Contents

Chapter 27 — Online Content

Articles

- Building Contest Scores by Killing Receive Noise — Parts 1 and 2, by Jim Brown, K9YC
- Can Home Solar Power and Ham Radio Coexist?, by Tony Brock-Fisher, K1KP
- Tracking RFI with an SDR One Source at a Time, by Alan Higbie, KØAV
- TV Channel, Amateur Band, and Harmonic Chart
- What to Do if You Have an Electronic Interference Problem — *CEA Handbook*

Projects

- A Home-made Ultrasonic Power Line Arc Detector and Project Update, by Jim Hanson, W1TRC
- A Simple TRF Receiver for Tracking RFI, by Rick Littlefield, K1BQT
- Active Attenuator for VHF-FM by Fao Eenhoorn, PAØZR (article and template)
- Handheld Loop Antenna for RFI Location, by Gary Johnson, NA6O
- RF Sniffer Construction Notes, by Mark Kupferschmid, AC9PR
- Simple Seeker by Dave Geiser, W5IXM
- Tape Measure Beam for Power Line Hunting, by Jim Hanson, W1TRC

Chapter 27

RFI and EMC

This chapter begins with an overview of RF Interference (RFI)-the regulations that manage it, important definitions, and key technical elements. These introductory sections help us understand what interference is along with our responsibilities and privileges as licensed amateurs.

The second part of this chapter is about evaluating and troubleshooting the problems associated with interference. It includes a discussion on identifying the causes and types of interference, RFI-related sources, and specific examples of common systems that are affected by RFI.

A new third section introduces topics associated with electromagnetic compatibility (EMC) that extend beyond RFI. The new material in this edition focuses on transients and protective devices.

The material in this chapter may provide enough information for you to deal with your RFI problem, but if not, the ARRL website offers extensive resources on RF interference at **www.arrl.org/radio-frequency-interference-rfi**. Many topics covered in this chapter are covered in more detail in the *ARRL RFI Book* from a practical amateur perspective.

For this edition, a new section showing how to use a portable SDR to locate sources of RFI was provided by Alan Higbie, KØAV. Alan Applegate, KØBG, also updated the material on RFI in electric and hybrid-electric vehicles.

What was once primarily a conversation about "interference" has expanded to include power systems; incidental, intentional, and unintentional radiators; bonding and grounding; managing transients; and many other related topics and phenomena. These are all grouped together under the general title of *electromagnetic compatibility (EMC)*. The scope of EMC includes all the ways in which electronic devices interact with each other and their environment.

The general term for interference caused by electrical signals or fields is *electromagnetic interference* or *EMI*. You will encounter this term in professional literature and standards. The most common term for EMI involving amateur radio is *radio frequency interference (RFI)* and when a television or video display is involved, *television interference (TVI)*. RFI is the term used most commonly by amateurs today, and that's what we'll use in this chapter.

A few words will be used to apply in a general sense, so they are defined here:

- Neighbor: a person or business either affected by RFI from your station or generating RFI that affects your station.
- Signal: any kind of RF energy, whether it is radiated as an electromagnetic wave or conducted as voltage and current. It doesn't matter if the energy is created intentionally or not.
- Noise: an undesired signal, regardless of what it may or may not sound like as audio and whether or not it is wide- or narrow-band.
- Interference: disruption or degradation of communication by an unwanted signal.

Throughout this chapter you'll also find references to "Ott," meaning the book *Electromagnetic Compatibility Engineering* by EMC consultant Henry Ott, WA2IRQ. EMC topics are treated in far greater depth in Ott's book than is possible in this *Handbook*. Readers interested in the theory of EMC, analysis of EMC mechanisms, test methodology, and EMC standards should be able to borrow a copy through a library.

How To Use this Chapter

RFI is a very broad topic, and there are too many variations of it to provide a "cookbook" approach that can be followed for even the most-common causes. Instead, this chapter provides enough background for you to understand the various ways in which RFI occurs and the tools for dealing with it, no matter what the exact type of RFI it may be. There are special sections for the widespread RFI from power lines and for the unique topics of RFI in mobile stations.

If you are dealing with a case of RFI and are already familiar with the general nature and tools of managing RFI, the sections on specific types of RFI or devices will be a good place to start. If you are just getting started and need background, read the first few sections so you will understand the terms and concepts before beginning your RFI detective work.

RFI is a very interesting part of amateur radio because it touches so many different aspects of the service — you can get a sense of how "connected" RFI is from the many sidebars in the chapters. It affects both the technical and operating aspects as well as all types of electronics fundamentals. Plus, it really develops and exercises your troubleshooting and analysis skills!

27.1 FCC Rules and Regulations

Before presenting the technical elements of RFI, here is an overview of the FCC rules and regulations governing interference. (See the sidebar Regulations and Interference Complaints for references to more detailed information.) This section summarizes the three sets of rules that apply to RFI affecting amateur stations.

The Amateur service is regulated by FCC Part 97. Part 97 rules are available at **www.arrl.org/part-97-amateur-radio.** To be legal, the amateur station's signal must meet all Part 97 technical requirements, such as for spectral purity and power output.

In the United States most unlicensed electrical and electronic devices are regulated by Part 15 of the FCC's rules. These are referred to as "Part 15 devices." Most RFI issues reported to the ARRL involve a Part 15 device. Some consumer equipment, such as certain medical and lighting devices, is covered under FCC Part 18, which pertains to ISM (Industrial, Scientific and Medical) devices. Although some wireless devices do operate in the ISM bands, all such devices that communicate information are not regulated by Part 18, but by other regulations such as Part 15.

As a result, it isn't surprising that most interference complaints involve multiple parts of the FCC rules. (The FCC's jurisdiction does have limits, though — ending below 9 kHz.) It is also important to note that each of the three parts (15, 18 and 97) specifies different requirements with respect to interference, including absolute emissions limits and spectral purity requirements. The FCC does not specify *any* RFI immunity requirements, although the Food and Drug Administration (FDA) does specify immunity levels for some medical devices. Non-radio consumer devices such as wired telephones, audio systems, and wired alarm systems therefore receive no FCC protection from a legally licensed transmitter, including an amateur transmitter operating legally according to Part 97.

PROTECTIONS FROM INTERFERENCE

Amateur radio, being a licensed service, is protected from interference to its signals from unlicensed devices, from spurious emissions from licensed and unlicensed transmitters, and from any transmission by a transmitter that is secondary to the Amateur service. Amateur radio is *not* offered protection from the fundamental signal from transmitters licensed to a service that is primary to amateur radio, such as radar signals operated by the military on the 420 – 450 MHz band. For example, consider RFI from an amateur transmitter's spurious emissions, such as harmonics, that meet the requirements of Part 97 but are still strong enough to be received by nearby FM receivers. The FM receiver itself is not protected from interference from the fundamental signal of nearby licensed transmitters, such as amateur radio, under the FCC rules. However, within its service area the licensed FM broadcast station's signal is protected from harmful interference caused by spurious emissions from other licensed transmitters. In this case, the amateur transmitter's interfering spurious emission would have to be eliminated or reduced to a level at which harmful interference has been eliminated.

27.1.1 FCC Part 97 Rule Summary

While most interference to consumer devices may be caused by a problem associated with the consumer device as opposed to the signal source, all amateurs must still comply with Part 97 rules. Regardless of who is at fault, strict conformance to FCC requirements, coupled with a neat and orderly station appearance, will go far toward creating a good and positive impression in the event of an FCC field investigation. Make sure your station and signal exhibit good engineering and operating practices.

The bandwidth of a signal is defined by §97.3(a)(8), while the paragraphs of §97.307 define the technical standards amateur transmissions must meet. Paragraph (c) defines the rules for interference caused by spurious emissions. As illustrated in **Figure 27.1**, modulation sidebands outside the necessary bandwidth are considered *out-of-band* emissions, while harmonics and parasitic emissions are considered *spurious emissions*. Paragraphs (d) and (e) specify absolute limits on spurious emissions, illustrated in **Figure 27.2**. Spurious emissions must not exceed these levels, whether or not the emissions are causing interference. Even if you meet the limits for spurious emissions, if they are causing interference, it's your responsibility to clean them up.

Strict observance of these rules can not only help minimize interference to the amateur service, but other radio services and consumer devices as well.

Regulations and Interference Complaints

Over the years, this book's RFI chapter has grown from the traditional treatment of TVI (interfering with an analog television receiver) and power line noise (still as big a problem as ever) to cover a wide range of interference and related issues. The subject of managing interference and the associated rules and regulations outgrew many technical sections! The information about regulations and handling interference complaints has been collected and published separately on the ARRL web page as a pair of stand-alone documents. They are available to everyone as a public resource at **arrl.org/rfi**.

FCC Rules and Regulations for Interference includes the FCC regulations and definitions related to interference both to and from your station.

Managing an RFI Complaint discusses how to prepare for and respond to RFI complaints. The various steps of getting your own station in order and obtaining technical assistance are presented along with basic "diplomacy" skills of assessing the problem and suggesting your responses.

These two papers are excellent resources when you are confronted with an interference problem to a neighbor's equipment and are wondering "What do I do now?" The information in the document is based on the experiences of ARRL Lab staff in assisting amateurs with RFI problems.

The material on RFI in this chapter of the *ARRL Handbook* focuses on the technical and practical aspects of interference: what causes it, how can you tell what the source is, techniques for preventing and eliminating it, and good practices that mitigate against it. You can then use these techniques and practices to deal with RFI issues.

When Is a Signal Noise?

In this chapter, the term "signal" can mean any kind of RF energy in a circuit, on a wire, or inside a cable. A signal can be conducted on or in a cable, and it can be radiated. An *interfering signal* disrupts or degrades the reception of a desired signal or disrupts the operation of some electronic device. The term "noise" doesn't necessarily mean buzzing power-line pulses or hissing, cracking static. In a very general sense, "*Noise is any electrical signal present in a circuit other than the desired signal*" (page 3 of Ott). So, noise is any signal you *don't* want, whether it sounds like static or not.

Noise could start out as an intentionally transmitted *signal*, be picked up by a cable shield, and become noise when it causes a device to misbehave. It doesn't matter if the noise is random electrical energy or an intentionally created signal. Your transmitted signal becomes noise when it gets into your home entertainment audio!

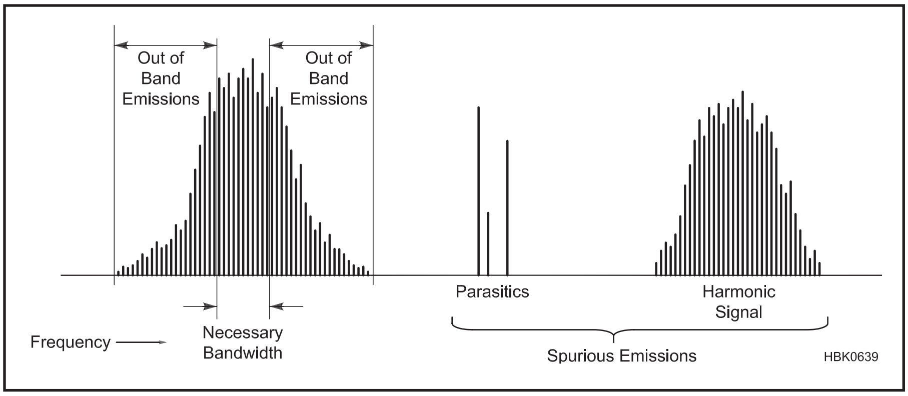


Figure 27.1 — An illustration of out-of-band versus spurious emissions. Some of the modulation sidebands are outside the necessary bandwidth. These are considered out-of-band emissions, not spurious emissions. The harmonic and parasitic emissions shown here are considered spurious emissions; these must be reduced to comply with §97.307.

27.1.2 FCC Part 15 Rule Summary

In the United States, most unlicensed devices are regulated by Part 15 of the FCC's rules. While understanding these rules doesn't necessarily solve an RFI problem, they do provide some important insight and background on interference to and from a Part 15 device.

There are literally thousands of Part 15 devices with the potential to be at the heart of an RFI problem. A Part 15 device can be almost anything not already covered in another Part of the FCC rules. In fact, many Part 15 devices may not normally even be associated with electronics, RF, or in some cases electricity. While televisions, radios, telephones, and even computers obviously constitute a Part 15 device, the rules extend to anything that is capable of generating RF, including electric motors and consumer devices such as baby monitors, wireless microphones and intercoms, RF remote controls, garage door openers, etc. With so many Part 15 consumer devices capable of generating and responding to RF, it isn't surprising therefore that most reported RFI problems involving amateur radio also involve a Part 15 device.

PART 15 SUMMARY

FCC's Part 15 rules pertain to unlicensed devices and cover a lot of territory. Although reading and understanding Part 15 can appear rather formidable — especially at first glance — the rules pertaining to RFI can be roughly summarized as follows:

• Part 15 devices operate under an unconditional requirement to not cause harmful interference to a licensed radio service, such as amateur radio. Even if the manufacturer meets the Part 15 limits for radiated and conducted emissions, if harmful interference occurs, the operator of the Part 15 device is responsible for eliminating the interference.

• Part 15 devices receive no protection from interference from a licensed radio service. There are no FCC rules or limits with regard to Part 15 device RFI immunity.

When is the operator of a licensed transmitter responsible for interference to a Part 15 device?

• The rules hold the transmitter operator responsible only if interference is caused by spurious emissions such as a harmonic that exceeds the Part 97 limits. An example would be a illegal harmonic from an amateur's transmitter interfering with a baby monitor. In this case, the transmitter is generating interfering RF energy beyond its permitted levels. A cure must be installed at the transmitter.

• The transmitter operator is not responsible when a Part 15 device is improperly responding to a legal and intentional output of the transmitter. An example of this case would be interference to a weather radio by the strong-but-legal signal from a nearby amateur transmitter. In this case, the Part 15 device is at fault and the cure must be installed there. It is important to note that this situation is typical of most

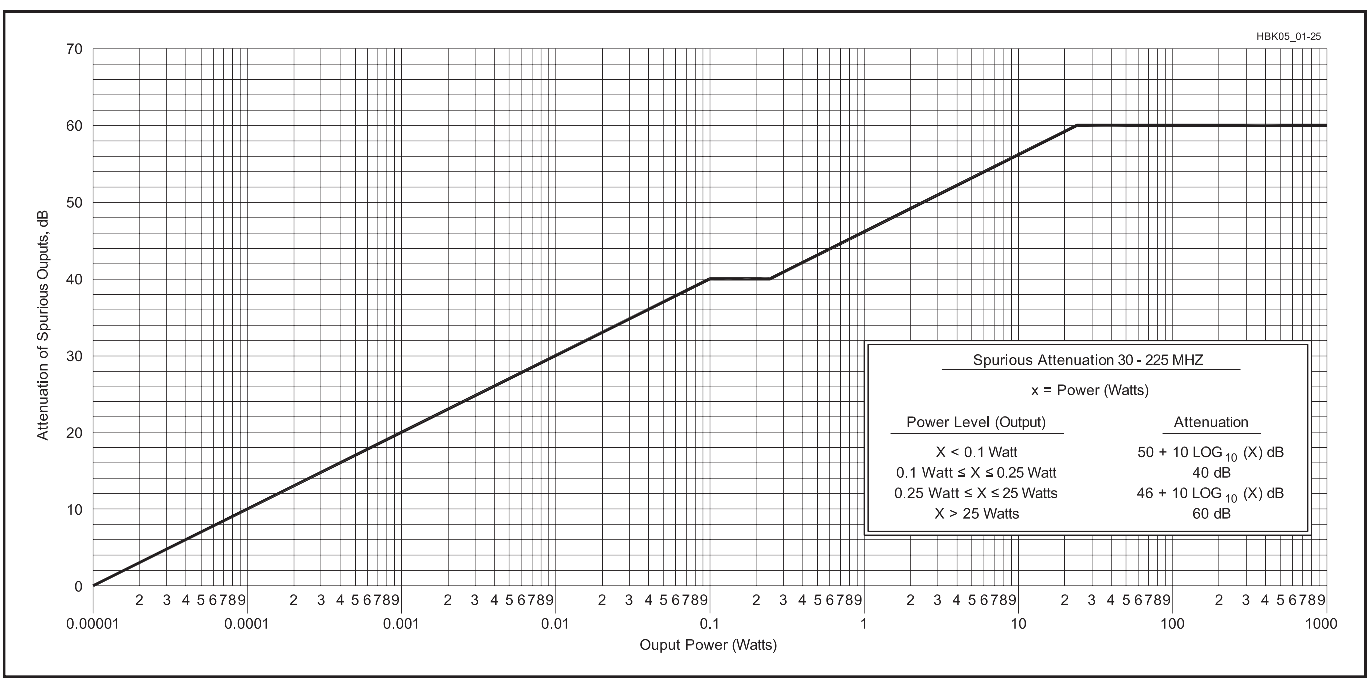


Figure 27.2 — Required attenuation of spurious outputs, 30-225 MHz. Below 30 MHz, spurious emissions must be suppressed by 43 dB for amateur transmitters installed after January 1, 2003.

interference to Part 15 devices.

Even though the causes and cures for these situations are different, the common element for all three situations is the need for personal diplomacy in resolving the problem.

TYPES OF PART 15 DEVICES

Part 15 describes three different types of devices that typically might be associated with an RFI problem. A fourth type of device, called a *carrier current device*, uses power lines and wiring for communications purposes. As we'll see, the rules are different for each type.

Intentional Emitters — Intentionally generate RF energy and radiate it. Examples include garage door openers, cordless phones, and baby monitors.

Unintentional Emitters — Intentionally generate RF energy internally, but do not intentionally radiate it. Examples include computers and network equipment, superheterodyne receivers, switchmode power supplies, and TV receivers.

Incidental Emitters — Generate RF energy only as an incidental part of their normal operation. Examples include power lines, arcing electric fence, arcing switch contacts, dc motors, and mechanical light switches.

Carrier Current Devices — Intentionally generate RF and conduct it on power lines and/or house wiring for communications purposes. Examples include Powerline and X.10 networks, Access or In-House Broadband-Over-Power-Line (BPL), campus radio-broadcast systems, and other power-line communications devices.

27.1.3 FCC Part 18 Rule Summary

Some consumer devices are regulated by Part 18 of the FCC Rules, which pertains to the Industrial, Scientific and Medical (ISM) bands. These devices convert RF energy directly into some other form of energy, such as heat, light, or ultrasonic sound energy. Some common household Part 18 devices therefore include microwave ovens, electronic fluorescent light ballasts, CFLs, and ultrasonic jewelry cleaners. (Note that LED bulbs are covered under Part 15 because of the process by which they generate light.)

Recently, indoor grow light ballasts and related equipment have been causing a lot of RFI. Those sold to consumers are required meet lower Part 18 rules than the higher emissions limits that apply to Part 18 devices sold to industrial and commercial customers. There have been reports of industrial Part 18 devices being sold at home-improvement and other consumer outlets. The ARRL is working with the FCC and manufacturers to resolve this issue.

Consumer Part 18 devices are generators of RF — but not for communications purposes — and can cause interference in some cases. However, there are no rules that protect them from interference. The purpose of Part 18 is to permit those devices to operate and to establish rules prohibiting interference.

From the standpoint of an RFI problem, although Part 18 devices can have unlimited emissions with various bands designated for ISM devices, the Part 18 rules aren't much different from Part 15. As with a Part 15 device, a Part 18 device is required to meet specified emissions limits outside of the ISM bands. Furthermore, it must not cause harmful interference to a licensed radio service operating in other than an ISM band. (The 902 MHz and 2.4 GHz bands are ISM bands, so if interference were to occur from an ISM device, the licensed user would not be protected in these bands). This gets a bit confusing, though, because some Part 15 devices also operate in the "ISM" bands, but as such, they are still Part 15 devices, so licensed services are protected.

27.2 Elements of RFI

This section defines basic terms and concepts associated with RFI that amateurs have to deal with. From these definitions, the chapter will proceed to address the various types of RFI and methods for dealing with them.

27.2.1 Source-Path-Victim

All cases of RFI involve a *source* of radio frequency energy, a device that responds to the electromagnetic energy (*victim*), and a transmission *path* that allows energy to flow from the source to the victim. Sources include radio transmitters, receiver local oscillators, computing devices, electrical noise, lightning, and other natural sources. Note that receiving unwanted electromagnetic energy does not necessarily cause the victim equipment to function improperly.

A device is said to be *immune* to a specific source if it functions properly in the presence of electromagnetic energy from the source. In fact, designing devices for various levels of immunity is one aspect of electromagnetic compatibility engineering. Only when the victim experiences a *disturbance* in its function as a consequence of the received electromagnetic energy does RFI exist. In this case, the victim device is *susceptible* to RFI from that source.

There are several ways that RFI can travel from the source to the victim: *radiation*, *conduction*, *inductive coupling,* and *capacitive coupling*. *Radiated RFI* propagates by electromagnetic radiation from the source through space to the victim. *Conducted RFI* travels over a physical conducting path between the source and the victim, such as wires, enclosures, ground planes, and so forth. Inductive coupling occurs when two circuits are magnetically coupled. Capacitive coupling occurs when two circuits are coupled electrically through capacitance. Typical RFI problems you are likely to encounter often include multiple paths, such as conduction and radiation. (See the section Shields and Filters, also Ott, sections 2.1 – 2.3.)

Many instances of RFI are a combination of radiated and conducted RFI. Conducted RFI exits the source as current on one or more conductors connected to the source. The conductors act as transmitting antennas for the common-mode current. A conductor connected to the victim then picks up the radiated noise as common-mode current which is conducted to the victim.

27.2.2 Differential-Mode vs Common-Mode Signals

The path from source to victim almost always includes some conducting portion, such as wires or cables. RF energy can be conducted directly from source to victim, be conducted onto a wire or cable that acts as an antenna where it is radiated, or be picked up by a conductor connected to the victim that acts like an antenna. When the noise is traveling along the conducted portion of the path, it is important to understand the differences between *differential-mode* and *common-mode* signals (see **Figure 27.3**).

Differential-mode signals usually have two easily identified conductors. In a two-wire transmission line, for example, the signal leaves the generator on one wire and returns on the other. When the two conductors are in close proximity, they form a transmission line and the two signals have opposite polarities as shown in Figure 27.3A. Most desired signals, such as the TV signal inside a coaxial cable or an Ethernet signal carried on CAT5 network cable, are conducted as differential-mode signals.

A common-mode circuit consists of two or more wires in a multi-wire cable acting as if they were a single path as in Figure 27.3B. Common-mode circuits also exist when the outside surface of a cable's shield acts as a conductor as in Figures 27.3C and 27.3D. (See the chapter on **Transmission Lines** for a discussion about isolation between the shield's inner and outer surfaces for RF signals.) The return path for a common-mode signal often involves earth ground. Common-mode currents are the net result of currents for which there is not an equal-and-opposite current in the same conductors or group of conductors

Figure 27.3D illustrates the case for a signal and its return path both enclosed in a separate shield. This is a common arrangement for digital data or control signals in a multiconductor cable with a dedicated signal return or signal ground wire. The cable shield should be kept separate from all data and data return connections.

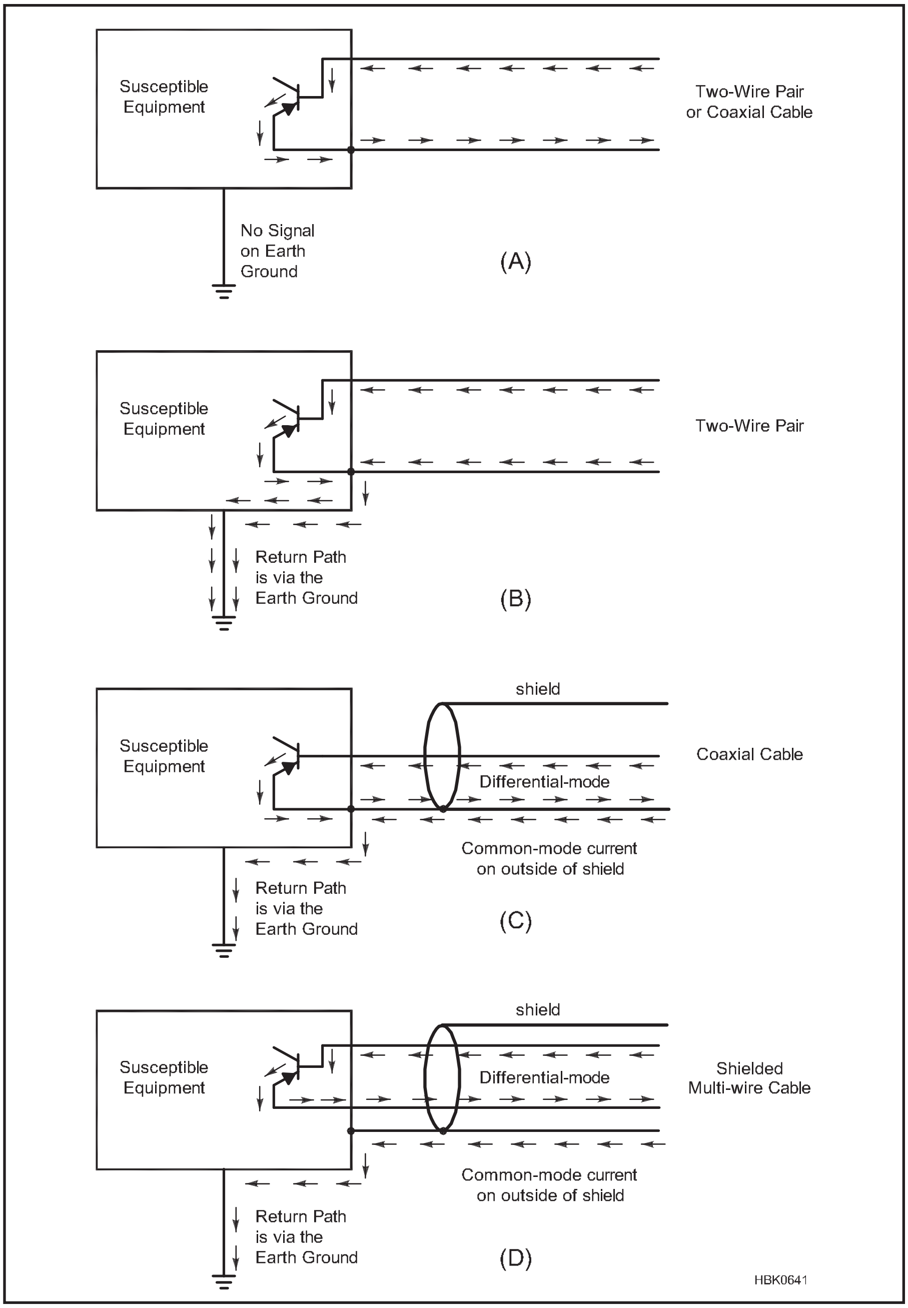


Figure 27.3 — Typical configurations of common-mode and differential-mode current. The drawing in A shows the currents of a differential-mode signal, while B shows a common-mode signal with currents flowing equally on all of the source wires. In C, a common-mode signal flows on the outside of a coaxial cable shield with a differential-mode signal inside the cable. In D, the differential-mode signal, such as a data signal with a dedicated return circuit, flows on the internal wires, while a common-mode signal flows on the outside of the cable shield.

