travels around each chassis to the equipment ground conductor without sharing audio signal ground conductors anywhere in the system. Regardless of the input used, the degradation of the system dynamic range was too small to measure, even with all input faders wide open and all unused inputs unterminated.

6.4 System Test 2: I/O Shields Connected to ∅VA

In test 2 the input cable to device 2 was successively moved to each connector with pin 1 connected to the ∅VA bus inside the mixer. All other cable shields remained connected to chassis ground, as shown in Fig. 8. Depending on the input used, a dynamic range degradation ranging between 40 and 70 dB was measured, even with all input faders completely closed.

6.5 Noise Coupling into Generic Mixer

Ground loop current flow through the ∅VA bus in Fig. 9 creates a voltage drop from one end of the bus to the other. At low frequencies this noise voltage is directly proportional to the dc resistance of the bus, which in this particular device is almost 1 Ω due to the length of the ribbon cable. An incremental portion of this noise voltage appears at each connection node along the bus, and is coupled to the mixing bus M by build-out resistors R_1–R_{16}. This presents the mixing amplifier with 16 in-polarity samples of the same noise signal, each at a different level. It can be shown that the increase in noise at the mixer output due to this phenomenon will be 20 log n (n being the number of inputs) greater than if the same noise voltage were delivered by only one input position as a signal. In this 16-input example the noise increase is 24 dB.

At high frequencies, noise voltage distribution will be determined by the inductive reactance of the ∅VA bus. RF energy entering via any I/O connector will be available to all circuitry in the device as a result.

7 LOCATING AND CORRECTING PIN 1 PROBLEMS

7.1 Testing for Pin 1 Problems

Pin 1 problems can be easily identified in any device. A very effective but yet elegantly simple test technique for pin 1 problems, which can be implemented in the field, is described by Windt [12]. In existing systems, equipment disassembly or removal from the system is not required. A version of this test procedure is illustrated in Fig. 10. Automated production testing for pin 1 problems is described in detail by Perkins [11].

7.2 Correcting Pin 1 Problems in Existing Systems

Correcting pin 1 problems poses several tradeoffs. One way to approach the problem is to identify each device with a pin 1 problem and modify it accordingly. This creates instant "orphans" which are no longer interchangeable with their unmodified counterparts.

Another way is to apply the OEO rule on a case-by-case basis. The immediate problem with this approach is that the equipment at each end of the cable will determine which end to disconnect. In cases where equipment with pin 1 problems is at both ends, the OEO rule may not work satisfactorily at all. One possible way to solve this dilemma is to extract the cable shield from the connector at the appropriate end and connect it directly to the chassis.

In some cases it may be possible to get around pin 1 problems by constructing a customized system wiring harness. This talent- and labor-intensive alternative is usually not practical in temporary installations because of time constraints.

Potential purchasers of new equipment who are aware of the pin 1 problem have the option of testing all candidates and buying only those that pass the test.

7.3 Correcting Pin 1 Problems in Existing Equipment Designs

At the manufacturing level, the correction of pin 1 problems in existing equipment designs which incorporate balanced I/O ports involves nothing more complicated than minor changes to circuit-board layouts and the possible installation of chassis ground terminals at connector entrances. RCA and ¼-in (63.5-mm) connectors can be mounted directly in chassis openings without insulators. XLR-type connectors with built-in chassis ground terminals are becoming available.

At the manufacturing level, the incremental hardware cost to implement the concepts shown in Fig. 7(c) and (d) in unbalanced equipment would be negligible compared to the cost of the endless in-warranty service problems that presently result from pin 1 problems.

In both instances, the long-term elimination of customer complaints, by itself, should be an adequate reward.

8 OBSERVATIONS

1) The present practice of deliberately connecting equipment I/O connector pin 1 terminals to any internal reference point within a shielded device is the most frequently overlooked cause of EMI problems in audio systems, both balanced and unbalanced. It appears to be without precedent in any other field involving electronic systems.

2) The pin 1 problem is unrecognized by many equipment manufacturers. This situation places equipment purchasers in a position of having to understand more about real-world systems than the designers of the equipment.

3) The origin of the OEO rule in balanced audio systems can be traced to much earlier work in broadcast installations involving vacuum-tube equipment interconnected by impedance-matched transmission lines. In electronically balanced systems the OEO rule has been perpetuated as a defensive reaction to the growth of the pin 1 problem for more than 20 years.

4) In portable applications, observing the OEO rule is generally not practical due to time constraints, which often leave little or no room for troubleshooting, and because of the potentially chaotic consequences of having mechanically interchangeable cables, some of which have shields connected at only one end, in the hands of personnel who know how to "plug things in," but do not know what to do when problems arise.