External noise generated by electronic equipment and RFI caused to electronic equipment is often associated with common-mode current on a cable shield that is improperly connected. For example, consider what happens when the cable shield in Figures 27.3C and 27.3D is not connected to the enclosure but enters the device before connecting to a circuit's common or ground connection. In this case, any noise generated by the circuit has a path out of the enclosure and onto the surface of the cable shield where it is then radiated. Similarly, any noise or signals picked up by the cable shield are conducted into the equipment, where it is connected to the circuit and can disrupt normal operation or interfere with the desired signals. This is discussed more in this chapter's section Elements of RFI Control.

COMMON-MODE AND POWER WIRING

There is an important difference between the preceding definition and what ac power companies consider common-mode. Corcom is a major manufacturer of power line RFI filters and related components. (See **www.te.com/usa-en/products/emi-filters/power-line-filters.html**.) Common-mode is defined in their Product Guide's appendix on "Understanding Insertion Loss," as "signals present on both sides of the line (hot and neutral) referenced to ground." The RF definition of common-mode in this book includes signals on the ground conductor, as well as hot and neutral.

Because the ground connection through a power-line RFI filter is typically a direct connection between input and output, a typical ac-line filter may be ineffective against common-mode RF flowing on the ground conductor. To block RF on the ground conductor of a three-wire ac power cord or cable, the usual remedy is to wind the ac power cord on a ferrite core. This places an impedance in all three conductors, not just hot and neutral.

27.2.3 Differential- and Common-Mode Paths

As shown in **Figure 27.4**, RFI's path from source to victim almost always includes some conducting portion, such as wires or cables. In addition, the interfering signal may be radiating from conductors and picked up by an antenna or by cables unintentionally acting as antennas. Four common paths include:

- Conducted directly from source to victim,
- Conducted on a wire or cable acting as an antenna where it is radiated, then received by the victim's antenna,
- Radiated then picked up by a conductor connected to the victim,
- Inductive and capacitive coupling when the source and victim are very close together.

Many RFI problems are caused by con-

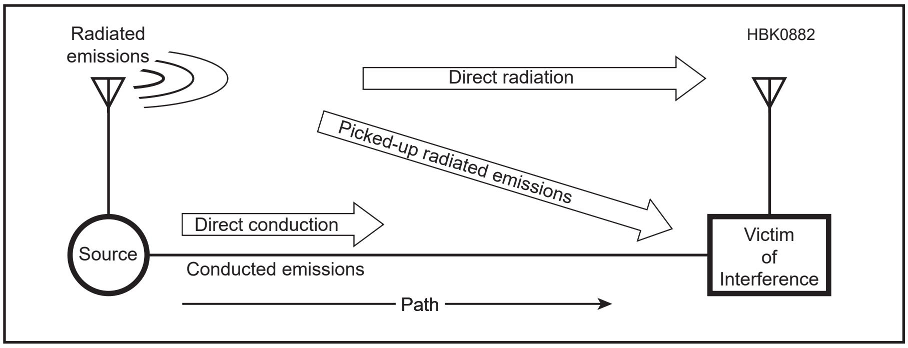


Figure 27.4 — A block diagram showing every RFI problem involves three elements — a source, a path, and a victim. Fixing the problem requires removing one or more of them.

ducted emissions which leave the source as common-mode signals on wiring connected to the source. The interfering signal may travel directly from the source to the victim, or it might be radiated by the wiring and picked up by wiring connected to the victim. The same design or production problems that enable conducted emissions can also work in reverse, allowing the signal that has been picked up to be conducted into the victim where it causes the interference.

The path also includes the interfering signal's return path back to the source, which is different for differential- and common-mode signals. A differential-mode signal's return path is almost always in the same cable. The return path for common-mode signals often involves earth ground, or even the chassis of equipment if it is large enough to form part of an antenna at the frequency of the RFI.

27.2.4 Grounding and Bonding

An electrical ground is not a huge sink that somehow swallows noise and unwanted signals. Ground is a *circuit* concept, whether the circuit is small, like a radio receiver, or large, like the propagation path between a transmitter and AM/FM receiver. Ground refers to a shared reference voltage between circuits. Bonding refers to connections between pieces of equipment.

GROUNDING

While grounding is not a cure-all for RFI problems, ground is an important safety component of any electronics installation. It is part of the lightning protection system in your station and a critical safety component of your house wiring. Any changes made to a grounding system must not compromise these important safety considerations. Refer to the **Safe Practices** chapter for important information about safety grounding. The ARRL book *Grounding and Bonding for the Radio Amateur* goes into detail about ground systems for electrical safety, lightning protection, and managing RF voltages and currents.

Many amateur stations have several connections referred to as "grounds:" the required safety ground that is part of the ac wiring system, an earth connection for lightning protection, and shared connections between equipment, such as the negative terminal of a dc power supply. These connections can interact with each other in ways that are difficult to predict. Rearranging the station ground connections may cure some RFI problems in the station by changing the RF current distribution so that the affected equipment is at a low-impedance point and away from RF "hot spots." It is better to address the problem by implementing proper bonding within the station.

BONDING

Bonding refers to a connection intended to minimize potential (voltage) differences. The purpose of bonding in the amateur station is to minimize the potential difference between equipment and all elements of the ground system — ground rods, entry wiring for electrical power, telephone or data systems, cable or satellite TV systems, and amateur antennas. This minimizes voltage differences in the event of lightning surges. It also minimizes hum and buzz and reduces RFI resulting from voltage differences between pieces of equipment.

Creating a low-impedance connection between your station's equipment is easy to do and will help reduce voltage differences (and current flow) between pieces of equipment. Bonding is discussed in this book's **Assembling a Station** and **Safe Practices** chapters.

Bonding also reduces voltage differences between the ends of cable shields that are connected to different pieces of equipment. This voltage difference is effectively in series with the cable shield and can be added to the desired signals carried by the cable or cause common-mode RF to flow on the shield. The voltage difference can be at ac power, audio, or RF so bonding helps reduce RFI across a wide frequency range.

The conductors used for bonding should be heavy enough to have low inductance and resistance. The standard for commercial and military facilities is solid copper strap, but heavy stranded or solid wire (bare or insulated)

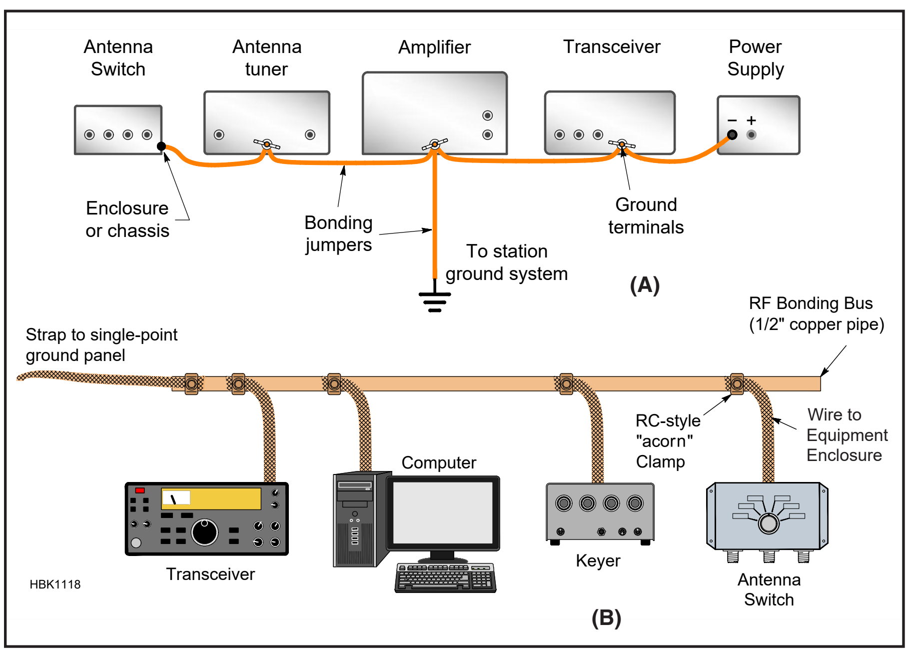


Figure 27.5 — Direct equipment-to-equipment bonding (A). Use heavy wire or strap connected to a single ground terminal or enclosure screw on each piece of equipment, including computers and related gear. The same approach can be used in home entertainment systems or with computers and accessories. Part B shows the common use of a bonding bus. This allows equipment to be added or removed without reworking other connections. The bonding bus works better with a ground reference plane.

Bonding and Chokes and RFI

Grounding and bonding in your station is also important for lightning safety and to help manage RF currents and voltages picked up by the wiring and cables. Bonding equipment in your station (see the **Assembling a Station** chapter) helps minimize common-mode RF current in the station that can cause improper operation. Make sure cable shields are connected properly and that RF current picked up from your transmitted signal by audio and power wiring is minimized. Learn how to apply ferrite RF chokes in sensitive spots. These are useful techniques in many different situations to eliminate interference.

RFI and End-Feeding in the Station

An end-fed antenna brought directly into the station is often adjusted to produce a current-maximum (low-impedance point) at the feed point. The feed point is often the output of an antenna tuner, so the feed point is actually *in* the station. If a resonant counterpoise is not attached to the tuner, the resulting current will couple to and flow on whatever conductors happen to be connected to or close to the enclosures of the transmitter and tuner, including ground system and signal connections. Common-mode current on the outside of an antenna feed line can act in the same way. To address this situation, make sure equipment is bonded together properly, as well as the ground system, and provide the necessary counterpoise for the end-fed wire or a common-mode choke for the antenna feed line (see the **Transmission Lines** chapter).

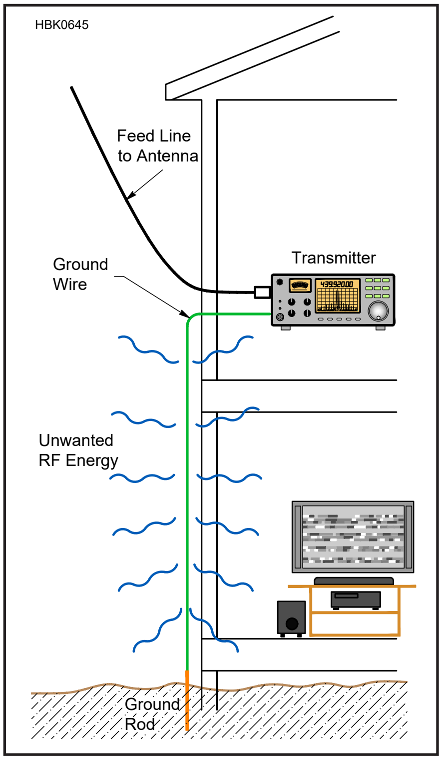


Figure 27.6 — An earth ground connection can radiate signals that might cause RFI to nearby equipment. This can happen if the ground connection is part of an antenna system, or if it is connected to a coaxial feed line carrying RF current on the outside of the shield.

works well. Flat woven braid will also work if kept dry and jacketed braid is available for use outdoors or in vehicles. Braid removed from coaxial cable is not recommended — leave the braid in the cable jacket and use it as a large wire.

As shown in **Figure 27.5**, equipment enclosures can be connected either directly together or by using a bonding bus or ground reference plane as shown in the chapter on **Assembling a Station**. Amateur radio and home entertainment equipment usually has a ground screw or terminal that can be used for bonding. Chassis connections for many computers can be found at the shell of video or data connectors.

LENGTH OF GROUND CONNECTIONS

The required ground connection for lightning protection between the station equipment and an outside ground rod is at least several feet long in most practical installations. (See the **Safe Practices** and **Assembling a Station** chapters for safety and lightning protection ground requirements.)

In general, however, a long connection to earth should be considered as part of an RFI problem since it will act as part of the antenna system. For example, should a long-wire HF antenna terminate in the station, a ground connection of *any* length is a necessary and useful part of that antenna and will radiate RF.

At VHF a ground wire can be several wavelengths long — a very effective antenna for any harmonics that could cause RFI! For example, in **Figure 27.6**, signals radiated from the required safety ground wire could very easily create an interference problem in the downstairs electronic equipment. Noise from the electronic equipment can also be picked up by the ground wire and carried back to the station as interference.

GROUND LOOPS, HUM, AND BUZZ

A *ground loop* is created by a continuous conductive path around a series of equipment enclosures. While this does create an opportunity for lightning damage and RF pickup, the ground loop itself is rarely a cause of problems at RF. The potential for problems created by loops can be minimized by proper bonding of equipment and by minimizing the loop area formed by cables and wiring.

Ground loops are usually associated with audio hum caused by coupling to power-frequency magnetic fields from transformers or motors and sometimes from coupling to high-current power wiring. The hum appears as a nearly pure sine wave at the frequency of the ac power system, 50 or 60 Hz. To avoid low-frequency ground-loop issues, use short cables that are the minimum length required to connect the equipment and bundle them together to minimize the area of any enclosed loop. Moving the cables away from the source of the magnetic field or reorienting the source or cables can reduce hum. Bonding equipment together to short-circuit a loop is sometimes effective.

Audio "buzz" is caused primarily by currents at harmonics of the ac power frequency. The current results from leakage in ac-powered equipment with rectifiers or switching circuits that conduct during parts of the ac power waveform. Buzz is addressed by bonding and by ensuring the ac power ground connections have a minimum of these voltages on them.

27.3 Tools for RFI Control

Building from the basic definitions and mechanisms of RFI in the previous section, we now turn our attention to the techniques for managing and controlling it. This section will become your "tool kit" for dealing with RFI.

Differential-Mode and Common-Mode Combinations

Most RFI problems involve a combination of differential-mode and common-mode signals or noise. The right type of filter is required for each type of signal. In many cases, a noisy device creates both differential-mode and common-mode currents due to various imbalances in the device and the wiring it is connected to. A susceptible device experiencing interference from a nearby transmitter can be the result of both common-mode and differential-mode signals being picked up on its wiring. Imbalance in ac or signal wiring usually results in both types of signals being created and coupled into and out of devices. For this reason, in many cases both common-mode and differential-mode filtering may be required, even on the same cable.

27.3.1 Breaking the Path

Even if you can't eliminate the source, by preventing the RFI-causing signals or noise from reaching the victim, the problem can be solved. As described above, the path may be conducting or radiated at different points along the way. Be aware there may be more than one path! Use the tools and techniques described in the following sections to "break the path."

Breaking the path between source and victim is often an attractive option, especially if either is a consumer electronics device. The path will involve one or more of the possibilities — radiation, conduction, or coupling. Determining the path can require analysis and experimentation in some cases. Obviously, you must know what the path is before you can break it. While the path may be readily apparent in some cases, more complex situations may not be so clear. Multiple attempts at finding a solution may be required, but identifying the path is crucial to successfully managing the problem.

When the interfering signal is traveling along the conducting portion of its path, it is important to understand whether it is as a differential- or common-mode signal. This determines what techniques will be effective against the signal *at that point in the path*.

Differential-mode techniques (a high-pass filter, low-pass filter, or a bypass capacitor across the ac power line, for example) do not attenuate common-mode signals. As another example, a differential-mode filter does not usually filter the ground lead in a three-wire ac cord or cable (see **Figure 27.7**), so any common-mode signals or noise present on the ground conductor of the ac wiring would be coupled directly through the filter. Similarly, a common-mode choke will not affect differential-mode signals. In practice, conducted emissions problems are more likely to be the result of common-mode than differential-mode signals.

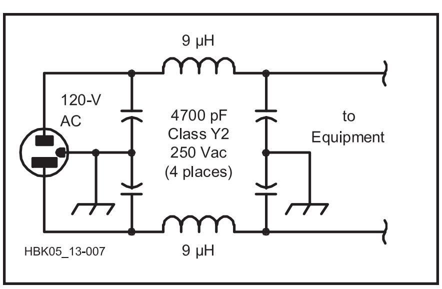


Figure 27.7 — A "brute-force" ac-line filter. Note there is no filtering on the chassis ground connections. See the text's discussion of differential- and common-mode paths.

27.3.2 Shielding

Shielding can be used to control radiated emissions — that is, signals radiated by wiring inside the device — or to prevent radiated signals from being picked up by signal leads in cables or inside a piece of equipment (direct detection). Shielding can also be used to reduce inductive or capacitive coupling, usually by acting as an intervening conductor between the source and victim.

Shields are used to set boundaries for radiated energy and to contain electric and magnetic fields. At RF, the small skin depth allows thin shields to be effective at these frequencies. (see the **RF Techniques** chapter). Thin conductive films, copper braid, and sheet metal are the most common shield materials for the electric field (capacitive coupling), and for electromagnetic fields (radio waves).

Thicker shielding material is needed for magnetic fields (inductive coupling) at low frequencies to minimize the voltage caused by induced current. At audio frequencies and below, the higher skin depth of common shield materials is large enough (at 60 Hz, the skin depth for aluminum is 0.43 inches) that special high-permeability materials such as steel or mu-metal (a nickel-iron alloy that exhibits high magnetic permeability) are required.

Maximum shield effectiveness usually requires solid sheet metal that completely encloses the source or susceptible circuitry or equipment. While electrically small holes generally do not affect shield effectiveness (fine-mesh screening makes good shielding at VHF and below, for example), seams can act as a slot antenna if they are a significant fraction of a wavelength long. In addition, mating surfaces between different parts of a shield must be conductive. To ensure conductivity, file or sand off paint or other nonconductive coatings on mating surfaces.

The effectiveness of a shield is determined by its ability to reflect or absorb the undesired energy. Reflection occurs at a shield's surface. In this case, the shield's effectiveness is independent of its thickness. Reflection is typically the dominant means of shielding for radio waves and capacitive coupling, but is ineffective against magnetic coupling. Most RFI shielding works, therefore, by reflection. Any good conductor will serve in this case, even thin plating.

Magnetic material is required when attempting to break a low-frequency inductive coupling path by shielding. A thick layer of high permeability material is ideal in this case. Although the near field of low frequency magnetic fields can extend for long distances, magnetic fields generally have their greatest effect at relatively short range. Simply increasing the distance between the source and victim may help avoid the expense and difficulty of implementing a shield.

Adding shielding may not be practical in many situations, especially for many consumer products that have non-conductive enclosures. Adding a shield to a cable can minimize capacitive coupling and RF pickup, but it has no effect on magnetic coupling. Replacing parallel-conductor cables (such as zip cord speaker wire) with twisted-pair is quite effective against magnetic coupling and also reduces electromagnetic coupling.

Additional material on shielding may be found in chapter 2 of Ott (see the References).

27.3.3 Filters

Filters can be very effective in dealing with RFI by blocking or suppressing the unwanted signal. Fortunately, filters are simple, economical, and easy to try. In many cases, filters can also be applied externally to the victim device, avoiding the need to open an enclosure. Solving an RFI problem without having to alter a device's internal wiring is almost always preferable to the alternative. (See the **Analog and Digital Filtering** chapter for more information on filters of all types.)

Most stand-alone filters are differential-mode filters for signals in a cable or connector. They may or may not affect common-mode signals depending on filter design. Be sure you know which type you want to use and how the filter will perform on the type of signal you are trying to reject. A common-mode cable filter, such as a choke, is designed not to affect differential-mode signals and noise in the cable, for example. (See the section below on Common-Mode Chokes.)

Filters vary in attenuation characteristics, frequency characteristics, and power-handling capabilities. The names given to various filters are based on these characteristics and their intended application. (More information on filters may be found in the **Analog and Digital Filtering** chapter.) Unless otherwise noted, the filter types in this section are differential-mode filters.

It's relatively simple to build a differential-mode filter that passes desired signals and blocks unwanted signals with a high series impedance. An alternative filter technique presents a low shunt or parallel impedance to the signal, effectively "shorting it out." Some filters, such as the popular pi-circuit ac line filters, combine both techniques.

Low-pass filters pass frequencies below some cutoff frequency, while attenuating frequencies above that cutoff frequency. A typical low-pass filter curve is shown in **Figure 27.8**. A schematic is shown in Figure 27.13B. Filters capable of handling 100 W of RF or more can be difficult to construct properly, so many hams choose to buy them. Many *QST* advertisers stock low-pass filters.

High-pass filters pass frequencies above some cutoff frequency while attenuating frequencies below that cutoff frequency. A typical high-pass filter curve is shown in **Figure 27.9**. Figure 27.9B shows a schematic of a typical high-pass filter. For receiving applications, designs for building your own filters are abundant, and components are fairly inexpensive. Commercial products are widely available.

Band-stop or ***band-reject filters*** reject a narrow range of frequencies. These are also referred to as "notch filters" or "traps" and are often used to reject strong signals from nearby FM, TV, or commercial VHF/UHF transmitters that operate on one channel. The filter can remove an entire band (for example, 88-108 MHz for FM broadcast) or a single channel (such as the common shore station frequency of 160.650 MHz, Marine VHF channel 1). Amateurs use band-reject filters to reduce the strength of nearby AM broadcast signals when operating on the HF bands.

AC-line filters, sometimes called "brute-force" filters, are used to remove RF energy from ac power lines. A typical schematic is shown in Figure 27.7. Note that no filtering is performed on the ground or common connection. (See the Elements of RFI section for the definition for common-mode by utilities and ac power systems.)

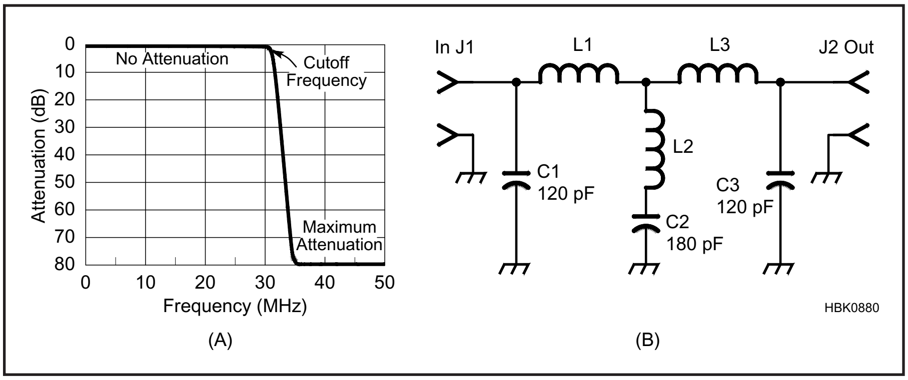


Figure 27.8 — (A) An example of a low-pass filter's response curve. (B) A low-pass filter schematic for amateur transmitting use. Complete construction information appears in the Transmitters chapter of *The ARRL RFI Book*. A high-performance 1.8-54 MHz filter project can be found in the Analog and Digital Filtering chapter of this *Handbook*.

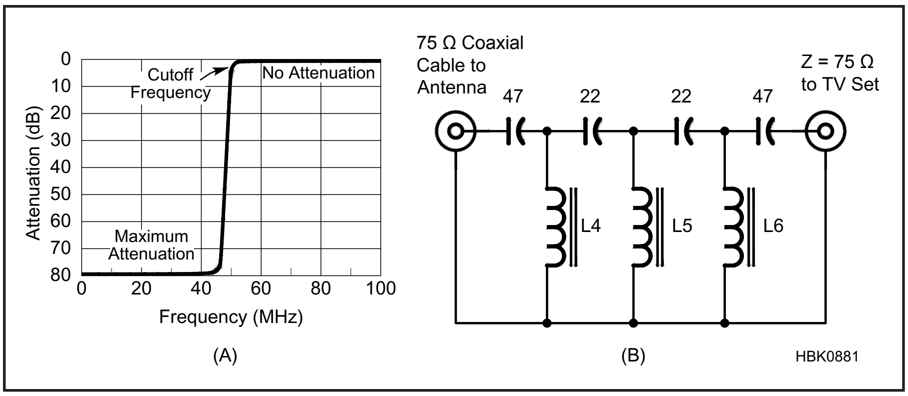


Figure 27.9 — (A) An example of a high-pass filter's response curve. (B) A differential-mode high-pass filter for 75-Ω coaxial cable. It rejects HF signals picked up by a TV antenna or that leak into a cable-TV system. All capacitors are high-stability, low-loss, NP0 ceramic disc components. Values are in pF. The inductors are all #24 AWG enameled wire on T-44-0 toroid cores. L4 and L6 are each 12 turns (0.157 μH) and L5 is 11 turns (0.135 μH).

AC-line filtering products are widely available from various sources. In addition to amateur radio equipment distributors, filters can be sourced direct from manufacturers such as Corcom **(www.corcom.com)** and Mor-gan Systems (**www.surgestop.com**). Some of these are stand-alone filters with ac plugs and sockets, such as the Morgan Systems M-471 filter shown in **Figure 27.10A**. Others, such as the Corcom model no. 10VS1 (Figure 27.10B), would need to be wired in

Figure 27.10 — Two AC line filters. A Morgan Systems M-471 (A) is a plug-in filter. The Corcom 10VS1 (B) is wired in place.

(A)

(B)

Warning: Bypassing Speaker Leads

Older amateur literature might suggest connecting a 0.01-µF capacitor across an amplifier's speaker output terminals to cure RFI from common-mode current picked up by speaker cables. Don't do this! Doing so can cause some modern solid-state amplifiers to break into a destructive, full-power, sometimes ultrasonic oscillation if they are connected to a highly capacitive load. Use common-mode chokes and twisted-pair speaker cables instead.

place by the installer. SMT EMI filters are now available for brush DC motors as well, which are increasingly common in consumer appliances. See the *Microwaves & RF* article by Jeff Elliott in the References section for more information.

AC-line filters come in a wide variety of sizes, current ratings, and attenuation. It is wise to look for an ac-line filter with both common- and differential-mode filtering (the Morgan Systems M-471 is a good example of such a filter). In general, a filter must be physically larger to handle higher currents at lower frequencies. The Corcom 1VB1, for example, is a compact filter small enough to fit in the junction box for many low voltage lighting fixtures, provides good common-mode attenuation at MF and HF (only on the hot and neutral lines), and its 1 A at 250 V ac rating is sufficient for many LV lighting fixtures. In general, you will get more performance from a filter that is physically small if you choose the filter with the lowest current rating sufficient for your application. (Section 13.3 of Ott covers ac-line filters.)

The best location for an ac-line filter is at the enclosure of the equipment causing the RFI. Filter modules can be bonded to the enclosure through the case of the filter (best) or via a bonding jumper to the enclosure. Bond the enclosure of the filter to the enclosure of the equipment by the shortest possible path. Many metal enclosures are painted, which defeats the bonding of either a filter case, terminal, or solder lug. Remove paint from wherever a bonding connection is made.

Some commercial filters are built with an integral IEC power socket, and can replace a standard IEC connector if there is sufficient space behind the panel. (IEC is the International Electrotechnical Commission, an international standards organization that has created specifications for power plugs and sockets. See the **Safe Practices** chapter for a drawing of an IEC connector.) The case of such a filter is bonded to the enclosure, and interconnecting leads are shielded by the enclosure, optimizing its performance.

AC-line filters connected externally to equipment through a cord require extra attention. Any wiring between a filter and the equipment being filtered acts as an antenna and forms an inductive loop that degrades the performance of the filter. All such wiring should be as short as possible, and should be twisted. As described above, they do not apply filtering to the ground conductor, which remains active for RFI. Wind several turns of the wiring on a ferrite core to block common-mode RF current on the ground conductor.

AC-line capacitors — A capacitor between line and neutral or between line and ground at the noise source or at victim equipment can solve some RFI problems. ("Ground" in this sense is not "earth," it is the power system equipment safety ground — the green wire — at the equipment.) Power lines, cords, and cables are often subjected to short-duration transients of very high voltage (4 kV). Ordinary capacitors are likely to fail when subjected to these voltages, and the failure could cause a fire. Only Type X1, X2, Y1 and Y2 capacitors should be used on power wiring. AC-rated capacitors can safely handle being placed across an ac line along with the typical voltage surges that occur from time to time. Type X1 and X2 capacitors are rated for use between line and neutral, and are available in values between 0.1 µF and 1 µF. Type X2 capacitors are tested to withstand 2.5 kV, type X1 capacitors to 4 kV. Type Y1 and Y2 capacitors are rated for use between line and ground; Y1 capacitors are impulse tested to 8 kV, Type Y2 to 5 kV. Note that 4700 pF is the largest value permitted to be used between line and ground — larger values can result in excessive leakage currents.

Bypass capacitors provide a low-impedance path for RF signals away from an affected lead or cable. A bypass capacitor is usually placed between a signal or power lead and the equipment chassis or enclosure. If the bypass capacitor is attached to a shielded cable, the shield should also be connected to the enclosure. Bypass capacitors for HF signals are usually 0.01 µF, while VHF bypass capacitors are usually 0.001 µF. Leads of bypass capacitors should be kept short, particularly when dealing with VHF or UHF signals.

27.3.4 Cable Shield Connections

The outer surface of cable shields are potential antennas for RFI, either radiating or receiving unwanted signals regardless of the shield's quality. Improperly connected shields on audio, RF, and data cables are a common source of radiated and conducted emissions. They provide a path into equipment for common-mode RF that has been picked up on a cable shield as common-mode current. As a result, an improperly connected shield is a likely cause of RFI if the victim device is unable to reject the unwanted common-mode signals. This is why it is important to connect cable

Filter Both Modes at Once

If an amateur decides on filtering the ac line supplying equipment belonging to a neighbor, it is often best to resolve that problem as quickly and efficiently as possible. Experimenting to find out which type of filter is needed often leads to frustration on the part of the neighbor, who may quickly lose confidence in the ham's ability to resolve the problem. For this reason, it is usually advisable to install both common-mode and differential-mode filtering on a neighbor's device as shown in **Figure 27.A1**, resolving the interference that is present and making future interference less likely.

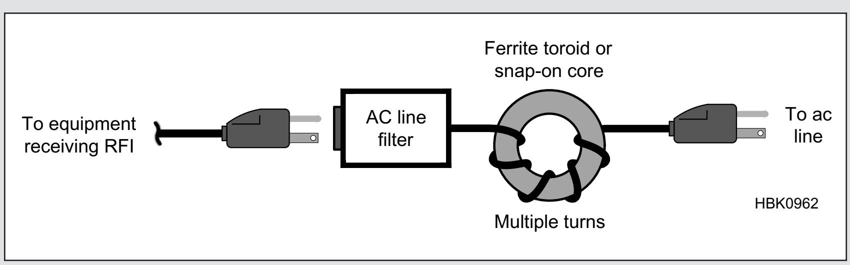


Figure 27.A1 — An ac line filter and a ferrite RF choke combined in the ac line to the affected equipment block both differential- and common-mode current. The line filter can be a stand-alone model with plugs and receptacles or a module in a grounded metal enclosure. The ferrite mix should be Type #31 (for HF) or Type #43 (for middle HF through VHF). Either a toroid or clamp-on core can be used if multiple turns can be wound on the core to create sufficient choking impedance.

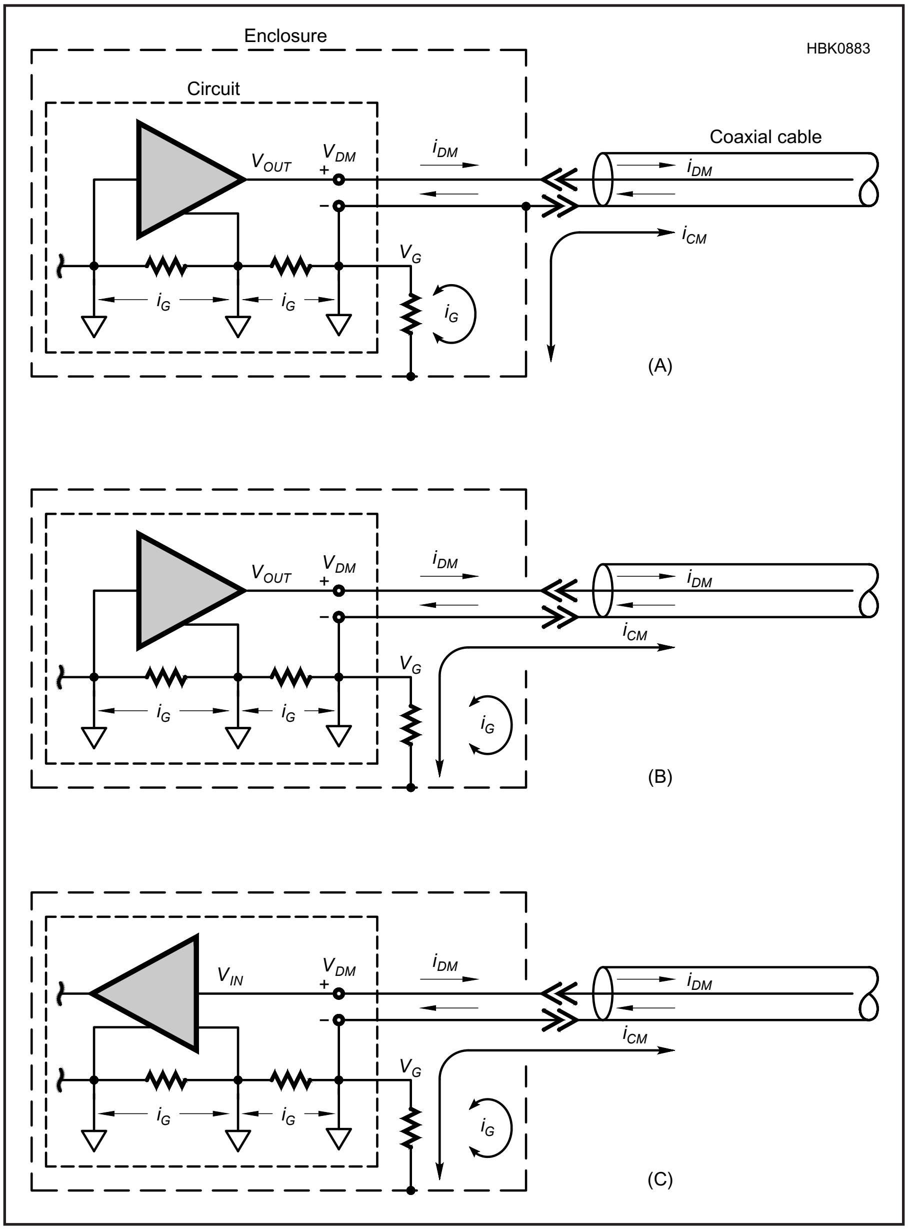


Figure 27.11 — Properly (A) and improperly (B, C) connected shields showing undesired paths for common-mode current into and out of equipment. Improperly connected shields create an ingress and egress path for RF common-mode current. See the text for discussion.

shields in such a way that common-mode currents flowing on the shields are not allowed to enter the victim device or leave the source device.

Figure 27.11 illustrates the basic reasoning as to how cable shields should be connected. This is a very simplified overview to illustrate the basic concepts. Figure 27.11A shows a metal enclosure and an internal circuit, usually on a PC board. In the circuit itself, there is a common connection that could be a ground plane or point-to-point wiring or traces. Either way, there is some small impedance between any two points in the circuit's ground system. This is shown by the resistor symbols. Current flowing in the ground system is shown as i_G. The usual practice is to connect the ground system to the enclosure (chassis ground) through a wire or hardware. That, too, has some impedance, shown as a resistor.

The actual voltage applied to the cable connection, V_{DM}, is not equal to V_{OUT}. The ground currents flowing through the ground system impedances create small voltages. So does the ground current flowing through the connection between the circuit ground system and the enclosure. All of these voltages combine to create V_G, which then combines with the amplifier output voltage, V_{OUT}, to create V_{DM}.

Outside the enclosure, a coaxial cable is terminated in an RF connector, such as a PL-259, BNC, Type N, or even a shielded, metal phono plug. The differential-mode signal currents inside the cable (shown as i_{DM}) flow on the cable's center conductor and the *inside* of the cable shield. If a signal is picked up by the cable, the resulting common-mode current (shown as i_{CM}) flows on the *outside* of the cable shield. Due to the skin effect, the inside and outside of the cable shield are independent conductors for RF currents.

On the inside of the mating connector (such as an SO-239) a cable or wire pair connect the i_{DM} currents to the circuit. In Figure 27.11A, the center conductor in the cable is connected to some kind of amplifier output (V_{OUT}) and the enclosure-connected part of the connector to the circuit's common or ground terminal. If the connector and shield are attached properly, there is no path between the circuit's differential-mode common terminal and the outside, common-mode surface of the cable shield. Similarly, whatever current i_{DM} is flowing inside the cable, it cannot flow to the outside of the cable where it would become common-mode current and radiate an unwanted signal — a radiated emission.

Figure 27.11B shows what happens when the shield connection goes through the enclosure and is connected directly to the inner circuit ground system. The common-mode current path is now open to i_G that flows in the connection from the circuit ground system to the enclosure. This allows noise and signals from the circuit to escape the enclosure as a radiated emission. The path is also open for i_{CM} to flow in the enclosure connection and add to the voltage that makes up V_G. Depending on the ground system impedance, some of i_{CM} can add to i_G, as well. This allows external noise and signals to get into the circuit's ground system and disrupt its operation.

Figure 27.11C illustrates the situation when the differential-mode signal is an input to the circuit. Noise and signals on the circuit ground system can still escape the enclosure. In addition, the common-mode current i_{CM} combines with i_G, which modifies V_G and V_{IN}. This can easily cause a lot of problems if the circuit is a receiver front end or other sensitive function.

Figure 27.3D showed a similar situation with two wires inside a shield. This is common for data or control connections where there might be several data lines and a dedicated signal return or signal ground circuit that is separate from the overall shield. Treat the signal return circuit as an independent circuit and do not connect it to the enclosure. Most shielded data cables have separate signal ground and shield connections. Only the shield should connect to the enclosure.

Not connecting the shield at all breaks the path for the desired differential-mode current on the inside of the shield. This forces it to find another return path, often through ground systems or power wiring. The gap in the shield creates an antenna similar to a magnetic loop that not only radiates the differential-mode signal but allows the undesired common-mode current to combine with the differential-mode signals. The whole system acts as if it were unshielded.

The need to connect the shields of cables to a shielding enclosure is clear whether they are coaxial cables, shielded twisted-pair, or multiconductor data cables. If the shield connection penetrates the enclosure and is connected directly to the circuit's ground system, both radiated emissions and incoming RFI are the likely result. In addition, the unintended current path can affect the impedance of the connection to the cable as discussed in the material on common-mode chokes later in this section and in the **Transmission Lines** chapter. It is possible to devise alternate connections, such as for transceiver microphone cables, but RF filtering or chokes and careful circuit ground system design and construction are required.

27.3.5 Common-Mode Chokes

Common-mode chokes on ferrite cores are the most effective answer to RFI from a common-mode signal. Differential-mode filters are *not* effective against common-mode signals. (AC-line filters usually only perform differential-mode filtering as described in the preceding section.) Common-mode chokes work differently, but equally well, with coaxial cable and paired conductors. (Additional material on common-mode chokes is found in sections 3.5 and 3.6 of Ott.) Common-mode chokes can often solve RFI problems, especially at HF where common-mode current is more likely to be the culprit.

The most common form of common-mode choke is multiple turns of cable wound on a ferrite toroid core as shown in **Figure 27.12**. The following discussion applies to chokes wound on rods as well as toroids, but avoid rod cores since they may couple to nearby circuits at HF. At HF, toroid cores are recommended — beads and clamp-on ferrite cores are usually adequate.

Common-mode chokes using ferrite cores are discussed at length in the **RF Techniques** and **Transmission Lines** chapters. They block common-mode RF current by adding a large value of resistive impedance in series with the common-mode circuit. The choke actually behaves as a parallel-self-resonant circuit that includes the winding inductance and stray capacitance along with the resistance of the core material at that frequency. (The electrical characteristics of ferrite at RF are discussed in the **RF Techniques** chapter.)

Most of the time, a common-mode signal on a coaxial cable or a shielded, multi-wire cable is a current flowing on the outside of the cable's shield. By wrapping the cable around a magnetic core the current creates a flux in the core, creating a high impedance in series with the outside of the shield. (The impedance required for an effective choke depends on the circumstances and can range from a few hundred to several thousand ohms.) The impedance then blocks or reduces the common-mode current. Because equal-and-opposite fields are coupled to the core from each of the differential-mode currents, the common-mode choke has no effect on differential-mode signals inside the cable.

When the cable consists of two-wire, unshielded conductors such as zip cord or twisted-pair, the equal-and-opposite differential currents each create a magnetic flux in the

Figure 27.12 — A common-mode RF choke wound on a toroid core is shown at top left. Several styles of ferrite cores for common-mode chokes are also shown.

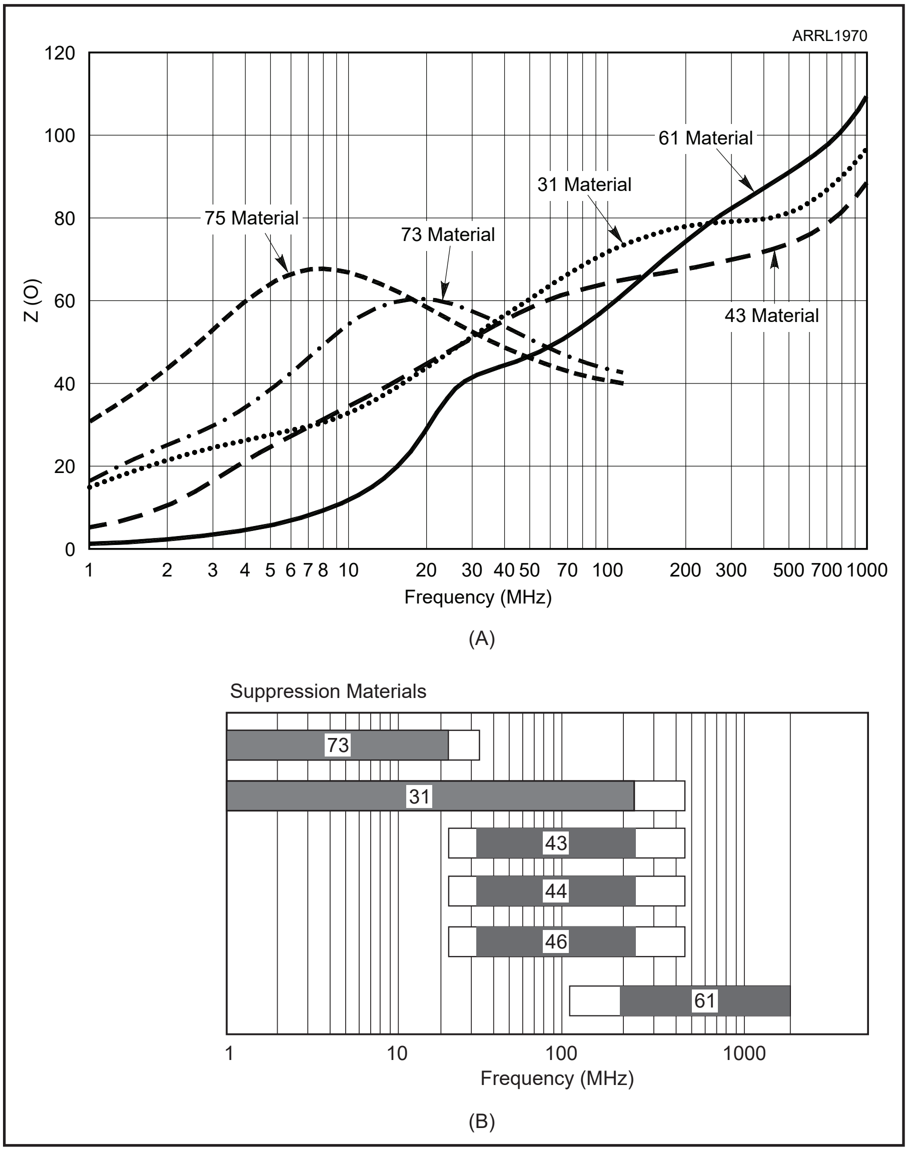


Figure 27.13 — Impedance vs. frequency plots (A) for a single wire passed through one ferrite bead, 3.50 mm diameter x 6.00 mm long (Fair-Rite size 301). Not all mixes are available is all types of cores and beads. The chart at (B) shows frequency ranges for various ferrite mixes used for EMI suppression. Type #73 and 75 material cover approximately the same range. [Charts provided courtesy of the Fair-Rite Products Corporation].

core. The equal-and-opposite fluxes cancel each other, and the differential-mode signal experiences zero net effect. To common-mode signals, however, the choke appears as a high impedance in series with the signal: the higher the impedance, the lower the common-mode current.

It is important to note that common-mode currents on a transmission line, coaxial or parallel-conductor, will result in radiation of a signal from the feed line. (See this section's sidebar for an explanation of balanced and unbalanced transmission lines.) The radiated signal can then cause RFI in nearby circuits. This is most common when using coaxial cable as a feed line to a balanced load, such as the dipole in the sidebar. Reducing common-mode current with a common-mode choke at the antenna feed point and where the feed line enters the residence can help reduce RFI caused by signals radiated from the feed line's shield.

Common-mode noise is also picked up by feed lines. If it is allowed to flow into the station, it can also be converted to differential-mode signals at connectors and by coupling to other cables and wiring in the station. Chokes can block this current and eliminate this source of received noise and unwanted signals, which can contribute to the noise level considerably.

FERRITE MATERIALS FOR RFI CONTROL

The self-resonance of a conductor passing once through most ferrite cores (considered to be one turn) used for suppression is in the range of 150 MHz, and this is where a core simply clamped around a cable will be effective. To obtain good suppression in the range of 1 – 50 MHz, we must wind multiple turns through the ferrite core to lower the resonant frequency. Common-mode chokes are typically wound on toroid cores with a 1-inch or greater inside diameter or a split-core clamp-on core. (Ferrite materials are discussed extensively in the **RF Techniques** chapter.)

Figure 27.13 is a combined graph of the impedance of single turns through a ferrite bead of different mixes. It gives an idea of the range of available ferrites. By using the right material and the right number of turns through the core, choke impedance can be optimized for resistance and for the frequency range desired. Resistive impedance is desired to avoid interacting with the conductor's reactance at the frequency of use. The right material to use is specified for "suppression" over the frequency range required. (From low to high frequencies, Fair-Rite mixes #73 (beads only), #75, #31, #43, and #61 are of the most use to amateurs.) This means the core's impedance is primarily resistive in that range. Chokes wound on these cores have a very low Q (because they are dissipating energy instead

Warning: Surplus Ferrite Cores

Don't use a core to make a common-mode choke if you don't know what type of material it is made of. Such cores may not be effective in the frequency range you are working with. This may lead to the erroneous conclusion that a common-mode choke doesn't work when a core with the correct material would have done the job. The **RF Techniques** chapter includes a test procedure for determining the type of ferrite. It is often better to simply purchase known cores.

Feed Line Radiation — The Difference Between Balanced and Unbalanced Transmission Lines

The physical differences between balanced and unbalanced feed lines are obvious. Balanced lines are parallel-type transmission lines, such as ladder line or twin lead. The two conductors that make up a balanced line run side-by-side, separated by an insulating material (plastic, air, whatever). Unbalanced lines, on the other hand, are coaxial-type feed lines. One of the conductors (the shield) completely surrounds the other (the center).

In an ideal world, both types of transmission lines would deliver RF power to the load (typically your antenna) without radiating any energy along the way. It is important to understand, however, that both types of transmission lines require a balanced condition in order to accomplish this feat. That is, the currents in each conductor must be equal in magnitude, but opposite in polarity.

The classic definition of a balanced transmission line tells us that both conductors must be symmetrical (same length and separation distance) relative to a common reference point, usually ground. It's fairly easy to imagine the equal and opposite currents flowing through this type of feeder. When such a condition occurs, the fields generated by the currents cancel each other — hence, no radiation. An imbalance occurs when one of the conductors carries more current than the other. This additional "imbalance current" causes the feed line to radiate.

Things are a bit different when we consider a coaxial cable. Instead of its being a symmetrical line, one of its conductors (usually the shield) is grounded. In addition, the currents flowing in the coax are confined to the outside portion of the center conductor and the inside portion of the shield.

When a balanced load, such as a resonant dipole antenna, is connected to unbalanced coax, the outside of the shield can act as an electrical third conductor (see **Figure 27.A2**). This phantom third conductor can provide an alternate path for the imbalance current to flow. Whether the small amount of stray radiation that occurs is important or not is subject to debate. In fact, one of the purposes of a balun (a contraction of balanced to unbalanced) is to reduce or eliminate imbalance current flowing on the outside of the shield. See the **Transmission Lines** chapter of this book for more information on baluns.

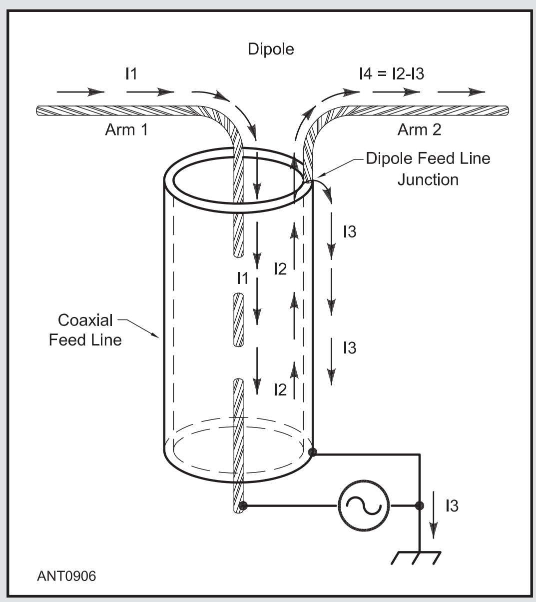


Fig 27.A2 — Various current paths are present at the feed point of a balanced dipole fed with unbalanced coaxial cable. The diameter of the coax is exaggerated to show the currents clearly.

of storing it) so the choke's bandwidth can be as much as an octave. Chokes can be combined to work over different frequency ranges by placing chokes optimized for different ranges in series.

Type #31 material is a good all-purpose material for HF and low-VHF applications, especially at low HF frequencies. Type #43 is widely used for HF through VHF and UHF. See the **RF Techniques** chapter for more information on ferrite materials and characteristics. This discussion only touches on the basic characteristics of ferrite-core common-mode chokes as they apply to dealing with RFI.

27.4 Types of RFI

There are several basic types of RFI involving amateur radio. The appropriate remedies for each are different, and the correct one must be used for each mechanism. It is important to note that RFI may be caused by more than one type of RFI, particularly from one of the strong-signal causes.

The first three occur when a strong signal causes RFI. This can occur even for a transmitted signal that is in complete compliance with all rules for signal quality. In order of likelihood:

1) Fundamental Overload — Disruption or degradation of a receiver's function in the presence of a transmitted fundamental signal (the intended signal from the transmitter). The unwanted signal is received normally along with desired signals, but the transmitted signal is simply too strong for the victim receiver's circuitry to reject — a true overload situation.

2) Common-mode breakthrough — The interfering signal is picked up as common-mode current on an external cable which is then conducted into the victim device's circuitry, where it disrupts normal operation. This is also referred to as *common-mode ingress* and RF "getting into" a piece of equipment.

3) Direct pickup* or *direct detection — The interfering signal is picked up directly by the victim device's internal wiring without any external cabling or wiring required.

The following types of RFI occur, again in order of likelihood, when the receiver functions normally but reception of a desired signal is interfered with by RF energy received along with the desired signal.

1) Spurious Emissions — Signals from the transmitter as defined in the previous section on Part 97 definitions and Figure 27.1. For example, harmonics of a transmitted signal can be received with and interfere with a desired signal even though they are not strong enough to cause fundamental overload.

2) External Noise Sources — RF energy transmitted incidentally or unintentionally by a device that is not a licensed transmitter. For example, impulse noise from motors or power lines.

3) Intermodulation — Intermodulation distortion (IMD) products generated by signals mixing together internally or externally to the receiver.

As an RFI troubleshooter, start by determining which of these is involved in your interference problem. Once you know the type of RFI, identifying the cause and selecting the most appropriate cure for the problem becomes much easier.

27.4.1 Interference from Strong Signals

FUNDAMENTAL OVERLOAD

Most cases of interference caused by an amateur transmission are due to fundamental overload. Properly designed radio receivers of any sort should be able to select the desired signal while rejecting all others. Unfortunately, because of design limitations or deficiencies such as inadequate shields or filters, some radio receivers are unable to reject strong out-of-band signals. Even amateur receivers can exhibit fundamental overload. There does not need to be anything wrong with the interfering signal — it's just too strong for the receiver to reject.

A signal causing fundamental overload is received along with the desired signals in the normal signal path, such as an FM or TV antenna, usually as a differential-mode signal such as inside coaxial cable. A good solution might be to put a filter in the path of the incoming signals to block the strong amateur signal while passing the desired signals, which are presumably in some other band. An attenuator at the receiver's signal input path can also help as long as the desired signals can still be received properly.