5) The pin 1 problem makes it very difficult to design permanent systems wherein the OEO rule can be universally applied, as disconnecting cable shields at either end in some circumstances may result in RFI problems.

6) The consistent application of the OEO rule at either end of system cables will not solve all noise problems, especially those involving EMI from RF sources both inside and outside a device.

7) The degree of circuit balance achieved by line receiver circuitry in a device is relatively inconsequential in preventing EMI problems if a device has a pin 1 problem.

8) Regardless of the type of equipment setup, system designers should have the ability to connect or disconnect shields according to their own specific requirements, rather than be forced into a compromise situation which does not account for all possible environmental situations.

9) EMI has a negligible effect on equipment that is completely free of pin 1 problems.

9 CONCLUSIONS

1) A cause-and-effect relationship between EMI problems in audio signal processing systems and the practice

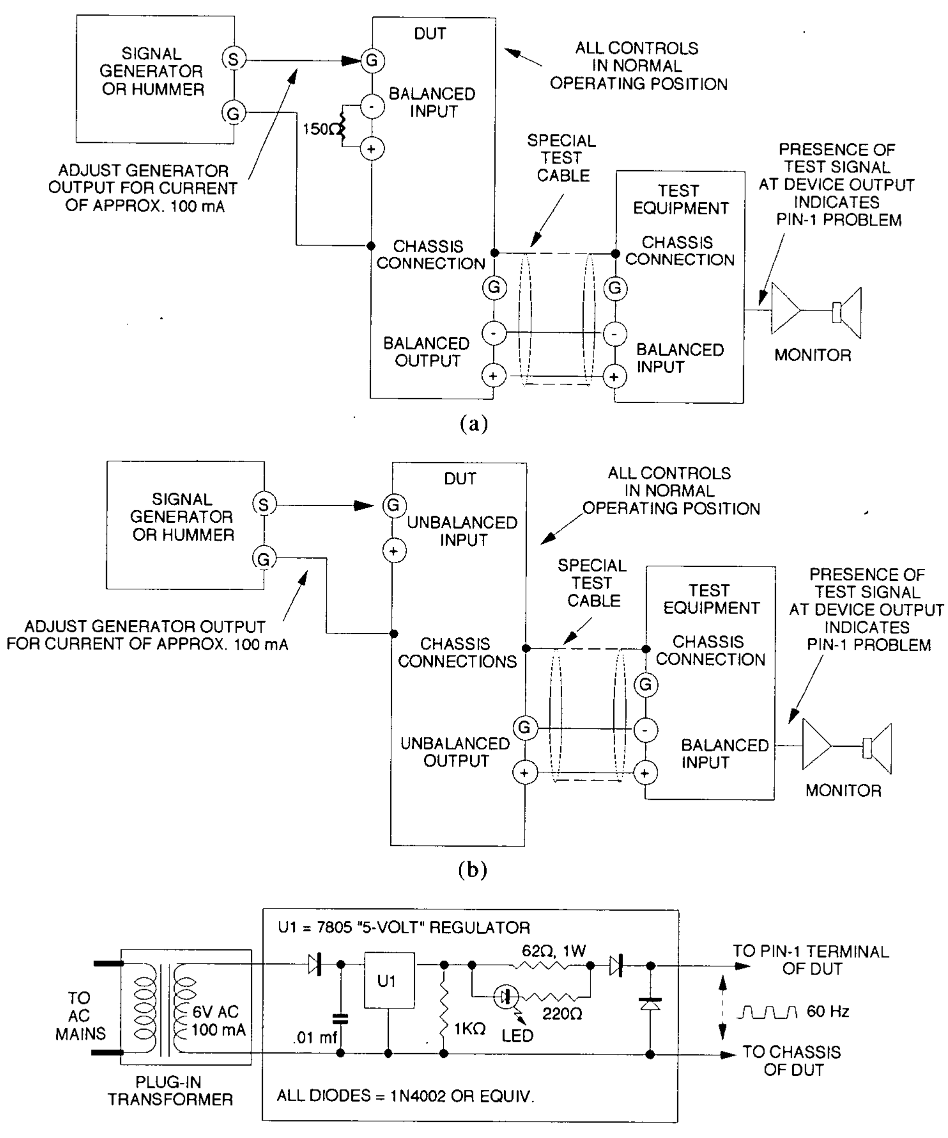


Fig. 10. (a) Connections to balanced device under test (DUT). (b) Connections to unbalanced DUT. (c) "Hummer 2" pin 1 problem locator [12].

of deliberately connecting I/O cable shields to the most convenient circuit ground point within a shielded enclosure has been shown.