Significant improvement can often result from just moving the victim equipment's antenna and the signal source farther away from each other. The effect of an interfering signal is directly related to its strength, diminishing with the square of the distance from the source. If the distance from the source doubles, the strength of the RF signal decreases to one-fourth of its power density at the original distance from the source.

Reducing the level of the offending strong signal often returns the receiver to normal operation and eliminates the undesirable effects. This characteristic can often be used to help identify an RFI problem as fundamental overload. If gradually reducing the strength of the signal source causes the interference to abruptly disappear, that is a signature of fundamental overload.

COMMON-MODE BREAKTHROUGH

A strong signal can enter equipment in several different ways. Most commonly, it is conducted into the equipment after being picked up by connecting wires and cables. Possible RFI conductors include antennas and feed lines, interconnecting signal and control cables, power cords, and ground wires. TV antennas and feed lines, telephone or speaker wiring, and ac power cords are the most common points of pickup and subsequent entry.

Once inside the equipment, the signal is conducted to electronic circuits that are probably not designed to reject unwanted RF signals. The unwanted signal might then be detected or transformed by the circuit to ac or dc signals that disrupt its normal functions. Since the cause of the problem is an unintended RF signal path from outside the equipment, the usual remedy is to block the path with an RF choke or filter, depending on the type of connection. The common-mode RF signal must be kept out of the affected equipment to cure the problem.

DIRECT DETECTION

Direct detection occurs when wiring or circuitry that is internal to the equipment being affected picks up RF energy directly. Direct detection RFI can be very difficult to eliminate since it does not involve an external signal path that can be blocked or filtered. Examples of equipment that experience direct detection are battery-powered consumer devices in unshielded (plastic or wood) or poorly shielded metal enclosures. This permits the RF signal to be picked up by the wiring in the device. Eliminating the interference would require modifying the device, adding shielding, or perhaps simply moving the device farther from the transmitted signal source.

27.4.2 Interference from Spurious Signals

All transmitters generate some (hopefully few) RF signals that are outside their intended transmission bandwidth — these are the out-of-band emissions and spurious emissions as shown in Figure 27.1. Out-of-band signals result from distortion in the modulation process or consist of broadband noise generated by the transmitter's oscillators that is radiated along with the intended signal. Harmonics, the most common spurious emissions, are signals at integer multiples of the operating (or fundamental) frequency.

Transmitters may also produce broadband noise and/or parasitic oscillations as spurious emissions. (Parasitic oscillations are discussed in the **RF Power Amplifiers** chapter.) Overdriving an amplifier often creates spurious emissions. Amplifiers not meeting FCC certification performance standards but sold illegally are frequent sources of spurious emissions.

Regardless of how the unwanted signals are created, if they cause interference, FCC regulations require the operator of the transmitter to correct the problem. The usual cure is to adjust or repair the transmitter or use filters at the transmitter output to block the spurious emissions from being radiated by the antenna.

27.4.3 Interference from External Noise Sources

Most cases of interference to amateur stations reported to the FCC are eventually determined to involve some sort of external noise source, rather than signals from a radio transmitter. Noise in this sense means an RF signal that is not essential to the generating device's operation.

The most common external noise sources are electrical, primarily power lines. Motors, switching equipment, and street lighting can also generate electrical noise. The section Power Line Noise addresses this type of interference.

Noise radiated by switchmode systems such as power supplies, digital equipment, and variable-speed drives is increasingly common. Other common sources of external noise are grow lights being used in various forms of indoor gardening and some solar power installations. External noise can also come from unlicensed Part 15 RF sources such as computers and networking equipment, video games, appliances, and other types of consumer electronics.

Regardless of the source, if you determine that the problem is caused by external noise, elimination of the noise must take place at the source. As an alternative, several manufacturers also make noise canceling devices that can help in some circumstances.

27.4.4 Interference from Intermodulation Distortion

Intermodulation distortion (IMD) is caused by two signals combining in such a way as to create intermodulation products — signals at various combinations of the two original frequencies. The two original signals may be perfectly legal, but the resulting intermodulation distortion products could occur on frequencies used by other services and cause interference in the same way as a spurious signal from a transmitter. The process of combination can occur outside or inside the receiver.

External IMD is sometimes called the "rusty bolt effect" because it can occur in any nonlinear connection that is located very near transmitting sources or very near victim receivers. This is often caused by contact between dissimilar metals, with corroded metals being the worst offenders.

The resulting IMD product signals include the modulation of both signals. For example, intermodulation from two SSB or FM voice signals produces somewhat distorted signals with the modulating signals of both stations. Since the two signals are not synchronized, the intermodulation products come and go unpredictably, existing only when both of the external signals are present.

INTERFERENCE FROM EXTERNAL IMD

IMD can be generated externally by signals mixing together in non-linear junctions or connections. IMD products generated externally cannot be filtered out at the receiver and must be eliminated where the original signals are being combined.

IMD is a common problem at sites that host multiple high-power transmitters such as AM broadcast stations or commercial and public safety communications sites, which are often hosts to amateur repeaters. In some cases, two or more signals can combine in the output stages of one of the transmitters (also known as *cross-modulation*) to create the IMD products. The solution is to increase isolation between the affected transmitter(s).

INTERFERENCE FROM INTERNAL IMD

As discussed in the chapter on **Receiving**, IMD can also be generated *inside* a receiver by strong signals. This is a situation similar to fundamental overload in which the signals are so strong that the receiver circuits can't process them as independent signals. The solution is generally to reduce signal levels into the receiver by using an attenuator or filter so that it is no longer acting non-linearly.

27.5 RFI Troubleshooting Guidelines

Troubleshooting an RFI problem is a multistep process, and all steps are equally important. Each step in troubleshooting an RFI problem will involve asking and answering several questions: Is the problem caused by harmonics, fundamental overload, common-mode breakthrough, conducted emissions, radiated emissions, or a combination of all of these factors? Should it be fixed with a low-pass filter, high-pass filter, common-mode chokes, or ac-line filter? How about shielding, isolation transformers, a different ground or antenna configuration? By the time you finish with these questions, the possibilities could number in the millions. You probably will not see your exact problem and cure listed in this book or any other. You must not only diagnose the problem but find a cure as well!

Now that you have learned some RFI fundamentals, you can work on specific technical solutions. A systematic approach will identify the problem and suggest a cure. Most RFI problems can be solved in this way by the application of standard techniques. The following sections suggest specific approaches for different types of common interference problems. This advice is based on the experience of the ARRL RFI Desk, but is not guaranteed to provide a solution to your particular problem. Armed with your RFI knowledge, a kit of filters and tools, your local TC, and a determination to solve the problem, it is time to begin. You should also get a copy of the *ARRL RFI Book*. It's comprehensive and picks up where this chapter leaves off.

> **RFI Email Reflector**
>
> A good source of information and help is the RFI email reflector maintained on the **contesting.com** website **lists.contesting.com/mailman/listinfo/RFI**. Simply subscribing in digest form provides a daily dose of RFI discussion. Before asking your question, however, be sure to check the reflector's searchable archives to see if your topic has been covered recently.

27.5.1 Basic Troubleshooting Principles

Amateur radio teaches a lot of skills, and a very valuable skill is thinking in terms of the whole communications system, from the power supply all the way through the antenna, to the other station, and back again. RFI is just one type of system-level troubleshooting and as you will discover even involves non-amateur equipment! The troubleshooting skills you learn from finding and fixing RFI can also be applied to other problems in your station, so here are some general principles to learn:

Know the Symptoms — Before beginning any kind of troubleshooting, be sure you know what it is you're trying to fix! Write down what the problem is and list all of the symptoms you can.

Be Sure It's Not Improper Configuration — Make sure the features of affected equipment are configured properly and its controls and switches are set correctly. Many a "dead" radio simply has the squelch turned all way up so that no signals are strong enough to be heard.

Make a Plan — After you have the symptoms defined and are sure the affected equipment is not just misconfigured, sketch out a few steps from making tests to trying solutions. Be sure to think about how you will know the problem is really fixed!

Take Controlled Steps — Each step in the process should be intended to discover or measure something specific. Don't just "shotgun" a problem or try things on a whim hoping that you'll get lucky.

Change One Thing at a Time — Try to change as few things as possible in each step. If you have to change several things, have a plan for figuring out the effect of each change.

Keep Notes — Have a notebook or open a memo file to record what you're doing and what you learn. Clearly labeled photos or sketches are also helpful. This is the place to capture "What if…" ideas and things you notice.

Don't Jump to Conclusions — Along with taking controlled steps, avoid the temptation to abandon your plan and decide what the cause of the problem is without taking the intermediate steps to be sure.

Test Your Conclusions — At the end, after you're sure you've identified and corrected the problem, make tests to verify the problem has, indeed, been solved.

Report What You've Learned — Don't assume you'll remember what you found out. Capture it in writing or in a voice memo or a video/photo. If you made changes to your station, record them in your station notebook. Share the results with others if the solution has value beyond your station!

27.5.2 RFI Troubleshooting Steps

Here are the general steps in RFI troubleshooting. Remember that "noise" refers to whatever type of signal is causing the problem.

1. Determine the type(s) of RFI problem you have.
2. Determine the type of noise source(s) and the victim(s) that are involved.
3. Diagnose the problem by locating the noise source and the means by which it creates the noise.
4. Identify the path by which the noise or signals reach the victim device.
5. Eliminate the source or break the path from source to victim.

AT THE BEGINNING

At Your Station — Make sure that your own station and consumer equipment are operating correctly. This eliminates them as possible sources of interference, and when this is done, you won't need to diagnose or troubleshoot your station. Also, any cures successful at your house may work at your neighbor's as well. If you do have problems in your own home, continue through the troubleshooting steps and specific cures and take care of your own problem first.

Is It Really RFI? — Before trying to solve a suspected case of RFI, verify that the symptoms actually result from external causes. A variety of equipment malfunctions or external noise can look like interference. (Remember that we are using "RFI" to apply to any kind of RF-related EMI, including TVI.) For example, a failing power supply can turn something on and off erratically. A misconfigured TV can behave in unexpected ways. Just mistuning a receiver can create distorted audio. There are lots of ways to cause problems besides RFI, so start with an open mind about what the problem actually is.

RFI Survival Kit — **Table 27.1** is a list of material most often needed to troubleshoot and solve most RFI problems. Having all of these materials in one container, such as a small tackle or craft box, makes the troubleshooting process go a lot smoother.

ASSESS THE SITUATION

Look Around — Aside from the brain, the eyes are a troubleshooter's best tool. Installation defects contribute to many RFI problems. Look for loose connections, shield breaks in a cable-TV installation, corroded battery contacts, damaged cables, or anything that looks like it might cause a problem. Fix these first.

Look for Unintended Antennas — Look for wiring connected to the victim equipment that might be long enough to be resonant on one or more amateur bands. If so, a common-mode choke may be an easy cure. Ideally, you'll generally want to place the choke as close to the victim device as practical. If this placement proves too difficult or additional suppression is required, chokes placed at the middle of the wiring may help break up resonances. These are just a few of the possible deficiencies in a home installation.

Is It a Transmitted Signal from Your Station? — "Your" RFI problem might be caused by another ham or a radio transmitter of another radio service, such as a local CB or police transmitter. If it appears that your station is involved, operate your station on each band, mode, and power level that you use. Note all conditions that produce interference. If no transmissions produce the problem, your station *may* not be the cause. (Although some contributing factor may have been missing in the test.) Have your neighbor take notes about when and how the interference appears: what time of day, what station, what other appliances were in use, what was the weather? You should do the same whenever you operate. If you can readily reproduce the problem with your station, you can start to troubleshoot the problem.

Table 27.1
RFI Survival Kit

Quantity	*Item*
(2)	75-Ω high-pass filter
(2)	Commercially available clamp-on ferrite cores: #31 and #43 material, 0.3" ID
(12)	Assorted ferrite cores: #31 and #43 material, FT-140 and FT-240 size
(3)	Telephone RFI filters
(2)	Brute-force ac line filters
(6)	0.01-µF ceramic capacitors
(6)	0.001-µF ceramic capacitors

Miscellaneous:
- Hand tools, assorted screwdrivers, wire cutters, pliers
- Hookup wire
- Electrical tape
- Soldering iron and solder (use with caution!)
- Assorted lengths of 75-Ω coaxial cable with connectors
- Spare F connectors, male, and crimping tool
- F-connector female-female "barrel"
- Clip leads
- Notebook and pencil
- Portable multimeter

WHILE TROUBLESHOOTING

Take One Away — Can you remove the source or victim entirely? The best cure for an RFI problem is often removing the source of the noise. If the source is something broken, for example, the usual solution is to repair it. Power-line noise and an arcing electric fence usually fall into this category. If a switchmode power supply is radiating noise, replace it with a linear supply. Victim devices can sometimes be replaced with a more robust piece of equipment as well, such as replacing an old 49 MHz cordless phone with a current model that uses spread-spectrum multi-GHz signals instead.

Simplify the Problem — Don't tackle a complex system all at once, such as a home entertainment system with a TV receiver, audio system, DVD player, video game console, satellite TV receiver, and remote audio to other rooms. You could spend the rest of your life running in circles and never find the true cause of the problem!

There's a better way. Start with the minimum configuration for the system — just the TV receiver, for example. Remove every cable (label them as you go!) from the TV except power and a video source such as an antenna or cable system connection. If you still have the problem, try cures until the problem is solved, then start adding cables and equipment back one at a time, fixing the problems as you go along. If you are lucky, you will solve all of the problems in one pass. If not, at least you can point to one piece of equipment as the source of the problem. (While rebuilding the system, watch carefully for loose or intermittent connections and connectors and damaged cables you might have missed during the first inspection.)

Multiple Causes, Multiple Cures — Many RFI problems have multiple causes. These are usually the ones that give new RFI troubleshooters the most difficulty. For example, consider a TVI problem caused by the combination of harmonics from the transmitter due to an arc in the transmitting antenna, an overloaded TV preamplifier, fundamental overload in the TV tuner, common-mode RF on the ac-power connections, and more common-mode RF picked up on the shield of the TV's coaxial feed line. You would never find a cure for this multiple-cause problem by trying only one cure at a time.

In this case, the solution requires that all of the cures be present at the same time. When troubleshooting, if you try a cure, leave it in place even if it doesn't solve the problem. When you add a cure that finally solves the problem entirely, start removing the "temporary" attempts one at a time. If the interference returns, you know that there were multiple causes.

Take Notes — In the process of troubleshooting an RFI problem, it's easy to lose track of what remedies were applied, to what equipment, and in what order. Configurations of equipment can change rapidly when you're experimenting. To minimize the chances of going around in circles or getting confused, take lots of notes as you proceed. Sketches and drawings can be very useful. Take pictures with your camera or smartphone. When you do find the cause of a problem and a cure for it, be sure to write all that down so you can refer to it in the future.

Common Mistake — Using Ferrite Improperly

Amateurs often read about "ferrite cores" and hear only the word "ferrite." They may read that they need to use 10 turns of wire on an FT-240-43 ferrite core and instead choose to use one clamp-on ferrite bead. This will not create enough impedance to form an effective choke. Grabbing a junk-box core and wrapping wire on it may work, and that's okay, but if doesn't, don't discount using a common-mode choke because using one with the right material and construction may work very well. Read the sections on Common-Mode Chokes and follow the directions!

27.5.3 Simple Troubleshooting with Chokes and Filters

Filters and chokes are the number one weapons of choice for many RFI problems, whether the device is the source or the victim. They are relatively inexpensive, easy to install, and do not require permanently modifying the device. The following suggestions will solve many RFI problems.

Common-mode choke — Making a common-mode choke is simple as described in the earlier section, "Common-Mode Chokes." Select the type of core and ferrite material for the frequency range of the interference. (Type #31 is a good HF/low-VHF material, Type #43 from 5 MHz through VHF) Wrap several turns of the cable or wire pairs around the toroid. Six to 8 turns is a good start at 10-30 MHz and 10 to 15 turns from 1.8 to 7 MHz. (Ten to 15 turns is probably the practical limit for most cables.) Ferrite clamp-on split cores and beads that slide over the cable or wire are not as effective as toroid-core chokes at HF but are the right solution at VHF and higher frequencies. For a clamp-on core, the cable doesn't even need to be disconnected from its end. Use Type #31 or Type #43 material at VHF, Type #61 at UHF. At 50 MHz, use two turns through Type #31 or #43 cores.

"Brute-Force" ac-line filters — RF signals often enter and exit a device via an ac power connection. "Brute-force" ac-line filters (see the preceding section on Filters) are simple and easy to install. Most ac filters only provide differential-mode suppression as described in the text. It is essential to use a filter rated to handle the device's required current.

General installation guidelines for using chokes and filters:

1. If you have a brute-force ac-line filter, put one on the device or power cord. If RFI persists, add a common-mode choke to the power cord at the device.

2. Simplify the problem by removing cables one at a time until you no longer detect RFI. Start with cables longer than 1/10th-wavelength at the highest frequency of concern. If the equipment can't operate without a particular cable, add common-mode chokes at the affected or source device.

3. Add a common-mode choke to the last cable removed and verify its effect on the RFI. Some cables may require several chokes in difficult cases.

4. Begin reconnecting cables one at a time. If RFI reappears, add a common-mode choke to that cable. Repeat for each cable.

5. Once the RFI goes away, remove the common-mode chokes you added one at a time. If the RFI does not return, you do not need to reinstall the choke. If the RFI returns after removing a choke, reinstall it.

If you are troubleshooting RFI at a neighbor's house, it may be prudent to leave the extra chokes installed. Some neighbors may want to have you come in and leave quickly, and if the neighbor starts to lose confidence in your skills, the neighbor may ask you to leave and fix the "problem at your station."

27.6 Identifying the Type of RFI Source

This section assumes that you can use a receiver of some sort to observe the presence and characteristics of the RFI signal. That might mean an AM or FM receiver that coverts the signal to audio you can hear and evaluate. Another type of receiver is an SDR with waterfall or spectrum displays that can show you what the signal "looks like" in the frequency domain. If you do not have a receiver but the RFI is causing a particular symptom in the victim device, you can use the device to detect the presence of the interfering signal or noise. The same advice about using repetitive patterns and timing apply, however.

It is useful to recognize an offending noise source as one of several broad categories at the early stages of any RFI investigation. Since locating and resolution techniques can vary somewhat for each type of noise, the process of locating and resolving RFI problems begins with identifying the *general* type of RFI source. It is not useful, however, to go farther and attempt to identify a particular type of equipment or device at the beginning of the search. The purpose of this section is to help you determine the general category of the noise being received and choose the right set of tools and methods to locate its source.

It is often impossible to identify the exact type of device generating the RFI from the sound of the interference. Because there are many potential sources of RFI, it is often more important to obtain and interpret clues from the general noise characteristics and the patterns in which it appears.

A source that exhibits a repeatable pattern during the course of a day or week, for example, suggests something associated with human activity or time of day. A sound that varies with or is affected by weather suggests an outdoor source. Noise that occurs in a regular and repeating pattern of peaks and nulls as you tune across the spectrum, every 50 kHz for example, is often associated with a switchmode power supply or similar pulsed-current devices. A source that exhibits fading or other sky wave characteristics suggests something that is not local. A good ear and careful attention to detail will often turn up some important clues. A detailed RFI log can often help, especially if maintained over time.

Common Mistake — What Is It?

When someone has an unusual RFI problem, the first question he or she almost always asks is: What is it? That's an interesting question, and you may need to ask it during the troubleshooting process, but it is not the first question you should ask. Even if someone were to say that it's a Model XYZ Panashibi switching power supply, what would that tell you? You would still have to go into the world and find it. It could be useful, though, to know whether you are searching for a switching power supply, DSL or cable leakage, or a plasma TV. But be general, not specific, because you don't want to be misled. (An extended version of this sidebar is available on this book's online material.)

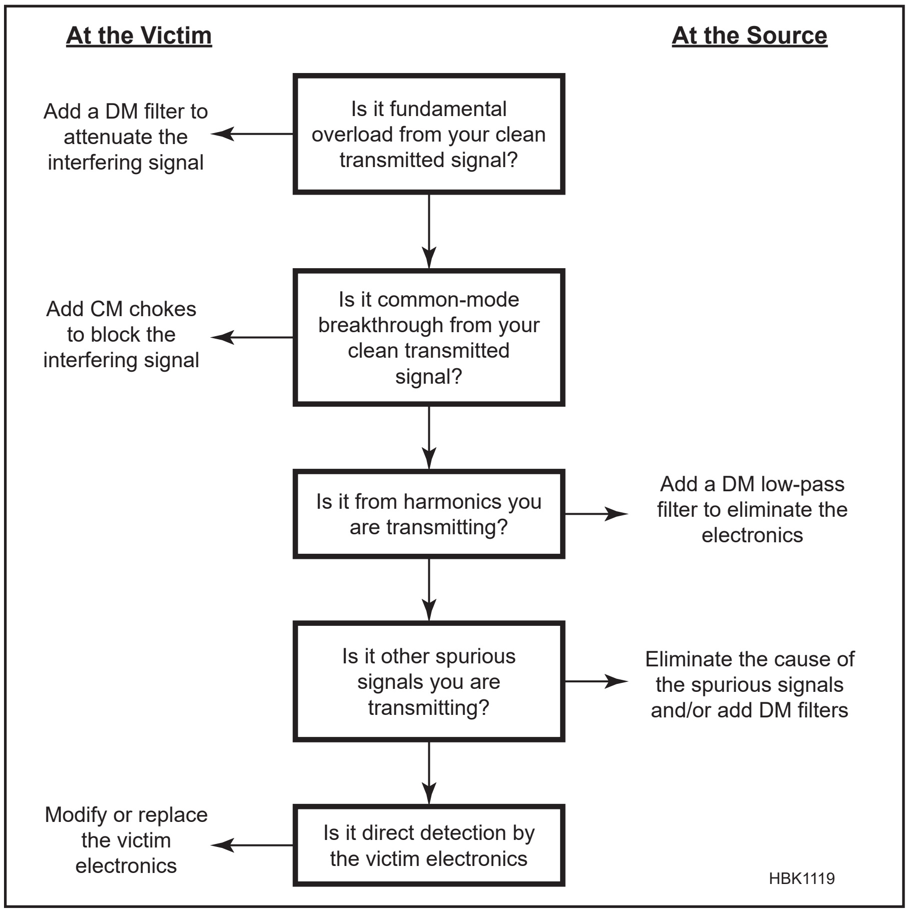


Figure 27.14 — A general process for dealing with RFI from your station's transmitted signal. Remember that RFI can result from both differential-mode and common-mode signals. You may need to perform several of these steps to eliminate the RFI.

27.6.1 RFI From Transmitted Signals

We start with transmitters not because most interference comes from transmitters, but because your station transmitter is under your direct control. In addition, it is relatively simple to determine if your station is the cause of the RFI. If it is, the location of the source is known right away! If it is another antenna, they

Keeping an RFI Log

The importance of maintaining a good and accurate RFI log cannot be overstated. Be sure to record time and weather conditions. Correlating the presence of the noise with periods of human activity and weather often provide very important clues when trying to identify power-line noise. It can also be helpful in identifying noise that is being propagated to your station via sky wave. A log showing the history of the noise can also be of great value should professional services or FCC involvement become necessary at some point.

are generally fairly easy to locate and identify. **Figure 27.14** provides a general guide for dealing with RFI caused by your station's transmitted signal.

Many of the troubleshooting steps in other parts of this chapter assume that your transmitter is "clean" (free of unwanted RF output). This point has been made before, but it is simply good practice to be sure your station is transmitting a signal that meets all FCC regulations *at a minimum*. That includes harmonics, wideband noise, distortion and IMD products, and parasitic oscillations. Be sure there is no arcing to generate noise, either across an insulator or between an antenna and some nearby conductor, even a tree limb. Overloaded or damaged connectors or components can also generate spurious signals, including connectors or antennas that have been damaged by lightning or from failed weatherproofing.

Start by looking for patterns in the interference. Problems that occur only on harmonics of a fundamental signal usually indicate the transmitter is the source of the interference, although harmonics can be generated as non-linear 2nd-order IMD or in the front end of an overloaded receiver. Harmonics can also be generated in nearby semiconductors, such as an unpowered VHF receiver left connected to an antenna, rectifiers in a rotator control box, or a corroded connection in a tower guy wire. Harmonics can also originate in the front-end components of the TV or radio experiencing interference.

If HF transmitter spurious signals or "spurs" at VHF are causing interference, a low-pass filter at the transmitter output will usually cure the problem. If an amplifier is used, be sure it is adjusted properly and not mistuned. If a filter at the transmitter is insufficient, either the amplifier or transmitter may need repair or something else may be creating the harmonics.

Transmitting filters are generally designed for 50 Ω input and output impedances, so install any filters on the input side of an antenna tuner, if one is used. Install a low-pass filter as your first step in any interference problem that involves another radio service at VHF or higher frequencies.

Interference from non-harmonic spurious emissions is extremely rare in commercial radios. Any such problem indicates a malfunction that should be repaired.

27.6.2 Noise from Part 15 Devices

The most common RFI problem reported to the ARRL comes from an unknown and unidentified source. Part 15 devices and other consumer equipment noise sources are ubiquitous. Although the absolute signal level from an individual noise source may be small, their increasing numbers makes this type of noise a serious problem in many suburban and urban areas. The following paragraphs describe several common types of electronic noise sources.

Electronic devices containing oscillators, microprocessors, or digital circuitry produce RF signals as a byproduct of their operation. The RF noise they produce may be radiated from internal wiring as a result of poor shielding. The noise may also be conducted to external, unshielded, or improperly shielded wiring as a common-mode signal where it radiates noise. Noise from these devices is usually narrowband that changes characteristics (frequency, modulation, on-off pattern) as the device is used in different ways. HF and lower frequency problems are typically caused by conducted emissions, although they may travel to the victim as radiated signals. As we'll see, the cure in these cases usually involves common-mode chokes and filters. At VHF and higher frequencies, the probable cause is radiated emissions from the source device. In these cases, shielding is often the solution of choice.

Another major class of noise source is equipment or systems that control or switch large currents. Among them are variable-speed motors in products as diverse as washing machines, elevators, and heating and cooling systems. Charging regulators and control circuitry for battery and solar power systems are a prolific source of RF noise. So are switchmode power supplies for computers and low-voltage lighting. This type of noise is only present when the equipment is operating.