2) Common impedance coupling of EMI from external sources can be expected to occur in any device in which signal ground buses are directly connected to an active I/O terminal.

3) Easily implemented means of testing for the pin 1 problem have been outlined. It has been shown that this is not a difficult process.

4) The OEO rule has been reviewed in light of the pin 1 problem. It has been shown that the consistent application of this rule is not possible in systems in which equipment with pin 1 problems is present.

5) The relationship between cable construction and shield-current-induced noise (SCIN) in a signal circuit has been shown in principle. Cable types suitable for portable use generally appear to present negligible shield-current-induced noise problems in systems that afford a dynamic range of 16 bits or less. The potential value of additional work in this area is indicated.

6) Shield-current-induced noise is particularly likely in twisted-pair cable with a shield drain wire that is wrapped in the same direction and pitch as the circuit conductors. The type of shield construction (braid versus foil) is also of importance.

7) The OEO rule should be observed in any low-level signal application involving shielded cable in which the shield drain wire is wrapped with the circuit conductors.

8) Moderate LF cable shield current (<0.1 A) in electronically balanced audio signal transmission lines will be a minor cause of noise in audio systems provided that the cable employed does not incorporate a shield drain wire wrapped with the circuit pair, and provided that the path taken by this noise current does not share audio signal circuit conductors anywhere in the system.

9) It should be obvious to all who have looked toward grounding and shielding as a total answer to all system noise problems that they have been looking in the wrong place.

10) The pin 1 problem will not be permanently eliminated until formal pin 1 recommended practices are developed and universally adopted. AES Standards Committee group SC-05-05 is presently addressing this problem. Interested parties are invited to contact the author.

10 ACKNOWLEDGMENT

The author wishes to thank Philip Giddings, Walt Jung, Ralph Morrison, Cal Perkins, and John Windt for the generous contribution of their insight, expertise, wisdom, comments, and time. Additional thanks are due to Charlie Atkinson, Dennis Bohn, Alan Burdick, Andy Condon, Ken Fause, Fred Gilpin, Irv Joel, Dale Manquen, Dan Queen, Denis Tremblay, Saul Walker, Bill Whitlock, Bill Windsor, and many others for their support. Particular thanks are also due to J. M. Woodgate for reviewing the manuscript and making many helpful suggestions, and finally to Mary Muncy for her endless patience during the creation of this paper.

11 REFERENCES

[1] P. Giddings, *Audio System Design and Installation* (Howard W. Sams, Indianapolis, IN, 1990).

[2] D. Gerke and B. Kimmer, "The Designer's Guide to Electromagnetic Compatibility," *EDN Mag.*, vol. 39, no. 2 (1994).

[3] C. Paul, *Introduction to Electromagnetic Compatibility* (Wiley, New York, 1992).

[4] R. Morrison, *Noise and Other Interfering Signals* (Wiley, New York, 1992).

[5] R. Morrison, *Grounding and Shielding Techniques in Instrumentation*, 3rd ed. (Wiley, New York, 1986).

[6] H. W. Ott, *Noise Reduction Techniques in Electronic Systems*, 2nd ed. (Wiley, New York, 1988).

[7] K. R. Fause, "Fundamentals of Grounding, Shielding, and Interconnection," *J. Audio Eng. Soc. (Engineering Reports)*, vol. 43, pp. 498–516 (1995 June).

[8] B. Whitlock, "Balanced Lines in Audio Systems: Fact, Fiction, and Transformers," *J. Audio Eng. Soc.*, vol. 43, pp. 454–464 (1995 June).

[9] R. Morrison and W. H. Lewis, *Grounding and Shielding in Facilities* (Wiley, New York, 1990).

[10] C. Atkinson and P. Giddings, "Grounding Systems and Their Implementation," *J. Audio Eng. Soc. (Engineering Reports)*, vol. 43, pp. 465–471 (1995 June).

[11] C. Perkins, "Automated Test and Measurement of Common Impedance Coupling in Audio System Shield Terminations," *J. Audio Eng. Soc. (Engineering Reports)*, vol. 43, pp. 488–497 (1995 June).

[12] J. Windt, "An Easily Implemented Procedure for Identifying Potential Electromagnetic Compatibility Problems in New Equipment and Existing Systems: The Hummer Test," *J. Audio Eng. Soc. (Engineering Reports)*, vol. 43, pp. 484–487 (1995 June).

[13] S. R. Macatee, "Considerations in Grounding and Shielding Audio Devices," *J. Audio Eng. Soc. (Engineering Reports)*, vol. 43, pp. 472–483 (1995 June).

[14] S. Harris, "How to Achieve Optimum Performance from Delta-Sigma A/D and D/A Converters," *J. Audio Eng. Soc.*, vol. 41, pp. 782–790 (1993 Oct.).

[15] *Trans. Am. Inst. Elec. Eng.*, vol. 38 (1919 Jan.–June).

[16] P. J. Schram, Ed., *The National Electrical Code Handbook* (National Fire Prevention Association, 1990).

[17] F. Terman, *Radio Engineering* (McGraw-Hill, New York, 1937).

[18] N. Farr, "Professional Audio Wiring Practices Reviewed," (Farrtronics, Ltd., Kitchener, Ont., Canada, 1994).

[19] H. W. Augustadt and W. F. Kannenberg, "Longitudinal Noise in Audio Circuits," *J. Audio Eng. Soc.*, vol. 16, pp. 275–285 (1968 July).

[20] C. Perkins, "Measurement Techniques for Debugging Electronic Systems and Their Interconnection," *Proc. 11th Int. AES Conf.* (Portland, OR, 1992 May).

[21] D. Bohn, "Rane Note 102," Rane Corp., Mukil-

teo, WA (1985).

[22] W. Jung and A. Garcia, "Op Amps in Line-Driver and Receiver Circuits, Part 2," *Analogue Dialog*, vol. 27, no. 1 (1993).

[23] T. M. Hay, "Differential Technology in Recording Consoles and the Impact of Transformerless Circuitry on Grounding Techniques," presented at the 67th Convention of the Audio Engineering Society, *J. Audio Eng. Soc. (Abstracts)*, vol. 28, p. 924 (1980 Dec.), preprint 1723.

THE AUTHOR

Neil Muncy studied electrical engineering at the George Washington University and the Capitol Radio Engineering Institute in Washington, DC. He began his professional career in 1959 as a member of the technical staff of the Johns Hopkins University Applied Physics Laboratory, where he worked on low-level instrumentation, radar, and other related communications research projects. In 1966, after pursuing further studies in physics and business administration at the American University, he founded SSI, Inc., a company that pioneered in the application of operational-amplifier technology in large custom-built multichannel recording consoles, real-time and high speed tape recording, and duplicating systems, and related equipment.

As an independent consultant since 1976, he has specialized in the design of recording and broadcast facilities, the development of solutions to acoustical and technical problems including the elimination of grounding, EMI, and RFI problems in completed installations, and the presentation of papers, lectures and training seminars on audio-related topics. From 1968 to 1986, Mr. Muncy was a guest instructor at the Eastman School of Music in Rochester, NY, participating each summer in the Eastman Recording Institutes. From 1980 to 1989, he also served as one of the principal instructors in the Music Recording Workshop Program sponsored by National Public Radio, in Washington, DC. Recent seminar clients include the Harris Institute for the Arts in Toronto; The Fanshawe College Music Industry Arts Program in London, Ontario; and the Recording Program at the State University of New York at Fredonia. Mr. Muncy has contributed to a number of U.S. and International patents, holds a TEF licence from the California Research Institute Foundation, and was a contributor to the development of the Reflection Free Zone (RFZ™)[1] control room design concept. Recent projects include the redesign and renovation of the second-year music industry arts recording facilities at Fanshawe College in London, Ontario; the development of the LARES[2] reverberation and sound enhancement system for the restoration of the Elgin Theatre in Toronto; the development of the sound recording studio at the Ford Centre for the Performing Arts in North York, Ontario; the redesign and upgrading of the analog disc mastering system for Wilson Audio Specialties in Provo, UT; and the development of the WAVE[3] system for the Wenger Corporation in Owatonna, MN.

He is a member of the Acoustical Society of America, the Audio Engineering Society, the Canadian Acoustical Association, and the Society of Motion Picture and Television Engineers. He has served as chairman of the AES Washington, DC, and Toronto Sections, facilities chairman of the AES International Conference on Digital Audio in Toronto (1989), cochairman of Audio Overview-II in Toronto (1991), membership secretary of the AES Toronto Section for 1990–91, and has twice been nominated for the AES Board of Governors. He is currently serving as chairman of the AES Standards Committee SC-05-05 working group on grounding and EMC practices.

Neil Muncy resides in Toronto with his wife Mary. His hobbies include cooking, gardening, and the restoration of vintage tape recorders.

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[1] RFZ™ RPG Diffusor Systems, Inc.

[2] (Lexicon Acoustic Reverberance Enhancement System) LARES™ Lexicon, Inc.

[3] (Wenger Acoustic Virtual Environment) WAVE™ Wenger corporation.