Switchmode or "switching" supplies, solar controllers, and inverters often produce noise signals every N kHz, with N typically being from 5 to 50 or more kHz, the frequency at which current is switched. This is different from noise produced by spark or arc sources that is uniform across a wide bandwidth. This pattern is often an important clue in distinguishing switching noise from power-line or electrical noise. Switching supplies tend to be somewhat unstable in frequency, so you may see the noise signals drift a bit across the band, especially when the supply is first turned on. They may also change a bit in frequency with load changes or with ac voltage dips or surges.

Wired computer networks radiate noise directly from their unshielded circuitry and from network and power supply cables. The noise takes two forms — broadband noise and modulated carriers at multiple frequencies within the amateur bands. As an example, Ethernet network interfaces often radiate signals heard on a receiver in CW mode. 10.120, 14.030, 21.052, and 28.016 MHz have been reported as frequencies of RFI from Ethernet networks. Each network interface uses its own clock, so if you have neighbors with networks you'll hear a cluster of carriers around these frequencies, ±500 Hz or so. All of these signals from digital equipment will be fairly stable with frequency, not drifting across the band. They may be broadband, though, to the point where they may just be a fairly constant hiss across the entire band.

In cable TV systems video signals are converted to RF across a wide spectrum and distributed by coaxial cable into the home. Some cable channels overlap with amateur bands, but the signals should be confined within the cable system. No system is perfect, and it is common for a defective coax connection to allow leakage to and from the cable. When this happens, a receiver outside the cable will hear RF from the cable and the TV receiver may experience interference from local transmissions. Interference to and from cable TV signals is discussed in detail later in this chapter.

Broadband and Narrowband Noise

Noise can be characterized as broadband or narrowband — another important clue. *Broadband noise* is defined as noise having a bandwidth much greater than the affected receiver's operating bandwidth and reasonable uniformity across a wide frequency range. Noise from arcs and sparks, such as power-line noise, tend to be broadband. *Narrowband noise* is defined as noise having a bandwidth less than the affected receiver's bandwidth. Narrowband noise is present on specific, discrete frequencies or groups of frequencies, with or without additional modulation. In other words, if you listened to the noise on an SSB receiver, tuning would cause its sound to vary, just like a regular signal. Narrowband noise often sounds like an unmodulated carrier with a frequency that may drift or suddenly change. Microprocessor clock harmonics, network equipment leakage, oscillators, and transmitter harmonics are all examples of narrowband noise.

27.6.3 Identifying Power-Line and Electrical Noise

POWER-LINE NOISE (PLN)

Next to external noise from an unknown source, the most frequent cause of an RFI problem reported to the ARRL involving a known source is power-line noise. (For more information on power-line noise, see this chapter's section on Power-Line Noise and *The ARRL RFI Book*.) Virtually all power-line noise originating from utility equipment is caused by spark or arcing across some hardware connected to or near a power line. A breakdown and ionization of air occurs and current flows

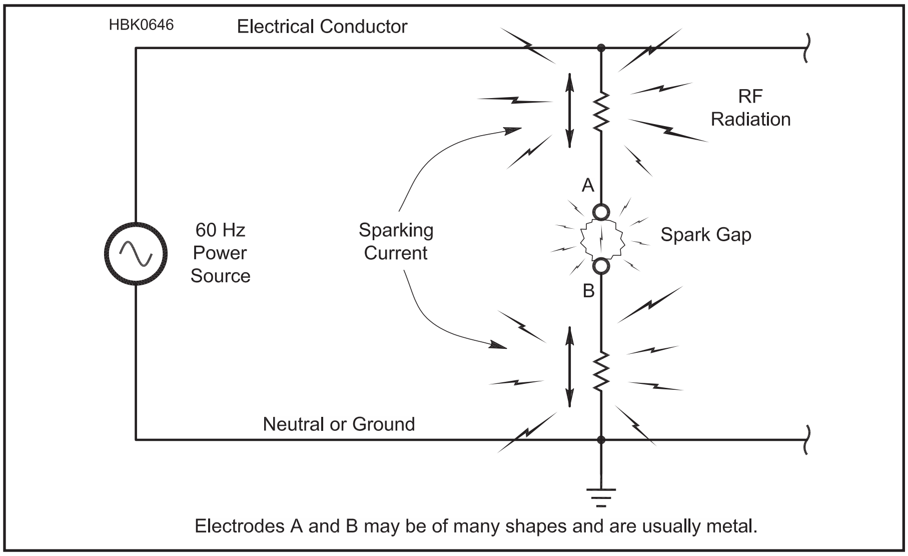


Figure 27.15 — The gap noise circuit on a power line — simplified. (From Loftness, *AC Power Interference Handbook*)

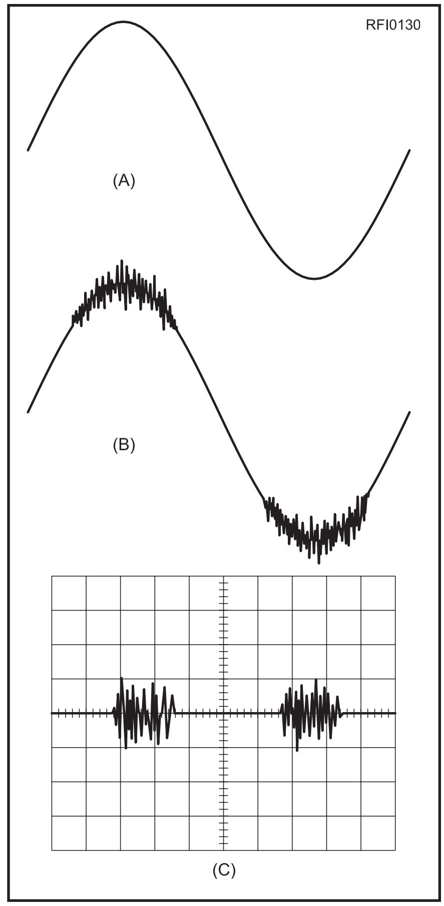


Figure 27.16 — The 60-Hz signal found on quiet power lines is almost a pure sine wave, as shown in A. If the line, or a device connected to it, is noisy, this will often add visible noise to the power-line signal, as shown in B. This noise is usually strongest at the positive and negative peaks of the sine wave where line voltage is highest. If the radiated noise is observed on an oscilloscope, the noise will be present during the peaks, as shown in C.

across a gap between two conductors, creating RF noise as shown in **Figure 27.15**. Such noise is often referred to as "gap noise" in the utility power industry. The gap may be caused by broken, improperly installed, or loose hardware. Typical culprits include insufficient and inadequate hardware spacing such as a gap between a ground wire and a staple. Contrary to common misconception, corona discharge is almost never a source of power-line noise.

While there may not be one single conclusive test for power-line noise, there are a number of important telltale signs. On an AM or SSB receiver, the characteristic raspy buzz or frying sound, sometimes changing in intensity as the arc or spark sputters a bit, is often the first and most obvious clue.

Power-line noise is typically a broadband type of interference, relatively constant across a wide spectrum. Since it is broadband noise, you simply can't change frequency to eliminate it. Power-line noise is usually, but not always, stronger on lower frequencies. It occurs continuously across each band and up through the spectrum. It can cause interference from below the AM broadcast band through UHF, gradually tapering off as frequency increases. If the noise is not continuous across all of an amateur band, exhibits a pattern of peaks and nulls at different frequencies, or repeats at some frequency interval, you probably do not have power-line noise.

The frequency at which power-line noise diminishes can also provide an important clue as to its proximity. The closer the source, the higher the frequency at which it can be received. If it affects VHF and UHF, the source is relatively close by. If it drops off just above or within the AM broadcast band, it may be located some distance away — up to several miles.

Power-line noise is often affected by weather if the source is outdoors. It frequently changes during rain or humid conditions, for example, either increasing or decreasing in response to moisture. Wind may also create fluctuations or interruptions as a result of line and hardware movement. Temperature effects can also result from thermal expansion and contraction.

Another good test for power-line noise requires an oscilloscope. Remember that power-line noise occurs in bursts most frequently at a rate of 120 bursts per second and sometimes at 60 bursts per second. Observe the suspect noise from your radio's audio output. (Note: The record output jack works best if available). Use the AM mode with wide filter settings and tune to a frequency without a station so the noise can be heard clearly. Use the LINE setting of the oscilloscope's trigger subsystem to synchronize the sweep to the line. Power-line noise bursts will remain stable on the display and should repeat every 8.33 ms (a 120-Hz repetition rate) or less commonly, 16.67 ms (60 Hz) if the gap is only arcing once per cycle. (This assumes the North American power-line frequency of 60 Hz.) See **Figure 27.16** for an explanation. If a noise does not exhibit either of these characteristics, it is probably not power-line noise.

ELECTRICAL NOISE

Electrical noise sounds like power-line noise, but is generally only present in short bursts or during periods when the generating equipment or machinery is in use. Noise that varies with the time of day, such as daytime-only or weekends-only, usually indicates some electrical device or appliance being used on a regular basis and not power-line noise. Unless it is associated with a climate control or HVAC system, an indoor RFI source of electrical noise

Common Mistake — The Source Must Be Illegal Because It's So Loud

The FCC limits for consumer electronics are not sufficient to protect against interference to nearby receivers. In a typical suburban neighborhood, the interference can be loud even from a neighboring residence. Proving they meet the applicable limits, these devices can be legally marketed and sold. If and when interference occurs, the burden then falls on the operator of the device to correct the problem.

Conclusion: Don't automatically assume that the device illegally exceeds the FCC limits just because it is causing harmful interference, even if it seems excessive.

is less likely to be affected by weather than power-line noise.

ELECTRIC FENCES

A special type of electrical noise that is easy to identify is the "pop…pop…pop" of an electric fence. High voltage is applied to the fence about once a second by a charging unit. Arcs will occur at corroded connections in the fence, such as at a gate hook or splice. If brush or weeds touch the fence, the high-voltage will cause an arc at those points until the vegetation burns away (the arc will return when the vegetation re-grows). Each arc results in a short burst of broadband noise, received as a "tick" or "pop" in an HF receiver.

27.6.4 Identifying Intermodulation Distortion (IMD)

IMD GENERATED OUTSIDE A RECEIVER

Mixing of signals can occur in any non-linear junction where the original signals are both strong enough to cause current to flow in the junction. This is a particular problem at multi-transmitter sites, such as broadcast facilities and industrial or commercial communications sites. Non-linear junctions can be formed by loose mechanical contacts in metal hardware, corroded metal junctions, and by semiconductor junctions connected to wires that act as antennas for the strong signals. Non-linear junctions also detect or demodulate RF signals to varying degrees, creating interfering audio or dc signals in some cases.

An intermodulation product generated externally to a receiver often appears as an intermittent transmission, similar to a spurious emission. It is common for strong signals from commercial paging or dispatch transmitters sharing a common antenna installation to combine and generate short bursts of voice or data signals. AM broadcast transmissions can combine to produce AM signals with the modulation from both stations audible.

Signals near a broadcast or other communications facility can be strong enough that metal fencing or roofing or a poor cable or wire connection is sufficient to act as a mixer. Curing RFI caused by externally generated IMD requires identifying the signals that are being mixed and then the equipment or structure that generates the unwanted products. Finding where the mixing is occurring can be difficult but is generally easy to fix once identified.

IMD can also be created in a broadcast FM or TV receiver or preamplifier. The solution is to add suitable filters or reduce overall signal levels and gain so that the strong interfering signal or signals can be processed linearly.

IMD GENERATED INSIDE A RECEIVER

Since the products are generated internally to the receiver, the strong signals must be filtered out or attenuated before they can enter the receiver circuits in which IMD products are generated. Like external intermodulation products, those generated by a receiver acting non-linearly appear as combinations of two or more strong external signals. Intermodulation generated within a receiver can often be detected simply by activating the receiver's incoming signal attenuator. If attenuating the incoming signals causes the intermodulation product to by reduced in strength by a greater amount than that of the applied attenuation, intermodulation in the receiver is a strong possibility.

Superheterodyne receiver IMD generally increases and decreases with signal strength. Direct-sampling SDR receivers, however, do not exhibit IMD in the same way as superhets. The SDR will be essentially IMD-free until the limits of the input ADC are reached, and then many distortion products are generated. Hybrid receivers with analog front-ends and DSP functions performed at an IF frequency have IMD performance somewhere between all-analog and direct-sampling SDR.

The following simple "attenuator test" can be used to identify an IMD product, even in cases where it appears similarly in multiple receivers. This procedure applies mainly to superheterodyne receivers with analog circuitry in the sensitive front-end stages.

• If your receiver does not have one, install

Common Mistake — Radiated vs. Conducted Emissions

The FCC does not impose radiated emissions limits below 30 MHz. There are only conducted emissions below 30 MHz. Specifically, the FCC requirements are for the RF conducted on the ac power connection, a power cord for most consumer devices. The limits in the case are expressed in terms of a voltage from both the phase (or "hot") conductor and neutral conductor to the ground conductor.

Note: Typical consumer devices are too small to be an effective antenna at HF. While the device may generate the RF, it doesn't radiate it. The actual radiation takes place from the wires and cables connected to the source device. The FCC rules in this regard only address the connection to ac power.

Above 30 MHz, the situation is reversed. There are no limits for conducted emissions — only for radiated emissions. The limits in this case are expressed as a field strength at a specified distance from the device.

Unbypassed Diode Junctions and RFI

Any conductor in an amateur station more than a small fraction of a wavelength long will pick up considerable RF from the strong transmitted signal. If this conductor is then connected to a diode (or bipolar transistor) junction, a non-linear current will flow in the junction. This, in turn, creates a multitude of harmonics. The harmonics will then be radiated by the same conductor where they are received by nearby stations, including the station that is transmitting.

It is very common to see rectifiers or low-power signal diodes used to protect circuits against reversed power polarity or lightning-induced transients. In addition, rotator control boxes and other station accessories contain rectifiers, signal diodes, and LED indicators. All of these can create harmonics.

In a single-transceiver station, these harmonics may not be apparent since the operator is typically not receiving and transmitting at the same time. If a second receiver is in use, however, these harmonics can be a real problem! Multioperator stations, including Field Day setups, are frequently bedeviled by harmonics, and diode-generated harmonics are an important source of the problem, along with non-linear operation of transmitters.

Luckily, the fix is simple and inexpensive in most cases. Bypass each diode with a small-value capacitor (0.001 to 0.01 μF) — just solder it across the diode leads. Disc or monolithic ceramic capacitors of an adequate voltage rating are sufficient. The trick is to find all of the diodes! An alternative is to add a capacitor from each conductor to the equipment enclosure, which is then connected to the station ground reference plane or bonding bus. Adding ferrite chokes to reduce RF current on the conductors is also good practice.

One place where you should *not* install bypass capacitors is across shunt protection diodes on RF feed lines or other conductors. The capacitor will also shunt the RF! Diodes should not be used as protection devices at RF because of their non-linearity, but they are sometimes used at receiver inputs.

Product Review Testing and RFI

The ARRL Laboratory mostly considers RFI as an outside source interfering with the desired operation of radio reception. Power line noise, power supplies, motor controls, and light dimmers are all *outside* a radio receiver and antenna system and can be a major annoyance that distracts from the pleasure of operating. Have you ever considered RFI generated *inside* your own receiver or by another legally operating amateur radio station?

Harmonics

RFI is just that: radio frequency interference. For instance, a harmonic from another radio amateur's transmitter could be interfering with the desired signal you're trying to receive. One might think in this day and age harmonics are minimal and do not cause interference, but you should reconsider.

The maximum spurious output of a modern amateur transmitter must be 43 dB lower than the output on the carrier frequency at frequencies below 30 MHz. While that figure may be "good enough" for an FCC standard, it's not good enough to eliminate the possibility of causing interference to other radio amateurs or possibly other services. Here at the ARRL Laboratory, the measurement of harmonic emission level is a measurement we make of RFI generated *outside* your receiver.

A radio amateur contacted the Lab, concerned about a report that he was causing interference to operators on the 80-meter CW band while operating at full legal limit power during a 160 meter CW contest. Knowing FCC rule part 97.307, he made the effort to measure his 80-meter harmonic. Easily meeting FCC standards at 50 dB below carrier output on 160, he wondered how his transmitter could cause interference.

Here's a breakdown of power output and signal reduction:

0 dB down from 1500 W = 1500 W
10 dB down from 1500 W = 150 W
20 dB down from 1500 W = 15 W
30 dB down from 1500 W = 1.5 W
40 dB down from 1500 W = 150 mW
43 dB down from 1500 W = 75.2 mW
(this is the FCC legal limit)
50 dB down from 1500 W = 15 mW

While 15 mW may seem too low of a power to cause interference, it wasn't in this case; the interfering signal was reported to be S9. QRP enthusiasts know that at 15 mW, signals can propagate well with the right conditions. Using a single band, resonant antenna will reduce interference caused by harmonics located on other bands, but today many stations employ antennas resonant on more than one ham band. (In this case, the use of a bandpass filter designed for 160 meters would significantly attenuate the harmonic on 80 meters, eliminating the interference.)

RFI Generated in the Receiver

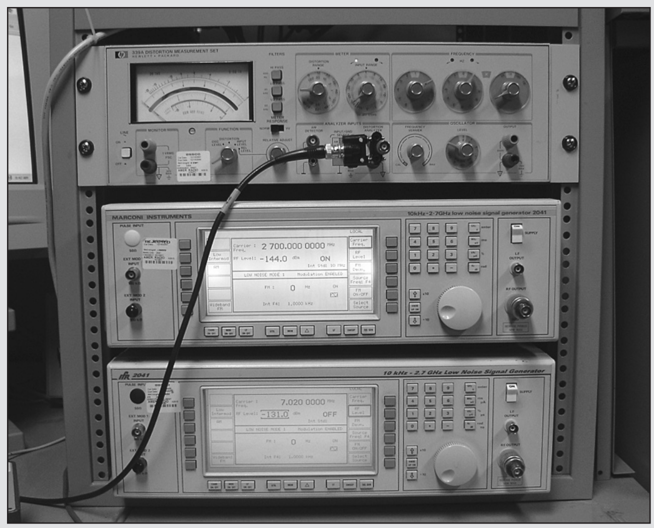
What about RFI generated *inside* the receiver you're operating? You're tuning across the 15-meter band when, all of a sudden, you hear what seems to be an AM broadcast station. Is it a jammer? It is definitely interference — radio frequency interference — caused by two strong shortwave stations! In this particular case, a Midwest radio amateur experienced interference on 15 meters and figured out what was happening. One station was transmitting near 6 MHz and another transmitting above 15 MHz. Signals from these two strong stations combined to create a second order IMD (intermodulation distortion) product at the first IF stage, and this unwanted signal was passed along to subsequent stages and to the speaker. The RFI in this case was caused by insufficient receiver performance (second order IMD dynamic range) where the frequencies of the two stations added up to exactly the frequency that the operator was tuned to. Third-order IMD products from strong in-band signals are another form of RFI created within a radio receiver.

Nearby stations transmitting at or near the IF frequency will cause interference not because the transmitter is at fault, but because of a receiver's insufficient IF rejection. The same interference will be heard if a nearby transmitter is operating at an image frequency.

Power Supplies

RFI can also be created from another part of a radio system, such as an external power supply. In addition to transmitter and receiver testing, the Lab also measures the conducted emission levels of power supplies. This is an indication of the amount of RF at given frequencies conducted onto power lines from a power supply as described in this chapter.

Through the ARRL Lab's published Product Review test results in *QST* magazine, readers can compare the above figures of modern HF transceivers when considering the purchase of a new or used transceiver. Our published data tables spawn friendly competition between radio manufacturers, who in turn strive to perfect their circuit designs. The result is a better product for the manufacturer and a better product for you, the radio amateur.



The Lab uses these signal generators to test receivers for internally generated intermodulation distortion, as well as other key performance parameters.

The ARRL Lab maintains a complete set of up-to-date equipment as well as an RF-tight screen room for Product Review testing.

Common Mistake — It's Everywhere, Joe Even Hears It Across Town!

RFI from a typical otherwise legal consumer device usually only propagates for a few hundred feet or less. However, the ARRL often receives reports of non-power line noise RFI covering an extraordinarily wide area. In this case multiple hams hear a noise at opposite ends of a town, across a state wide area, or in some cases, even a multi-state region.

The fact of the matter is that RFI is a very common problem. And if you look hard enough, noise from a consumer device can probably be heard in most suburban neighborhoods these days. Many of them sound alike, so much so that they can easily be mistaken for each other.

Conclusion: Don't rely on RFI reported by hams in other locations as being the same RFI at your location. Before concluding that the RFI covers a widespread area, always make sure that an RFI source is not local and nearby.

Note: While power-line noise at 80 or 40 meters can propagate for miles, it won't propagate much more than that. Most power-line noise sources can sound alike, so beware. Power-line noise will not propagate across state or multi-state regions. In this case, the ARRL recommends the use of signature analysis to determine which source or sources are contributing to an RFI problem before making unnecessary repairs. See the section on Power-Line Noise for more information on signature analysis.

Prospecting for RFI

By using several types of radios at the same time, you can characterize a wide area. For example, RFI professional KB4T uses the following radios when driving: the vehicle AM/FM radio tuned to 1710 kHz AM, an IC-7000 mobile HF transceiver tuned to 15 MHz AM (WWV), and an IC-2820 VHF receiver tuned to 121.500 MHz in AM mode. All three are operated un-squelched with the volume turned down so only a slight hiss is heard. A noise source will be very apparent on one or more of the radios when approached or passed.

Hams aren't the only ones with RF noise problems. Two extensive studies of RF noise mitigation were also conducted by the US Navy; the authors of these studies were all radio amateurs. "The Signal-to-Noise Enhancement Program" and "The Mitigation of Radio Noise and Interference from On-Site Sources at Radio Receiving Sites" are both available from the ARRL. Scroll to the bottom of **www.arrl.org/radio-frequency-interference-rfi** to the section "Naval Postgraduate School RFI Handbooks".

a step attenuator at its RF input. If you use an attenuator internal to your receiver, it must attenuate the RF at the receiver's input.

- Tune the receiver to the suspected intermod product with the step attenuator set to 0 dB. Note the signal level.
- Add a known amount of attenuation to the signal. Typically, 10 or 20 dB makes a good starting point for this test.
- If the suspect signal drops by more than the amount of added attenuation, the suspect signal is an IMD product. For example, if you add 10 dB of attenuation and the signal drops by 30 dB, you have identified an IMD product. An S-unit of change usually represents around 6 dB.
- You can also compare the reduction in signal level between the suspect IMD product and a known genuine signal with and without the added attenuation. Use a known genuine signal that is about the same strength as the suspect signal with no added attenuation. If the suspect signal drops by the same as the added attenuation, it is not an IMD product.

Intermodulation distortion can be cured in a number of ways. The goal is to reduce the strength of the signals causing IMD so that the receiver circuits can process them linearly and without distortion.

If IMD is occurring in your receiver, adding additional filters to remove the strong unwanted signals causing the IMD while passing the desired signal are generally the best approach, since they do not compromise receiver sensitivity. (These are generally referred to as *roofing filters* and are options on many superheterodyne transceivers.) Turning off preamplifiers, adding or increasing the receiver's attenuation, and reducing its RF gain will reduce the signal strength in your receiver. Antenna tuners and external band-pass filters can also act as a filter to reduce IMD from out-of-band signals. Directional beams and antennas with a narrower bandwidth can also help, depending on the circumstances of your particular problem.

27.7 Locating Sources of RFI

Once you have determined the *general* nature of the noise, it's time to find out where it's coming from. "Pinpoint the source precisely and you will know what it is." Good advice! There is no need to know exactly what the source is until it is found or narrowed down to a few possibilities. So. the proper first question is, "How do I locate the source?"

Along with the material in this chapter, the Radio Direction Finding chapter of *The ARRL RFI Book* describes the many methods available to locate sources. There are numerous websites with information about direction finding at all frequencies. This information helps educate the amateur that locating the source is the first step rather than speculating about what it might be.

Locating an offending device or noise source might sometimes seem like trying to find a needle in a haystack. With a little patience and know-how, it is often possible to find the source of a problem in relatively short order. RF detective work is often required, and some cases require a little more perseverance than others. In any case, armed with some background and technique, it is often easier to find an offending source than the first-time RFI investigator might expect. Once the source is pinpointed and its exact nature is known, proper treatment can be applied to eliminate the RFI.

27.7.1 Preparing to Search

Consider the following questions:

1) First and foremost, does the searcher have an open mind? This kind of search is not a visual search until the structure containing the source is located. Even then, equipment must still be relied upon to pinpoint the source. An open mind means a willingness to trust the equipment and not waste time guessing or

deviating from the search path to pursue something seen or guessed at.

2) Is the searcher equipped to produce useful results? A battery-operated AM-FM-SW-VHF receiver with a useful signal strength indicator and a directional antenna suitable for a walking search that receives fairly well at the highest relevant frequency is essential. See the Power-Line Noise section for examples of what works for that type of source. Handheld SDR receivers are now available that can act as a portable spectrum analyzer as well.

3) Does the searcher know how to direction-find? The type of power lines or potential sources in the area is irrelevant at this point. Finding the structure that contains the source is the only objective. Only by trusting your equipment and using it correctly to lead you to the source will the job get done with a minimum of wasted time and effort.

4) Has the searcher done enough listening and record keeping to have a good idea when the source is active, the best (highest?) frequency at which to listen to hear and track the source? Information includes:

- Signal strength
- Highest frequency at which each source can be heard
- A simple description of each source's character
- Any other descriptive data
- Brief notes about weather conditions

Recording the noise over a long period and noting the time whenever it occurs will provide a lot of information about the source.

5) Can it be decided what tools (receiver, antenna, attenuator) are best to locate the source? Even if the right tools are in hand, mastery of them is essential. Make sure you know how to interpret the measurements or work with an experienced user to learn how.

NOISE SOURCE SIGNATURES

Be wary of assuming too much about a source based on what the interference "sounds like" on a receiver or even "looks like" on an oscilloscope or spectrum analyzer. At the beginning of the search, "keep it simple" by not making too many assumptions about the nature of the source. Once the location of a source has been determined, you can begin to narrow the search based on the source's "fingerprint" or signature.

Keep an open mind, be deliberate in your search, and don't act on assumptions about what a source is or isn't until you have exhausted the search techniques. Much time has been wasted in looking for sources of RFI because of assuming a location or type of source at the beginning.

MULTIPLE NOISE SOURCES

Consider that the source may be more than a single piece of equipment! You might have power-line noise combined with switchmode power supply noise, for example. Trying to find the source based on the combination of noise signatures will be frustrating at best. Most suburban and urban locations have multiple noises active at any time. Survey the area to see if different sources are stronger in different areas.

Take careful notes about the nature and behavior of the source, then let your location-finding equipment lead you to each source in turn. It is often most productive to work on the strongest noise source first. Be prepared to discover there are multiple levels of noise sources — after dealing with the top-level source, you may find that additional (and equally objectionable) sources remain. Be patient!

VERIFY NOISE IS EXTERNAL TO THE RADIO

Whenever an unknown source of interference becomes an issue, you can begin the process of identifying the source by verifying that the problem is external to your radio. This advice might not sound very useful, but it can save you a lot of wasted time. Start by removing the antenna connection. If the noise disappears, the source is external to your radio and you are ready to begin hunting for the noise source.

27.7.2 Locating Noise Sources Inside Your Home

Professional RFI investigators and the experiences of the ARRL RFI desk confirm that most RFI sources are ultimately found to be in the complainant's home. Furthermore, locating an in-house source of RFI is so simple that it makes sense to start an investigation by simply turning off your home's main circuit breaker while listening to the noise with a battery-powered portable radio. Dave Cole, NK7Z, has developed a helpful and informative flowchart for investigating RFI in your home. See **Figure 27.17** and Dave's website at **www.NK7Z.net** for further information on his experiences investigating RFI.

Remember that battery-powered equipment may also be a noise source — also turn off or disable battery-powered consumer devices. If you have a UPS (uninterruptable power supply), it will continue to operate with ac power removed. It may be necessary to actually disconnect the UPS battery to shut it completely down.

> ***Common Mistake* — It's Not Me, I've Already Eliminated My House as the Source**
>
> Consumer devices are by far one of the most common sources of RFI. And once found, a surprisingly high percentage of them are actually in the complainant's home. For this reason, we recommend that hams affected by noise open the main breaker to their residence while listening with a battery-powered radio. (See the text's caution about making sure battery-powered devices are off.) If the noise goes away, you can further isolate the source by opening the individual circuit breakers.
>
> While all this sounds simple enough, many hams actually skip this step. Unplugging or turning off suspect sources is not the same as opening the main breaker. Another mistake is to conclude that the source could not be in your home because you haven't bought or changed anything. Even though quiet when new, devices that fail or otherwise break down can become a source of RFI.
>
> Conclusion: When it comes to consumer devices, do not assume that a noise source is not in your home until you open the main breaker. This is a simple and easy test to perform. Many hams have spent months — even years — searching for a noise that they could have easily found with a simple breaker test. Why skip it?

> ***Common Mistake* — Nothing in My Home Could Cause Noise Like That**
>
> One of the most common sources of RFI is the ubiquitous switchmode power supply. They are found in almost everything these days. Devices such as "wall warts," many light bulbs, computers, battery chargers, televisions, and various other appliances all may and probably do include switchers capable of causing RFI. In addition, many other electronic devices have clocks and other oscillators that can cause RFI.
>
> Despite this reality, it is surprising how many hams are convinced that the source of an RFI problem could not possibly be located in their home. They are often proven wrong.
>
> Conclusion: Do not automatically assume that nothing in your home could cause an RFI problem. Almost every electronic device in a home can be suspect. Furthermore, a typical home these days can contain hundreds of potential RFI sources.

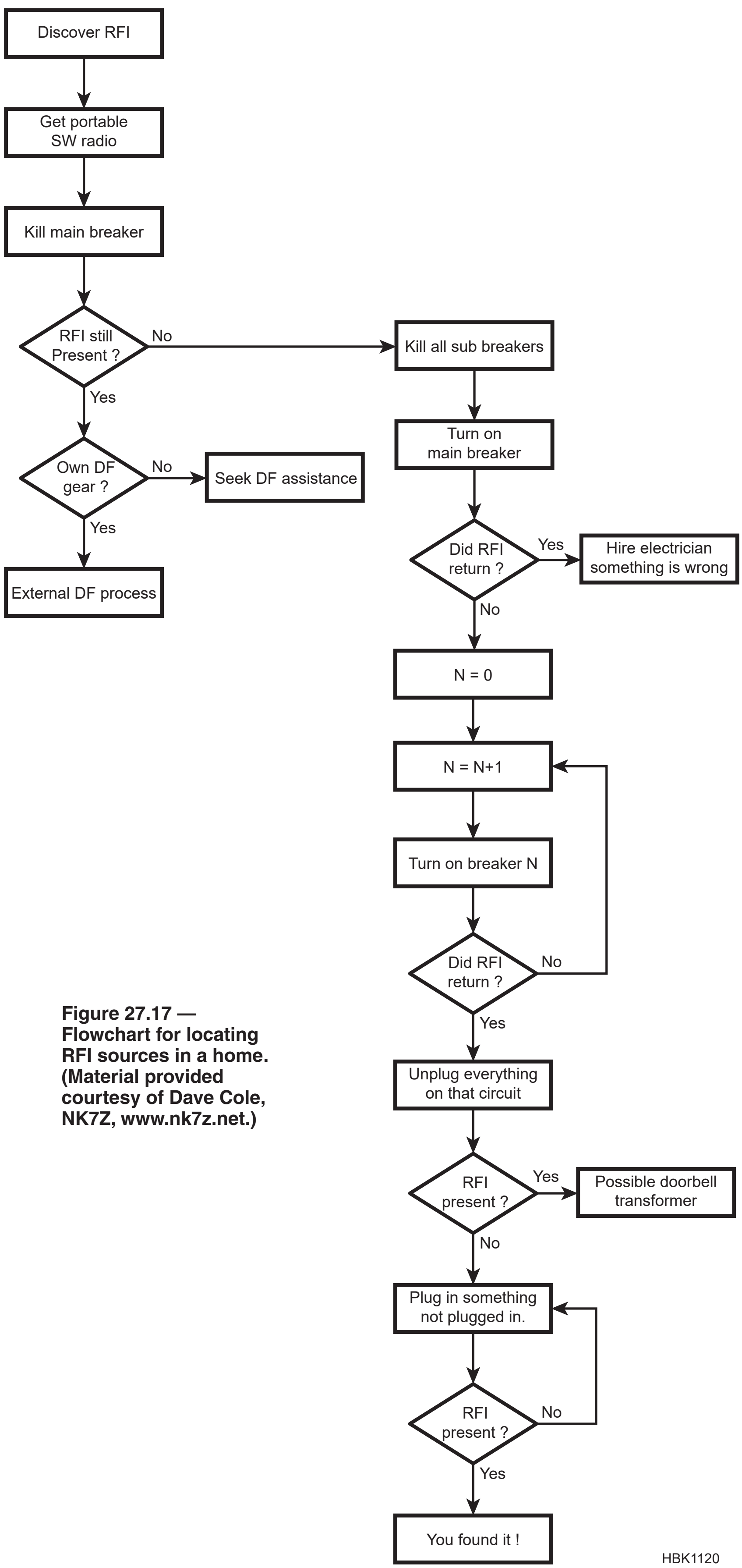


Figure 27.17 — Flowchart for locating RFI sources in a home. (Material provided courtesy of Dave Cole, NK7Z, www.nk7z.net.)

Common Mistake — I Don't Have the Equipment

Most consumer devices actually meet the FCC emission limits, so the RFI problem is usually limited to about 300 feet or less. They are also often in the complainant's residence, and if not, frequently in a home connected to the same power transformer secondary system as the complainant.

With this in mind, a simple portable (battery powered) shortwave radio capable of hearing the noise is all you typical need to find it. Opening the main breaker of your home will locate many of the problems. And if it's not in your home, it's likely in an adjacent or nearby residence. By collapsing or removing the antenna, adding a step attenuator, or reducing the RF gain of the locating receiver, you can often reduce the area in which you search for the source. Reducing the signal level to something at or below the receiver's AGC threshold (or turning AGC off) can often help.

An approach that often works is to find the loudest power pole. Next, look to see what houses are connected to that pole. And finally, if possible, hold the radio a short distance from the power meters at each house. Always be sure to minimize signal levels but do not make any adjustments when making comparisons between the different meters. If access to the power meters is not possible, you can use lawn lights or something similar. The house with the highest noise level will be the one containing the source.

Please note that spectrum analyzers are not needed. In fact, in many cases a spectrum analyzer can add to confusion, especially if there are other sources at other frequencies.

Conclusion: Finding noisy consumer devices is often easier than most people think. Furthermore, it does not require specialized equipment. A cheap battery powered shortwave radio will often do the job.

If the noise goes away, you know the source is in your residence. After resetting the breaker, you can further isolate the source by turning off individual breakers one at a time. Once you know the source circuit, you can then unplug devices on that circuit to find it.

CAUTION: *Do not attempt to remove cartridge fuses or operate exposed or open-type disconnects if it is possible to make physical contact with exposed electrical circuits.*

27.7.3 Locating Noise Sources Outside Your Home

It is often possible to locate a noise source outside your home with a minimum of equipment and effort. The following process will help you determine whether the noise is radiated directly to your equipment or conducted, most frequently by power lines or wiring which then radiate the noise signal themselves.

Because of Part 15's absolute emissions limits, most noise sources that are compliant with Part 15 are within a few hundred feet of the complainant's antenna. They are also often on the same power transformer secondary system as the complainant if the noise is conducted. This typically reduces the number of possible residences to relatively few.

If the noise source is not compliant with Part 15 limits, it may be blocks, or in some rare cases, even thousands of feet from your station. The ballasts of grow lights, for example, have been known to exceed the FCC limits by a considerable margin and have been heard for over ½ mile. Some Part 15 devices, battery chargers for electric scooters and wheelchairs, for example, are well known for exceeding Part 15 absolute emissions limits on conducted noise.

Electrical noise sources in a home, such as an arcing thermostat or a noisy washing machine controller, can also be tracked down in the same way as noise from consumer electronic devices. Electrical noise from an incidental emitter, such as a power line, can propagate much farther than noise from an otherwise legal, unintentional emitter.

The following procedure can be used to trace a noise source to a private home, town house, apartment, or condominium. The number of homes that could be host to a source generating noise could make searching house by house impractical. In such cases, use noise tracking techniques to narrow the search to a more reasonable area.

1) Verify that the noise is active before attempting to locate it. Don't forget this all-important first step. You cannot find the source when it's not present.

2) If possible, use a beam to record bearings to the noise before leaving your residence. Walk or drive through the neighborhood with particular emphasis in the direction of the noise, if known. Try to determine the rough geographic area over which the noise can be heard. If the geographic area over which you can hear the noise is confined to a radius of several hundred feet or less, or it diminishes quickly as you leave your neighborhood, this confirms you are most likely dealing with a Part 15 consumer device.

3) Since the noise will be strongest at an electrical device connected to the residence containing the source, you want to measure the noise at a device common to the exterior of all the potential homes. Suitable devices include electric meters, main service breakers (whether outside or in a utility room), front porch lights, electric lamp posts, outside air conditioner units, or doorbell buttons. Whatever radiator you choose, it should be accessible at each home. The device you select to test as the noise radiator will be referred to in these instructions as the "radiator." Using the same type of device as a test point at each home helps obtain consistent results.

4) You are now ready to compare the relative signal strengths at the radiator on each of the potential source residences. Use a detector suitable to receive the noise, typically a battery-powered receiver. Preferably, the receiver should have a variable RF gain control. An external step attenuator will also work if the antenna is external to the radio. If the antenna can be removed, a probe can also be made from a small piece of wire or paper clip to reduce the receiver's sensitivity. Start by holding the detector about two inches from the radiator at the residence where the noise source may be located. Turn the detector's RF gain control down to a point where you can just barely hear the noise. Alternately, increase the attenuation if using an external step attenuator. Record the RF gain or attenuator setting for each test. Because any wiring connected to a portable receiver becomes part of the receiver's antenna, including headphones, external battery, even the operator's hands and body, keep the configuration the same as you evaluate each potential source.

5) Proceed to the next residence. Again, hold the detector approximately two inches from the radiator. (The detector should be placed at the same location at each residence, as much as is practical.) Since you had previously set the detector to just barely hear the noise at the residence having the interference problem, you can move on to the next residence if you do not hear the noise. Remember, in order for your detector to hear the noise at the next house, the noise level will have to be the same or higher than the previous location. If you need to increase the detector's sensitivity to be able to hear the noise, you are moving away from the noise source.

6) When you reach the next residence, if the level is lower or not heard, you're moving further from the source. Continue your search to residences in other directions or across the street. If the level is higher, then you're headed in the right direction. Be sure to turn the gain control down to the point of just barely hearing the noise as its strength increases.

7) Continue on to the next house, repeating the previous steps as necessary. The residence with the source will be the one with the strongest noise at the radiator.

Depending on the circumstances of a particular situation, it may be possible to first isolate the power pole to which the source residence is connected. Walk or drive along the power lines in the affected area while listening to the noise with a battery-powered radio. Continue to decrease the receiver's RF gain as the noise gets louder, thus reducing the area over which you can hear it. Finally, isolate the loudest pole by reducing the RF gain to a point at which you can hear it at only one pole. Once the pole has been isolated, look to see which houses are connected to its transformer. Typically, this will reduce the number of potential residences to a very small number.

Common Mistake — It Must Be The XYZ Company — They Were Just Here

Many hams might notice activity in their neighborhood by a cable, power, or telephone company. Other variations include an installation of something electrical at an adjacent or nearby residence. Typical examples might include a swimming pool pump, broadband, satellite TV, or an alarm system. So far, so good...

The problem, however, will become apparent a few days later when the hams turn on the radio. Interference now plagues the amateur bands! The ham may now erroneously conclude that the interference is a result of the activity observed in the neighborhood several days prior. In some cases, the ham is so convinced of the source that they fail to take even the most rudimentary steps to confirm their suspicions. This often leads to significant delays in resolving the problem.

The reality in a typical suburban neighborhood is that there could easily be over a thousand devices in range of an amateur's antenna if those sources are all at the legal limit. This RFI environment is also constantly in transition as family members and nearby neighbors buy or turn on electronic devices and other appliances.

Conclusion: Do not automatically assume that you know what the source of an interference problem is based on activity that you've seen in the neighborhood. Always verify the source to the best extent possible.

Be aware that not all power poles have a grounding conductor (a wire running down the side of the pole into the ground). This wire will carry currents from the entire section of the power system for that pole. A receiver held close to that wire will hear more noise than at poles without a ground wire. This may create a "false positive" with respect to homes fed from that pole — the actual noise source may be in any home connected to that section of the power system. Follow up by checking the power drop to the home and, if possible, at the meter before identifying that residence as the source of the noise. Noise on power lines can travel a long way, and it is easy to be fooled by where it is heard.

CAUTION: *Always observe good safety practices! Only qualified people familiar with the hazards of working around energized electrical equipment should inspect power-line or other energized circuitry.*

When attempting to isolate the pole, it is often best to use the highest frequency at which you can hear the noise. Noise can exhibit peaks and nulls along a power line that are a function of its wavelength. Longer wavelengths can therefore make it difficult to pinpoint a particular point along a line. Furthermore, longer wavelength signals typically propagate further along power lines. You can often reduce your search area by simply increasing the frequency at which you look for the noise.

In some cases, tuning upward in frequency can also be used to attenuate noise. This can be especially helpful in cases where your receiver does not have an RF gain control. As mentioned previously, switchmode power supplies typically generate noise that exhibits a regular and repeating pattern of peaks and nulls across the spectrum. While a typical interval might be every 50 kHz or so, the noise will often start to diminish at the highest frequencies. The peaks in some cases might drift over time, but tuning to the highest frequency at which you can hear the noise will often attenuate it enough to help locate it. If the peak drifts, be sure to keep your receiver set on the peak as you attempt to locate the source.

Under FCC rules, the involved utility is responsible for finding and correcting harmful interference that is being generated by its own equipment. In cases where a utility customer is using an appliance or device that generates noise, the operator of the device is responsible for fixing it — even if the noise is conducted and radiated by the power company's power lines.

APPROACHING A NEIGHBOR

Once you identify the source residence and approach your neighbor, the importance of personal diplomacy simply cannot be overstated. The first contact regarding an RFI problem between a ham and a neighbor is often the most important; it is the start of all future relations between the parties. The way you react and behave when you first discuss the problem can set the tone for everything that follows. It is important, therefore, to use a diplomatic path from the very start. A successful outcome can depend upon it!

A self-help guide for the consumer published jointly by the ARRL and the Consumer Electronics Association (CEA) often proves helpful when discussing an interference problem to a neighbor's equipment with the neighbor. Entitled *What To Do if You Have an Electronic Interference Problem*, it may be printed and distributed freely. It is available on the ARRL website at **www.arrl.org/information-for-the-neighbors-of-hams** and also in the online information accompanying this book. Be sure to download and print a copy for your neighbor before you approach him or her.

With the noise active and with a copy of the pamphlet handy, approach your neighbor with a radio in hand, preferably an ordinary AM broadcast or short-wave receiver. Let them hear it, but not so loud that it will be offensive. Tell them this is the problem you are experiencing and you believe the source may be in their home. Don't suggest what you think the cause is. If you're wrong, it often makes matters worse. Give them the pamphlet and tell them it will only take a minute to determine whether the source is in their home. Most neighbors will agree to help find the source, and if they agree to turn off circuit breakers, it can be found very quickly. Start with the main breaker to verify you have the correct residence, then the individual breakers to find the circuit. The procedure then becomes the same as described for your own residence.

27.7.4 Radio Direction Finding

Radio direction finding (RDF) can be a highly effective method to locate an RFI source, although it requires more specialized equipment than other methods. RDF techniques can be used to find both broadband and single-signal, narrowband noise sources. Professional interference investigators almost always use radio direction finding techniques to locate power-line noise sources. See the **Antennas** chapter for more information on direction finding antennas. The following recommendations are most effective in locating noise from a broadband source. For narrowband, single-signal sources, regular RDF techniques are the most effective way to determine a source's location.

A good place to start, whenever possible, is at the affected station. Use an AM receiver, preferably one with a wide IF bandwidth. An RF gain control is particularly helpful, but an outboard step attenuator can be a good substitute. If there is a directional beam capable of receiving the noise, use it on highest frequency band at which the noise can be heard using the antenna. If you can hear the noise at VHF or UHF, you'll typically want to use those frequencies for RDF.

Select a frequency at which no other stations or signals are present and the antenna can discern a directional peak in the noise. Rotate the beam as required to get a bearing on the noise, keeping the RF gain at a minimum. Repeat with a complete 360° sweep using the minimum RF gain possible to hear the noise in its loudest direction. Try to decrease the RF gain to a point at which the noise clearly comes from one and only one direction. You can simultaneously increase the AF gain as desired to hear the noise.

Distant sources, including power-line noise, are generally easier to radio direction find at HF than nearby sources. Whenever possible, it's almost always better to use VHF or UHF when in close proximity to a source. Tracking a source to a specific residence by RDF at HF is sometimes possible. Such factors as balance and geometry of a home's internal wiring, open switch circuits, and distance may cause the residence to appear somewhat as a point source.

If the search is being conducted while mobile or portable, VHF and UHF are typically the easiest and most practical antennas. Small handheld Yagi antennas for 2 meters and 440 MHz are readily available and can serve double duty when operating portable. Many handheld receivers can be configured to receive AM on the VHF bands. Be sure to check your manual for this feature. VHF Aircraft band or "Air band" receivers are also a popular choice since they receive AM signals.

Using RDF to locate an HF noise source while in motion presents significant challenges. Conducted emissions are typical from a consumer device or appliance. In this case, the emissions can be conducted outside the residence and on to the power line. The noise can then propagate along neighborhood distribution lines, which in turn act as an antenna. The noise can often exhibit confusing peaks and nulls along the line, and if in the vicinity of a power line radiating it, RDF can be extremely difficult, if not impossible. Depending on the circumstances, you could literally be surrounded by the near field of an antenna! You would generally want to stay away from power lines and other potential radiators when searching at HF.

Antennas for HF RDF while walking typically include small loops and ferrite rod antennas. In some cases, a portable AM broadcast radio with a ferrite rod antenna can be used for direction finding. An HF dipole made from a pair of whip antennas may be able to get an approximate bearing toward the noise. Mount the dipole about 12 feet above ground (remembering to watch out for overhead conductors!)

and rotate to null out the noise. For all three types of antennas, there will be two nulls in opposite directions. Note the direction of the null. Repeat this procedure from another location and then triangulate to determine the bearing to the noise.

27.7.5 Using SDR Receivers

A portable SDR receiver with supporting software and a few accessories can be a powerful tool for locating RFI sources. Recent developments have greatly simplified the setup needed to effectively and inexpensively visualize and track down RFI sources. All you need to get started is a portable computer, an SDR receiver, SDR software, and a direction-finding antenna (see **Figure 27.18**). An SDR and display software provide the ability to see the characteristics of the RFI signal. This helps you focus on locating one RFI source at a time. This allows faster locating of the source. Once located, the source can usually be eliminated.

TYPES OF RECEIVERS

There are many SDR receivers to choose from. Be sure your receiver and accompanying SDR display and control software has the features and specifications suitable for tracking RFI. It may be best to select your SDR software first, and then let that decision drive your choice of SDR receiver.

The receiver should have frequency coverage from 100 kHz (where switchmode power supplies often operate) up through at least the UHF range (for tracking power line sources close-in). The accompanying software should allow you to see up to 5 to 10 MHz of spectrum at once. Observing this wide frequency range allows you to correlate which of the various pulses, spurs, and spikes (both in and out of the amateur bands) may be from the same source. It will help if your SDR is powered by a USB port on the portable computer so that a separate power source is not required.

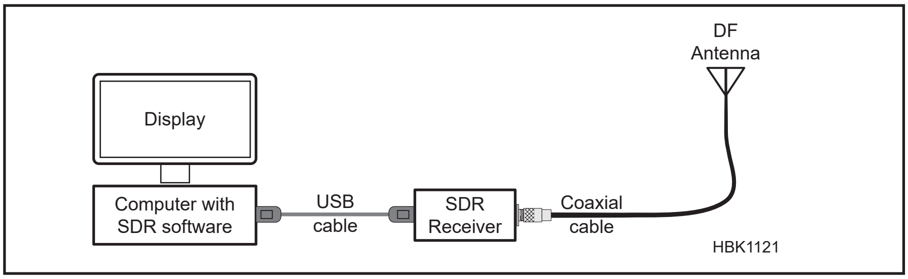


Figure 27.18 — Block diagram of PC+SDR+DF Antenna.

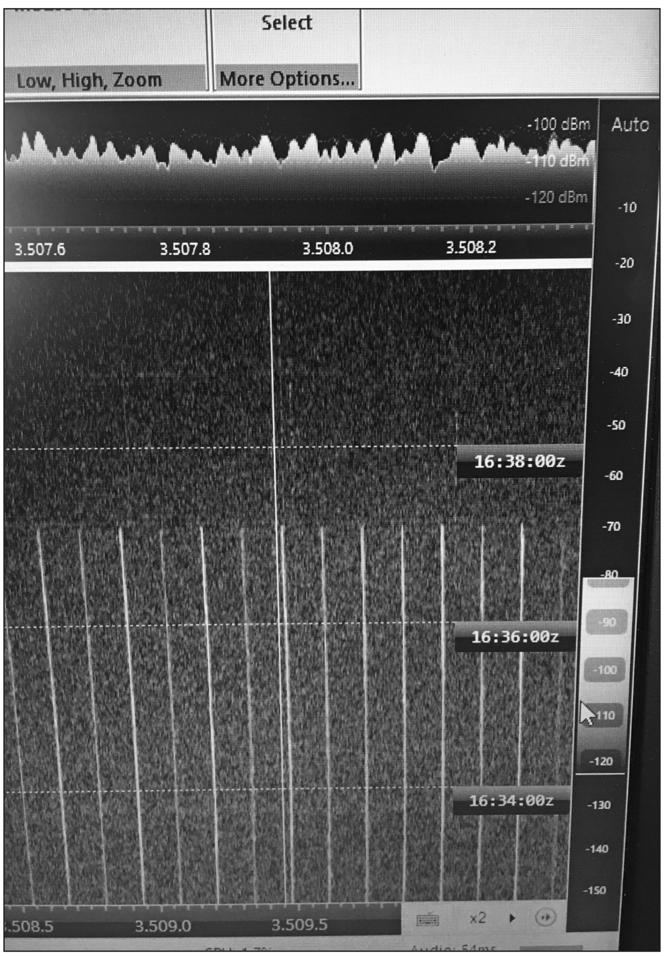


Figure 27.19 — Photo showing 2 kHz span with spikes from refrigerator's microprocessor, cured with a choke made from two snap-on Type #31 cores on ac power cord.

SDR SOFTWARE

Most SDR receivers require support from a user interface software application. Your choice of software will depend on your computer's operating system; whether the software supports the SDR receiver; and the software's features. The following SDR software features are useful for tracking RFI:

- Both spectrum and waterfall display
- Adjustable visible bandwidth with the ability to zoom in to a very narrow span of 1 or 2 kHz (helpful for identifying microprocessors) (see **Figure 27.19**)
- Ability to zoom out to see a wide span of 2 to 8 MHz (to match patterns of RFI from sources outside the amateur bands to what you are experiencing inside the bands) (see **Figure 27.20**)
- CW, SSB, AM and FM modes
- Ability to pre-set particular bands of interest
- Adjustable settings for IF and RF gain (useful for reducing receiver overload and artifacts, as well as allowing you to calibrate the software's signal strength readings)
- Ability to obtain screenshots of the spectrum and waterfall display (useful for documenting the signature of RFI source)
- Has speaker audio output

DISPLAY COMPUTER

For tracking down RFI in the field you will want a portable computer to display the signals received by the SDR. Your setup is most versatile when the SDR software is installed on a lightweight, battery-operated computer, such as a tablet or laptop with a bright screen. You will need to be able to read the screen in sunlight. The computer's system resources should be adequate to allow the SDR software to run smoothly without freezing or hesitation. The broader the spectrum being visualized, the more resources that will be required.

In addition to the spectrum and waterfall images on the computer display, it can also be

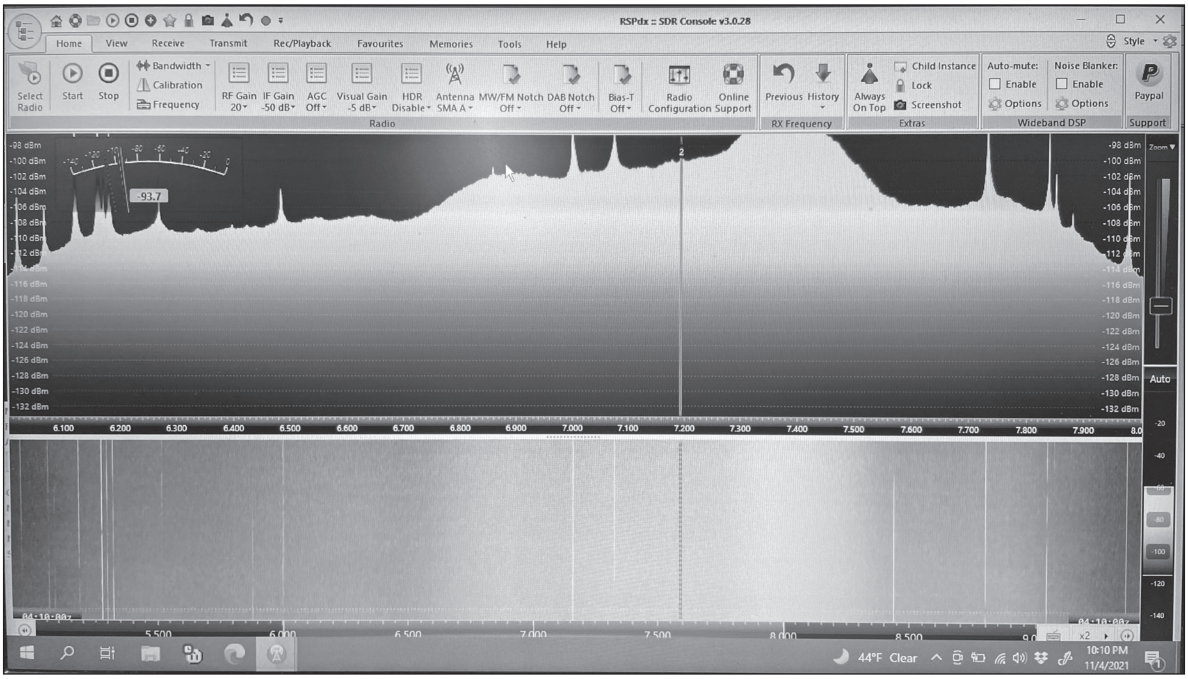


Figure 27.20 — Showing source of 160-meter RFI originating from a switchmode power supply source outside the band.

useful to have substantial audio output available either from the computer or through an accessory speaker. This is helpful when you are attempting to demonstrate the sound of the RFI. For example, you might be standing on the ground below a suspected power line source, while a utility lineman is up above moving hardware components to determine which component is the RFI source. With adequate volume, the lineman can directly hear how the movement affects the RFI.

ANTENNAS AND PROBES

Having a variety of different antennas available can be useful at various stages of the RFI hunt. The appropriateness of a particular antenna will depend upon the frequency of the RFI and your distance from the source. These will be the tools that will help you find out where the source is located.

You should start with your usual station antennas connected to your regular transceiver. Begin here and observe the behavior of the RFI. Try to correlate it to time of day, weather conditions, human activities, modulation characteristics, and bands where it is most prominent. Avoid becoming distracted by jumping to early conclusions. If your station has a directional antenna, that may be useful in determining the general direction of the source. Connect your station antennas to your SDR set-up and capture an image of its "signature" for future reference. Saving these snapshots of the RFI can be useful for future reference in the case of intermittent or recurring noise sources.

Most station antennas are tuned for particular bands. Having an antenna with a broadband response can be very useful for analyzing a wide range of the spectrum with the SDR. As mentioned above, this may help correlate your interference with primary RFI sources that are outside of the amateur bands. There are broadband dipole designs but these are not easily rotatable.

A very good broadband antenna choice is the portable flag antenna designed in 2021 by Don Kirk, WD8DSB. It was made specifically for hunting RFI and has impressive directional characteristics from 1 to 30 MHz. It is portable and has a sharp unidirectional sharp null. Due to its small size, it requires a preamplifier. Construction details are found in the March 2021 *QST* article by Don Kirk, WD8DSB, "Portable Flag Antenna for MF/HF Radio Direction Finding." DX Engineering (**www.dxengineering.com**) also offers a complete kit, part number DXE-NOISELOOP, based on this design. They also offer a broadband 30 dB preamplifier and attenuator, part number DXE-NL-PRE-ATT-1, designed for use with the portable flag.

Another direction-finding (DF) antenna option is a magnetic loop. These can be inexpensive, easy to construct, and relatively portable. Like the portable flag, these require preamplifiers. They are very narrow-banded and bi-directional, thus requiring triangulation to locate a source.

As you get closer to the RFI source, you may be able to detect it in the VHF/UHF range. In that case, a Yagi antenna is very useful. The Yagi is unidirectional and requires no preamplifier; however, they are relatively narrow-band antennas. They are particularly useful for pinpointing close-in power line sources. You may even be able to identify an individual component generating the RFI.

Another useful antenna for RFI sleuthing is a *sniffer probe*. This can be handy as you get very close to a suspected source such as a computer, power supply, or other device. The sniffer probe is very small (typically a short wire or small loop with a maximum dimension of about an inch). This allows you to get very close to the RFI source, possibly identifying a specific wire or component as the source. Sniffer probes as shown in **Figure 27.21** are inexpensive and easy to construct.

A sniffer probe can also be used to probe individual circuit breakers on a structure's electrical service panel. This can help identify

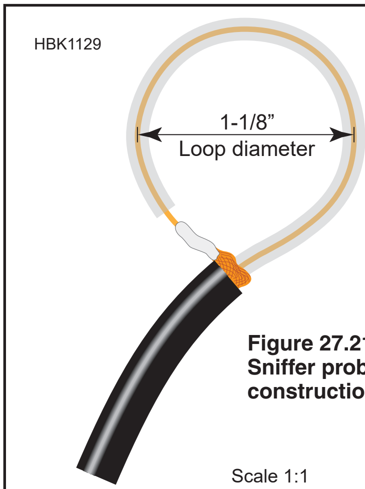


Figure 27.21 — Sniffer probe construction.

Common Mistake — Rotating the DF Antenna Too Quickly

SDR software works by performing sophisticated digital signal processing which introduces significant latency into the signal chain. A delay of perhaps 1 second occurs between when you point the antenna at an RFI source and the time signals from it appear on the SDR software's display or in the audio. Accurate direction-finding requires slow rotation of the antenna. This is not a time for wildly swinging the antenna back and forth!

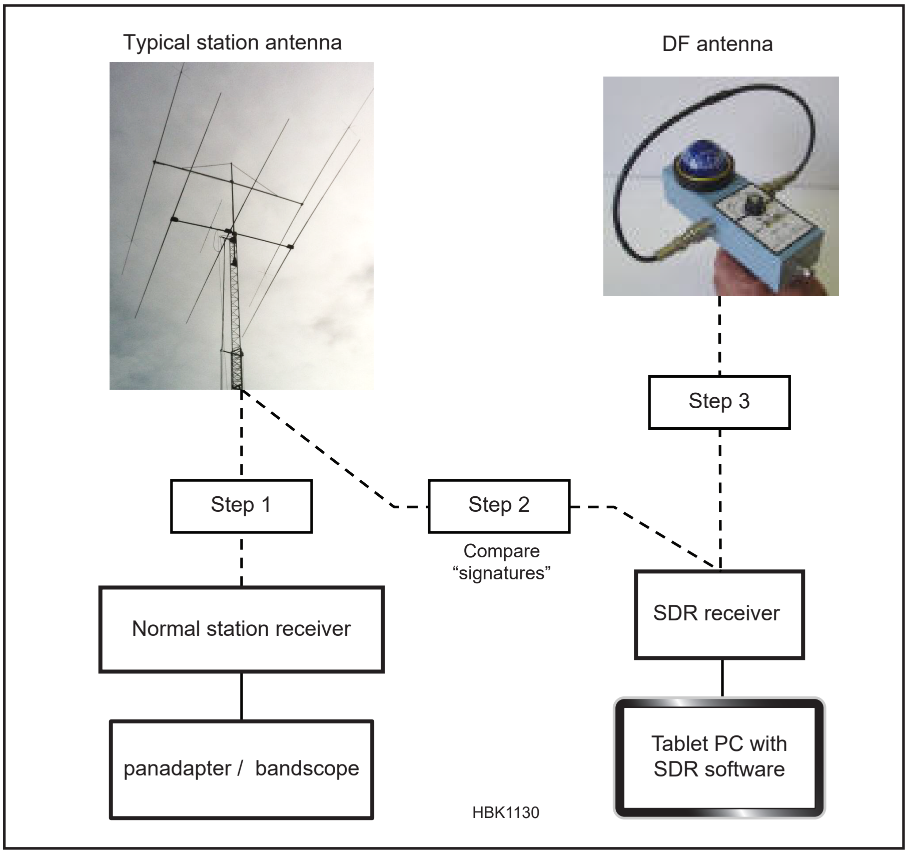


Figure 27.22 — Confirming signature between station transceiver + antenna versus SDR + DF antenna.

which branch circuit is connected to the RFI source. See WD8DSB's video of the configuration and process on YouTube at **www.youtube.com/user/wd8dsb**.

Several accessories will help round out your RFI detective kit. A camera tripod can hold your DF antenna steady as you make careful measurements. This will also assist in accurately repeating and confirming your direction measurements.

A step attenuator may be necessary to reduce signal strength from the RFI source as you move in closer. Strong RFI signals can easily overload a receiver and produce misleading artifacts. Place the step attenuator in the feed line between the DF antenna and the SDR's antenna input, then switch in the desired attenuation. If signals suddenly appear or disappear when attenuation is changed, the receiver may be overloading, creating spurious responses mistaken for RFI. The signals displayed should change only by the amount of attenuation added or removed.

Depending on the type of DF antenna you use, a preamplifier may be necessary. The flag loop and magnetic loop antennas require them to boost signal strength to a useable level. Broadband preamplifiers are more versatile because they allow for looking at larger segment of spectrum. Preamplifiers can make the receiver more susceptible to overload, so use them only when necessary.

An AM broadcast band hardware filter can help reduce potential artifacts caused by overload from nearby AM transmitters. The filter should be placed between the antenna and SDR input. Software filters will not protect the input of the SDR from overloading but can be useful in cleaning up the SDR display and removing strong signals not related to the RFI signals.

PRACTICING WITH YOUR EQUIPMENT

Once you have assembled your SDR, software, and DF antennas, you should, as with any other gear, practice using it before going into the field. This is especially true of the software. It is much easier to configure and experiment with the SDR software while sitting relaxed inside, not trying to do so the first time your equipment is out in the field. It will take a while to get comfortable with the system, so give yourself plenty of time. Then go outside to practice by locating a known RF source such as a signal generator, broadcast station, or friend's amateur station.

CHARACTERIZE THE RFI

Once you have RFI affecting your receiver's noise floor, begin by carefully studying its characteristics. This might include getting an image of what it looks like on your regular transceiver's spectrum scope or recording its audio characteristics. The results will become part of the signature you use to track the RFI source. Your goal will be to ensure you are

Common Mistake — Failing to Recognize SDR Artifacts

Beware of false signatures caused by artifacts. An artifact is something appearing on the SDR spectrum or waterfall display that is generated by the SDR, the computer, or a power supply close by. Some sources of artifacts include an overload of the SDR input and RFI generated by your computer or its power supply.

Take these steps to test for and prevent artifacts in the RFI hunting setup. Be sure the SDR receiver is not overloaded by strong signals such as local broadcast stations. You might use a broadcast band filter. You could also test by inserting an attenuator between the antenna and the SDR. Artifacts will usually not be reduced — but real RFI is.

A common source of artifacts is a computer's power supply. To test and eliminate these you can remove the power supply and run the computer on a battery.

A laptop's touchpad may generate close-in RFI. Test for this by touching the touchpad to see if the potential artifact is affected. This source may usually be eliminated by using a mouse instead.

Many computer artifacts can be eliminated by moving the antenna away from the computer.

And, finally, consider using a second receiver to confirm whether a "signal" is real or an artifact.

tracking the same RFI as is raising the noise floor in your station. There are many potential sources, but you should stay focused on whatever impedes your receiving ability. After you eliminate the top layer of RFI getting to your receiver, you can then move on the next RFI source.

Start by focusing on specific RFI while using your normal station receiver and antenna. Then change from that receiver (but with the same station antenna) to the SDR. Be sure to confirm that you are seeing the same RFI source on the SDR. Next, connect the SDR to your DF antenna. Again, confirm that you are seeing the same RFI source (see **Figure 27.22**). Now, you are ready to locate the same RF source that is on your radio.

LOOKING FOR THE RFI SOURCE

Before you start looking for an RFI source outside your own home, be sure to conduct a "power-off" test. Doing this will allow you to dramatically narrow the scope of your RFI hunt. This test consists of completely shutting off the power to your house, while listening on your regular receiver (operating on batteries) and using your normal antenna. The power is switched off at the main electrical switch panel. Be sure that no devices in the house are left powered on. Check for devices that may have standby batteries, UPS devices, chargers, battery tenders, and even vehicles parked at your house that may have active electronics.

If the RFI signature disappears during this test, you can be assured that the RFI source is located within your house. Once the power is restored, and after all devices have come out of standby mode, you can use a sniffer probe to test each of the circuits on your breaker panel. This allows you to sniff for a branch circuit with high RFI and to narrow your search to that circuit.

Additionally, a sniffer probe may also allow you to locate the offending source(s) inside your station. These sources can be switchmode power supplies, computer monitors, USB ports, etc. The source may also be isolated by sequentially powering-off individual devices.

To locate sources outside your house, obtain the RFI source's signature while using your regular station antennas, then match that image to what you can see with the SDR receiver and one of the portable antennas. Next, take the SDR, computer, and portable DF antenna into the field, e.g., near your regular antenna.

Mount the DF antenna on a rigid support, such as a tripod, then slowly rotate it to determine from which direction the RFI is coming. To maximize directional characteristics of the DF antenna, be sure to place the antenna away from other objects and up and away from your own body. A tripod helps assure repeatability of the measurements (either nulling or peaking, depending on the type of antenna being used).

When a suspected RFI source is further away, you will need to expand your search area. Initially, this may require taking your SDR and DF equipment in a vehicle. Have a partner drive while you operate the equipment.

Continually confirm that you are tracking the same RFI signature. Obtain an initial DF bearing and head in that direction while watching for changes in signal strength. This should eventually lead you closer and closer to the source. To avoid being confounded by possible re-radiation, attenuation, and reflections, you should obtain multiple bearings from various locations. Then triangulate on a map to find the approximate area where the bearings intersect.

When looking for SDR over long periods, an example of using an SDRPlay for "site surveys" is described by Dave Cole, NK7Z on the web page "Using a SDR as a RFI site survey tool" at **www.nk7z.net/sdr-for-rfi-survey-p1**. In that example, a PC stores data over an extended period across spectrum extending from audio through 2 GHz. Other resources are available, including RFI snapshots, at **www.nk7z.net**.

> ***Common Mistake — Blocking Directional Pattern of the DF Antenna***
>
> Having the direction-finding antenna blocked by objects may make its pattern unreliable. This will confound the results of your direction finding. Be sure to place the DF antenna in the clear. Keep your body and building structures out of the way. Great distances are required at lower frequencies.

POWER-LINE NOISE

These same techniques may also be used for locating power line sources. However, be aware that power lines present special challenges. Power lines consist of many discrete hardware components such as lightning arrestors, tie wires, ground wires, and staples, among other items. Any of these may be an RFI source.

RFI sources on power lines are also connected to long conductors, which often carry and re-radiate RFI over great distances. This may confound the process of pinpointing the source(s). Often, one stretch of power lines can contain multiple RFI sources that may be active at different times. Keep an open mind and remain alert for the possibility that you have more than one source. Use the SDR image to help differentiate multiple sources.

The SDR software can "zoom in" to show a very narrow bandwidth, and many have a DSP component that may allow demodulating the audio. This may allow you to see whether the signal has the characteristics of a 120 Hz signature. Additional clues may be found by correlating RFI intensity with weather patterns (humidity, temperature, wind). As you close in on a power line RFI source, it likely will be stronger at VHF/UHF where a highly directional beam for those frequencies becomes very useful.

27.8 Television Interference (TVI)

Beginning in 2009, over-the-air TV broadcasting in the United States began a transition from the NTSC analog AM format mostly on VHF and low-UHF channels to a digital DTV format exclusively on UHF channels. (See the **Modulation** and **Image Communications** chapters for more information about digital TV signals.) Due to the interference-rejection characteristics of the DTV system and the greater frequency separation between TV channels and most amateur operation, the scourge of TVI from amateur transmissions has been greatly reduced.

Digital TV has better immunity to interference than the obsolete analog system, but for both formats clear reception requires a strong signal at the TV antenna-input connector so the receiver must be in what is known as a *strong-signal area*. Outside this area, signal strength eventually falls below a threshold at which picture quality degrades rapidly. It is in the weak-signal areas where TV receivers are most likely to experience TVI, from amateur or other noise signals.

Along with over-the-air reception, some TV receivers can also be connected directly to cable TV systems through the antenna input (for "cable-ready" receivers). They can also act as video displays for cable TV converters and satellite receivers that translate the cable or satellite signals to RF signals for the TV receiver to display. If the converter experiences interference, it will likely be observed on the TV equipment.

The TV receiver is often central to a home entertainment system and may have audio, video, and control cables connected to it from various media players or gaming devices, creating additional opportunities for interference. Because of the different types of TV equipment and the many ways in which the equipment can be configured and connected, the general term "TV" will be used in this section.

models. Switchmode power supplies in current TV equipment, however, can still be a source of RFI to amateurs.

Note that most TV broadcasts are now in the UHF spectrum, regardless of what channel number they use in their identification. You can find the actual channel used by a TV station at **www.fcc.gov/media/engineering/dtvmaps**, which provides coverage maps based on Zip code.

The manufacturer of the TV or video equipment can sometimes help with an interference problem. The Consumer Technology Association (CTA) can also help you contact equip-

27.8.1 Causes of TVI

TVI to the reception and display of an RF television signal caused by problems receiving the over-the-air signal include:

• Spurious signals within the TV channel coming from your transmitter or station.

• The TV may be overloaded by your transmitter's fundamental signal.

• Signals within the TV channel from some source other than your station, such as electrical noise, an overloaded mast-mounted TV preamplifier, or a transmitter in another service.

• One or more connecting cables are loose or defective. Be sure cables are of good-quality and that connectors are installed properly, especially older crimp-type F connectors.

The *TVI Troubleshooting Flowchart* in **Figure 27.23** is a good resource for troubleshooting interference from a strong signal, although it is somewhat outdated and does not address TVI via non-RF or power connections. If you are following this diagram, treat "CATV" as including satellite or other over-the-air receiving equipment that produces an RF signal connected to the TV's antenna or similar input. If you get to the box with the label beginning "Possible Direct Pickup Problem," refer to the section below on Non-Radio Devices for further troubleshooting directions.

Interference to basic functions or features or disruption of a video signal from another piece of equipment is usually caused by common-mode breakthrough or direct detection of:

• Strong signals picked up on video or other cables connected to the TV as common-mode current

• Interference to an RF signal received by a device connected to the TV

• Common-mode breakthrough or direct detection of a strong signal by an unshielded TV or device connected to the TV.

And you should always check to see if the TV might be defective or misconfigured, making it look like there is an interference problem.

Certain types of television receivers and video monitors are reported to cause broadband RFI *to* amateur signals — large-screen plasma display models were at one time reported to be the most frequent offender — and this may be difficult to cure due to the nature of the display technology. Fortunately, less-expensive, more power-efficient, and RF-quieter LCD and OLED technology has displaced plasma technology for current

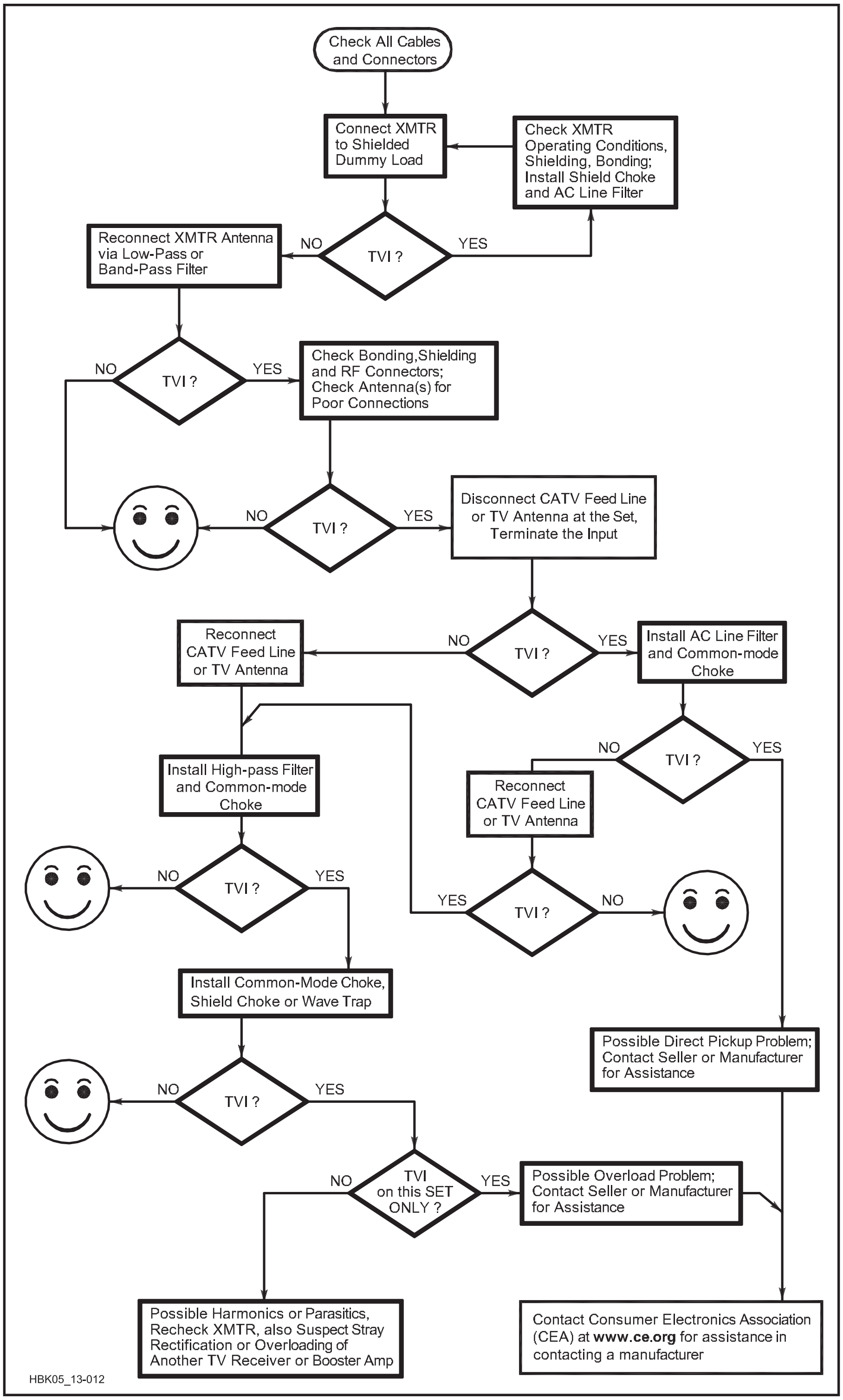


Figure 27.23 — TVI troubleshooting flowchart for over-the-air or cable TV interference.

ment manufacturers. Contact them directly for assistance in locating help at **www.cta.tech**.

COMMON SOURCES OF TVI

HF transmitters — A nearby HF transmitter is most likely to cause fundamental overload. This is usually indicated by interference to all channels, or at least all VHF channels. To cure fundamental overload from an HF transmitter to an antenna-connected TV, install a high-pass filter directly at the TV set's antenna input. (Do not use a high-pass filter on a cable TV input because the HF range is used for data and other system signals.)

A strong HF signal can also result in a strong common-mode signal on the TV's feed line. A common-mode choke will block signals on the outside of the feed line shield, leaving the desired signals inside the feed line unaffected. **Figure 27.24** shows how a common-mode choke is constructed for a coaxial feed line. The same choke can be applied to audio, control, and power cables as well, to prevent RFI caused by common-mode ingress via these non-RF paths. (See the section Common-Mode Chokes earlier in this chapter.)

These filters and chokes can probably cure most cases of TVI! **Figure 27.25** shows a "bulletproof" installation for both over-the-air and cable TV receivers. If one of these methods doesn't cure the problem, the problem may be common-mode breakthrough on a non-feed line connection. It may also be direct pickup in which a signal is received by the TV set's circuitry without any conducting path being required. In that case, don't try to fix it yourself — it is a problem for the TV manufacturer.

High-pass filters *should not* be used in a cable TV feed line (Figure 27.21A) with two-way cable devices such as cable modems, set-top boxes, and newer two-way or cable-ready CableCARD-equipped TVs. The high-pass filter may prevent the device from communicating via the cable network's upstream signal path.

VHF Transmitters — Most TV tuners are not very selective, and a strong VHF or UHF signal, including those from nearby FM and TV transmitters, can overload the tuner easily, particularly when receiving VHF or UHF broadcasts over the air and not via a cable or satellite system. In this case, a notch filter (also known as stop-band or band-reject filters) at the TV can help by attenuating the fundamental signal that overloads the TV tuner. Channel Plus (**www.solidsignal.com**), PAR Electronics (**www.parelectronics.com**), and Scannermaster (**www.scannermaster.com**) sell notch filters.

If the VHF transmitter is generating a harmonic or other spurious emission causing RFI, a transmission line stub filter may be a good solution. The stub can be designed to remove a signal at the transmitter. If the transmitter's fundamental signal is overloading the receiver, a notch filter stub can also be applied at the receiver. See the **Transmission Lines** chapter for more information about these filters.

A common-mode choke may also be necessary if the TV is responding to the fundamental signal present as common-mode RF on the TV's feed line or other connecting cable.

TV Preamplifiers — Preamplifiers are only needed in weak-signal areas and they often cause trouble, particularly when used unnecessarily in strong-signal areas. They are subject to the same overload problems as TVs, and when located on the antenna mast it can be difficult to install the appropriate cures. You may need to install a high-pass or notch filter at the input of the preamplifier, as well as a common-mode choke on the input, output, and power-supply wiring (if separate) to effect a complete cure. All filters, connections, and chokes must be weatherproofed. A common-mode choke will reduce RF current on the feed line's shield.

For a common-mode feed line choke, use two 1-inch-long Type #43 clamp-on ferrite

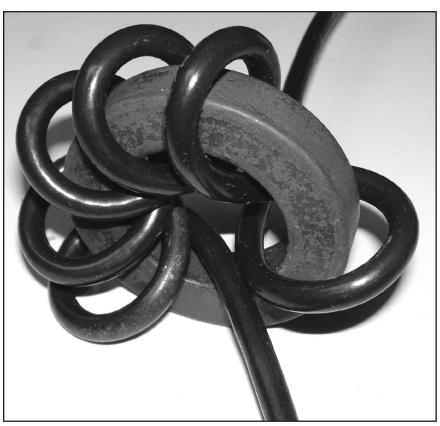


Figure 27.24 — To eliminate HF and VHF signals on the outside of a coaxial cable, use a 1- to 2-inch OD toroid core and wind as many turns of the cable on the core as practical.

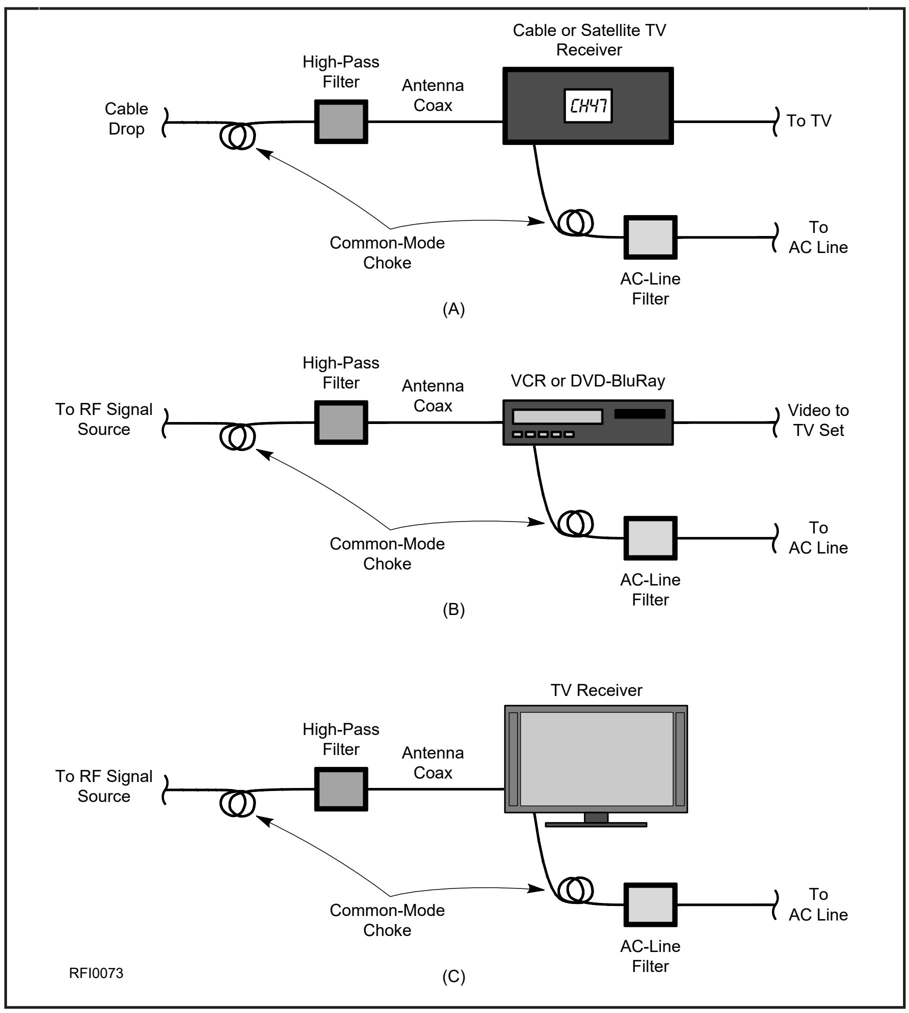


Figure 27.25 — Installing common-mode chokes and high-pass filters will cure most fundamental overload and common-mode breakthrough interference from HF sources. Apply common-mode chokes in the ac power cord before adding ac-line filters. This technique does not address direct pickup or spurious emission problems.

cores if VHF signals are causing the interference and Type #61 material for UHF. HF choke design is discussed in the section on Common-Mode Chokes.

Spurious Emissions — You are responsible for spurious emissions produced by your station. If your station is generating any interfering spurious signals, the problem must be cured there. Start by analyzing which TV channels are affected. A TV Channel Chart showing the relationship of the amateur allocations and their harmonics to over-the-air and cable channels is provided in this book's online material. Each channel is 6 MHz wide. If the interference is only on channels that are multiples of your transmitting frequency, you probably have interference caused by harmonics of your transmitted signal.

Harmonics from commercial transceivers, however, are quite rare. As mentioned earlier, significant harmonics from such equipment probably indicates a failure that needs to be repaired. Harmonics can also be generated by a poor connection somewhere in the transmission line or by arcing from the antenna. Both of these typically cause erratic or intermittently high SWR.

It is not certain that these harmonics are coming from your station, however. Harmonics can be generated by overloaded preamplifiers or tuner input circuits. Harmonics can also be generated like IMD products by nonlinear junctions near your station transmitter or very near the TV antenna. (See the section on Interference from Intermodulation Distortion.) If your transmitter and station do not cause interference on a TV set in your own home, then you must look elsewhere for the source of the harmonics.

An inexpensive SDR receiver is a good way to see if spurious emissions of any sort — not necessarily just harmonics — are present. See the section on Using SDR Receivers earlier in this chapter for information on how to use these tools.

Electrical Noise — Digital TV signals are fairly resistant to electrical noise, but in extreme cases can cause the picture to freeze or fail to be displayed as discussed in the following section on Digital TV Receivers.

On an AM receiver (including SSB or CW receivers), electrical noise usually sounds like a buzz, sometimes changing in intensity as the arc or spark sputters a bit. If you have a problem with electrical noise, refer to the section on Electrical Noise.

DIGITAL TV (DTV) RECEIVERS

Nearly all over-the-air TV broadcasters in the US, with the exception of low-power TV stations and translators, are using the DTV (digital TV) format. Digital TV signals can operate with much lower signal-to-noise ratios, but are still susceptible to interference.

Interference to digital TV signals from amateur signals — narrowband interference, for instance, a CW carrier — to a 6 MHz-wide digital TV signal generally has two effects. If the interfering signal is strong enough, it will cause degraded modulation error ratio (MER) and degraded bit error rate (BER) in the digital video signal. If the amplitude of the interference is sufficient, the digital receiver's forward error correction (FEC) circuitry will be unable to fix the broken bits, and the digital video signal will "crash." (See the **Image Communications** chapter for more information on coding and error correction in digital TV signals.)

TV viewers watching any of the multiple video streams that may be contained within the digital video signal won't see any problems in the picture (or hear anything wrong in the sound), until the so-called "crash point" is reached. At that point, the picture will begin to show intermittent "tiling" (the picture breaking up into small squares) or blocking (freezing) in the image. As the amplitude of the interfering signal increases perhaps another 0.5 dB to 1 dB, the crash point or "digital cliff" is reached, and the picture and sound are gone! As you can see, there is a tiny window between receiving a perfect picture and receiving no picture. The same effect is produced by signal fading and may be difficult to distinguish from RFI.

Interference to the digital signal does not make its presence known through visual or audible artifacts such as streaks, lines, tearing in the picture, or garbled audio. This means that a viewer experiencing interference may not be able to identify its source, but troubleshooting interference may also become more difficult. Nevertheless, the more robust digital modulation is often less susceptible to interference from narrowband amateur signals. A clue to the source of the interference is that interference caused by an amateur signal will occur in sync with the amateur's transmissions, while other types of interference will have no correlation.

ANALOG TV RECEIVERS

Even though over-the-air TV broadcasting largely switched to a digital format in 2009, many analog TV receivers are still in use for cable TV, satellite TV, with converter boxes for digital broadcast signals, and for displaying video from DVDs and other video sources. Older VCR and DVD players may also include an analog TV tuner to receive analog TV signals.

Interference to video displays and monitors that do not receive RF signals from an antenna or RF modulator should be assumed to be common-mode breakthrough or direct pickup. The same applies to interference to a TV displaying video signals (not through the antenna input). Interference that is present only on the audio is probably a case of common-mode RFI. (See the Non-Radio Devices section of this chapter.)

27.8.2 Cable TV

Cable TV (CATV) has generally benefited amateur radio with respect to TVI. The cable system delivers a strong, consistent signal to the TV receiver, reducing susceptibility to interference from amateur signals. It is also a shielded system so an external signal shouldn't be able to cause interference. Most cable companies are responsible about keeping signal leakage (*egress*) and *ingress* — the opposite

Common Mistake — It's the Cable System

The cable company is often incorrectly blamed for causing interference that is actually generated by consumer devices. Remember that all the individual circuit grounds in your home are bonded at the service entrance panel. The National Electrical Code also requires the cable TV ground to be bonded to this same ground system.

When you now consider that most RFI problems, especially at HF, involve conducted emissions, it's easy to see what can happen. Conducted emissions from a consumer device can propagate along ground conductors and wind up on the shield of the cable TV coax. The cable (and possibly other components of the cable TV system) can then radiate the noise.

Ron Hranac, NØIVN, also adds the following from an industry point of view:

"A key point that needs to be emphasized related to this topic is that in many cases wideband noise from consumer devices that is being coupled to and radiated from the cable TV network is often assumed to be leaking cable modem digital signals. The cable company channelizes its digital signals (downstream channel bandwidths are 6 MHz, and upstream channel bandwidths are typically either 3.2 MHz or 6.4 MHz). The cable company generally does not use upstream frequencies below about 15 MHz for cable modem data transmission, although there might be a narrowband data carrier from set-top boxes in the roughly 8 MHz to 12 MHz range. Cable modem upstream signals are generally found in the 20 MHz to 42 MHz range, sometimes as low as 15 MHz or so. The cable company does not transmit signals in the diplex filter cutoff region of about 42 MHz to 50 MHz, nor does it transmit signals below about the previously mentioned 8 MHz or so."

Conclusion: Don't automatically assume that the cable TV system is the cause of an RFI problem just because it is radiating the noise.

Table 27.2
Amateur Radio Bands Relative to Cable TV Downstream Channels

Amateur Band	*Over-The-Air Frequency Range*	*Cable Channel*	*Cable Frequency Range*
6 meters	50 – 54 MHz	Below Ch. 2	50 – 54 MHz, sometimes used for narrowband telemetry carriers
2 meters	144 – 148 MHz	Ch. 18	144 – 150 MHz
1.25 meters	222 – 225 MHz	Ch. 24	222 – 228 MHz
70 cm	420 – 450 MHz	Ch. 57	420 – 426 MHz
		Ch. 58	426 – 432 MHz
		Ch. 59	432 – 438 MHz
		Ch. 60	438 – 444 MHz
		Ch. 61	444 – 450 MHz
33 cm	902 – 928 MHz	Ch. 142	900 – 906 MHz
		Ch. 143	906 – 912 MHz
		Ch. 144	912 – 918 MHz
		Ch. 145	918 – 924 MHz
		Ch. 146	924 – 930 MHz

of leakage — under control, but problems do happen. Cable companies are not responsible for direct pickup or common-mode interference problems but are responsible for leakage, ingress, and any noise radiated by common-mode currents from their equipment.

Cable companies are able to take advantage of something known as frequency reuse. That is, all radio frequencies higher than 5 MHz are used to transmit TV signals. The latter is possible because the cables and components used to transport signals to and from paying subscribers comprise what is known as a closed network. In other words, a cable company can use frequencies inside of its cables that may be used for entirely different purposes in the over-the-air environment. As long as the shielding integrity of the cable network is maintained, the cable company's signals won't interfere with over-the-air services, and vice-versa.

The reality is that the shielding integrity of a cable network *is* sometimes compromised, perhaps because of a loose or damaged connector, a cracked cable shield, rodent damage, poorly shielded customer premises equipment (CPE) such as cable-ready TVs and various media players, and problems that may happen when someone tries to steal cable service! §76.605(a)(12) of the FCC Rules defines the maximum allowable signal leakage (*egress*) field strength at specified measurement distances, and §76.613 covers harmful interference. FCC Rules also mandate that cable operators "…shall provide for a program of regular monitoring for signal leakage by substantially covering the plant every three months," and leaks greater than 20 microvolts per meter (µV/m) at a 10 ft. measurement distance repaired in a reasonable period of time. As well, an annual "snapshot" of leakage performance must be characterized via a flyover measurement of the cable system, or a ground-based measurement of 75% of the network.

CABLE TV FREQUENCY USAGE

A typical modern North American cable network is designed to use frequencies in the 5 to 1002 MHz spectrum. Signals that travel from the cable company to the subscriber occupy frequencies from just above 50 MHz to as high as 1002 MHz range (this is the downstream or forward spectrum), and signals that travel from the subscriber to the cable company are carried in the 5 to as high as 42 MHz range, known as the upstream or return spectrum. The downstream is divided into 6 MHz-wide channel slots, which carry 64- or 256-QAM digitally modulated signals used for digital video, high-speed data, and telephone services. (Analog cable service has been phased out.) Upstream signals from cable modems and two-way set-top boxes are generally carried on specific frequencies chosen by the cable company. **Table 27.2** summarizes cable downstream channel allocations that overlap amateur radio bands. The complete North American channel plan is controlled by EIA standard 542-B. A summary of the channel structure for North America is maintained at **en.wikipedia.org/wiki/North_American_television_frequencies**.

COMMON MECHANISMS FOR LEAKAGE AND INGRESS

As noted previously, cable TV leakage and ingress occur when the shielding integrity of the cable network is compromised. A large cable system that serves a major metropolitan area has literally millions of connectors, tens of thousands of miles of coaxial cable, thousands of amplifiers, hundreds of thousands of passives (splitters, directional couplers, and similar devices), and uncountable customer premises equipment connected to the cable network! Any of these may be a source of leakage and ingress.

DIGITAL SIGNAL LEAKAGE

The digitally modulated signals carried in a cable TV network use 64-QAM or 256-QAM, the latter more common. If a QAM signal were to leak from a cable TV network, it is possible for interference to an over-the-air service to occur, but very unlikely to be identified as from a digital TV signal. The reason for this is that a QAM signal is noise-like, and sounds like normal background noise or hiss on a typical amateur receiver. The QAM signal's digital channel power — its average power over the entire occupied bandwidth — is typically 6 to 10 dB lower than what an analog TV signal's visual carrier peak envelope power (PEP) would be on the same channel. As well, a QAM signal occupies most of the 6 MHz channel slot, and there are no carriers *per se* within that channel bandwidth. Note that over-the-air 8-VSB digital TV broadcast signals transmit a pilot carrier near the lower end of the digital "haystack," but the QAM format used by cable operators has no comparable pilot carrier.

What makes the likelihood of interference occurring (or not occurring) has in large part to do with the behavior of a receiver in the presence of broadband noise. While each downstream cable TV QAM signal occupies close to 6 MHz of RF bandwidth, the IF bandwidth of a typical amateur FM receiver might be approximately 20 kHz. Thus, the noise power in the receiver will be reduced by 10 $\log_{10}$ (6,000,000/20,000) = 24.77 dB because of the receiver's much narrower IF bandwidth compared to the QAM signal's occupied bandwidth. In addition, there is the 6 to 10 dB reduction of the digital signal's average signal PEP.

Field tests during 2009 confirmed this behavior, finding that a leaking QAM signal would not budge the S meter of a Yaesu FT-736R at low to moderate field strength leaks, even when the receiver's antenna — a resonant half-wave dipole — was located just 10 feet from a calibrated leak. In contrast, a CW carrier that produced a 20 µV/m leak resulted in an S meter reading of S9 +15 dB, definitely harmful interference! When the CW carrier was replaced by a QAM signal whose digital channel power was equal to the CW carrier's PEP and which produced the same leakage field strength (the latter integrated over the full 6 MHz channel bandwidth), the S-meter read <S1. When the leakage field strength was increased to 100 µV/m, the CW carrier pegged the S meter at S9 +60 dB, while the QAM signal was S3 in FM mode and between S1 and S2 in USB mode. It wasn't until the leaking QAM signal's field strength reached several hundred µV/m that the "noise" (and it literally sounded like typical white noise) could be construed to be harmful interference.

One of the most common signs of possible

Table 27.3
VHF Midband Cable Channels

Channel Number	*Standard Video Carrier (STD) (MHz)*	*Harmonically Related Video Carrier (HRC) (MHz)*	*Incrementally Related Video Carrier (IRC) (MHz)*	*Audio Carrier (MHz)*
98	109.25	108.0054	109.25	113.75
99	115.25	114.0057	115.25	119.75
14	121.25	120.006	121.25	125.75
15	127.25	126.0063	127.25	131.75
16	133.25	132.0066	133.25	137.75
17	139.25	138.0069	139.25	143.75
18	145.25	144.0072	145.25	149.75
19	151.25	150.0075	151.25	155.75
20	157.25	156.0078	157.25	161.75
21	163.25	162.0081	163.25	167.75
22	169.25	168.0084	169.25	173.75

leakage is interference to the 2-meter amateur band, especially in the vicinity of standard (STD) cable channel 18's visual carrier on 145.25 MHz. If you suspect cable leakage, listen for the telltale broadband noise from the digital video signal over the 144–150 MHz range, and check other STD, incrementally related carrier (IRC), and harmonically related carrier (HRC) visual carrier frequencies on nearby channels listed in **Table 27.3** using a wide range receiver or scanner. (Leakage of an analog TV signal on cable channel 18 sounds like buzzing at the carrier frequencies in the table on or near 145.25 MHz. Also listen for TV channel sound on the FM aural carriers 4.5 MHz above the visual carriers.)

LOCATING LEAKAGE SOURCES

When a cable company technician troubleshoots signal leakage, the process is similar to amateur radio fox hunting. The technician uses radio direction finding techniques that may include equipment such as handheld dipole or Yagi antennas, Doppler antenna arrays on vehicles, near-field probes, and commercially manufactured signal leakage detectors. Many leakage detectors incorporate what is known as "tagging" technology to differentiate a leaking cable signal from an over-the-air signal or electrical noise that may exist on or near the same frequency. Most leakage detection is done on a dedicated cable channel in the 108 – 138 MHz frequency range.

ELIMINATING LEAKAGE

A large percentage of leakage and ingress problems are not the result of a single shielding defect, although this does happen. For example, a squirrel might chew a hardline feeder cable, or a radial crack might develop in the shield as a consequence of environmental or mechanical damage. Most often, leakage and ingress are caused by several small shielding defects in an area: loose or corroded hardline connectors and splices, old copper braid subscriber drop cabling, improperly installed F connectors, subscriber-installed substandard "do-it-yourself" components, and the previously mentioned poorly shielded cable-ready TVs and other *customer premises equipment* (*CPE*).

Other leakage and ingress problems can be caused by improper shield connections at the cable TV set-top box. The return data signal in the low HF region (3.7 – 5.5 MHz) can be radiated in this way, as well. Common-mode chokes at the equipment with the poor shield connection can block the RF current.

After the cable technician locates the source(s) of the leakage, it is necessary to repair or replace the culprit components or cabling. In the case of poorly shielded TVs or DVD players, the cable technician cannot repair those devices, only recommend that they be fixed by a qualified service shop. Often the installation of a set-top box will take care of a cable-ready CPE problem because the subscriber drop cabling is no longer connected directly to the offending device.

It is important to note that interference from leakage that is received over the air cannot be eliminated at the receiver. It is an "in-band" signal just like the desired signal and can't be filtered out or suppressed with chokes. It must be eliminated at the source of the leakage.

Similarly, RFI from cable ingress — where a clean, transmitted signal gets into the cable system signals through similar defects to those that cause leakage — must also be eliminated at the point at which the transmitted signal enters the cable system.

In both cases, a little RFI detective work may be necessary. Refer to the various RFI troubleshooting sections of this chapter; radio direction finding techniques may come in handy, as well. Once the source of leakage or point of ingress is determined, like power-line noise, it becomes the job of the cable company to repair.

VERIFYING AN RFI SOURCE TO BE LEAKAGE

Spurious signals, birdies, harmonics, intermodulation, electrical noise, and even interference from Part 15 devices are sometimes mistaken for cable signal leakage. One of the most common is emissions from Part 15 devices that become coupled to the cable TV coax shield in some way. Non-leakage noise or spurious signals may radiate from the cable TV lines or an amplifier location, but only because the outer surface of the cable shield is carrying the coupled interference as a common-mode current.

A common non-leakage interference that may radiate from a cable network is broadband electrical interference or other noise in the MF and lower end of the HF spectrum. A common misconception is that since cable companies carry digital signals on frequencies that overlap portions of the over-the-air spectrum below 30 MHz, any "noise" that radiates from the cable plant must be leaking digital signals. This type of interference is almost always power-line electrical interference or other noise that is coupled to the cable network's shield as a common-mode signal.

Leakage of downstream digital signals sounds like broadband noise as described above, over a range of frequencies given in the channels of Table 27.3. Upstream digital signals from cable modems, which have channel bandwidths of 1.6, 3.2, or 6.4 MHz, are typically transmitted in the roughly 20 to 40 MHz range and are bursty in nature rather than continuous like downstream digital signals. Set-top box upstream telemetry carriers are narrowband frequency shift keying (FSK) or quadrature phase shift keying (QPSK) carriers usually in the approximately 8 to 11 MHz range.

If normal leakage troubleshooting techniques do not clearly identify the source of the interference, sometimes the cable company may temporarily shut off its network in the affected neighborhood. If the interference remains after the cable network is turned off, it is not leakage, and the cable company is not responsible for that type of interference. If the interference disappears when the cable network is turned off, then it most likely is leakage or something related to the cable network. Turning off even a small portion of the cable network is a last resort and may not be practical because of the service disruption to subscribers. It may be easier for the cable company to temporarily shut off a suspect cable channel briefly. Here, too, if the interference remains after the channel is turned off, the interference is not leakage.

HOW TO REPORT LEAKAGE

If you suspect cable signal leakage is causing interference to your amateur station, *never* *attempt your own repairs to any part of the cable network, even the cabling in your own home*! Document what you have observed. For instance, note the frequency or frequencies involved, the nature of the interference, any changes to the interference with time of day, how long it has been occurring, and so forth. If you have fox-hunting skills and equipment, you might note the probable source(s) of the interference, or at least the direction from which it appears to be originating.

Next, contact the cable company. You will most likely reach the cable company's customer service department, but ask to speak with the local cable system's Plant Manager (may also be called Chief Engineer, Director of Engineering, Chief Tech, VP of Engineering, or similar), and explain to them that you are experiencing what you believe to be signal leakage-related interference. If you cannot reach this individual, ask that a service ticket be created, and a technician familiar with leakage and ingress issues be dispatched. Share the information you have gathered about the interference. And as with all RFI issues, remember diplomacy!

In the vast majority of cases when cable leakage interference to amateur radio occurs, it can be resolved by working with local cable system personnel. Every now and then for whatever reason, the affected ham is unable to get the interference resolved locally. Contact the ARRL for help in these cases.

27.9 Consumer Electronics RFI

27.9.1 RFI to DVD and Other Media Players

A DVD or similar video player often contains a television tuner. Older models may have an analog TV channel output. (Newer models typically have an HDMI or similar digital video interface which is less susceptible to RFI.) It is also connected to an antenna or cable system and the ac line, so it is subject to all of the interference problems of a TV. Many media players can also playback to computer video monitors.

Start by proving that the media player is the susceptible device. Temporarily disconnect the device from the television or video monitor. If there is no interference to the TV, then the media player is the most likely culprit. Cables between the media player and TV can also be the means by which RF is getting into the monitor, so a cable dummy (see the sidebar Dummy Detectives below) may be a useful way to determine if that is the case and which cable or cable(s) are the problem.

Next, find out how the interfering signal is getting into the media player. Temporarily disconnect the antenna or cable feed line from the media player. If the interference goes away, then the antenna feed line is involved. In this case, you can probably fix the problem with a common-mode choke or high-pass filter.

Figure 27.25 shows a bulletproof video player installation. If you have tried all of the cures shown and still have a problem, the player is probably subject to direct pickup. In this case, you can replace it or contact the manufacturer through the CTA.

Older analog-type VCRs are quite susceptible to RFI from HF signals. The video baseband signal extends from 30 Hz to 3.5 MHz, with color information centered around 3.5 MHz and the FM sound subcarrier at 4.5 MHz. The entire video baseband is frequency modulated onto the tape at frequencies up to 10 MHz. Direct pickup of strong signals by VCRs is a common problem and may not be easily solved, short of replacing the VCR with a better-shielded model or a modern DVD player.

27.9.2 RFI to Non-Radio Devices

Interference to non-radio devices is not the fault of the transmitter. (A portion of the *FCC Interference Handbook,* 1990 Edition, is shown in **Figure 27.26**. Although the FCC no longer offers this *Handbook*, an electronic version is available in this book's online information, from the ARRL at **www.arrl.org/fcc-and-rfi-matters** or search the ARRL website for "cib interference handbook".) In essence, the FCC views non-radio devices that pick up nearby radio signals as improperly functioning; contact the manufacturer and return the equipment. The FCC does not require that non-radio devices include RFI protection, and they don't offer legal protection to users of these devices that are susceptible to interference.

TELEPHONES

Landline or "wired" telephones are much less common than they used to be, but they may still present possible interference prob-

PART II

INTERFERENCE TO OTHER EQUIPMENT

CHAPTER 6

TELEPHONES, ELECTRONIC ORGANS, AM/FM RADIOS, STEREO AND HI-FI EQUIPMENT

Telephones, stereos, computers, electronic organs and home intercom devices can receive interference from nearby radio transmitters. When this happens, the device improperly functions as a radio receiver. Proper shielding or filtering can eliminate such interference. The device receiving interference should be modified in your home while it is being affected by interference. This will enable the service technician to determine where the interfering signal is entering your device.

The device's response will vary according to the interference source. If, for example, your equipment is picking up the signal of a nearby two-way radio transmitter, you likely will hear the radio operator's voice. Electrical interference can cause sizzling, popping or humming sounds.

Figure 27.26 — Part of page 18 from the FCC *Interference Handbook* (1990 edition) explains the facts and places responsibility for interference to non-radio equipment.

lems from amateur radio. As more people switch over to mobile telephone service instead of landline, this problem is gradually diminishing. Nevertheless, landline and cordless phones will continue to be with us for many years. Most cases of telephone interference to these phones can be cured by correcting any installation defects and installing telephone RFI filters where needed. The remainder of this section assumes the telephone is connected to landline service known as POTS (Plain Old Telephone Service) and in many cases to telephone *premises wiring* throughout a home to connect several phones to one telephone line.

Telephones can improperly function as radio receivers. Semiconductor devices inside many telephones act like diodes. When such a telephone is connected to the telephone wiring (a large antenna), an AM radio receiver can be formed. When a nearby transmitter goes on the air, these telephones can be affected.

Troubleshooting techniques were discussed earlier in the chapter. The suggestion to simplify the problem applies especially to telephone interference. Disconnect all telephones except one, right at the service entrance if possible, and start troubleshooting the problem there.

If any single device or bad connection in the phone system detects RF and puts the detected signal back onto the phone line as audio, that audio cannot be removed with filters. Once the RF has been detected and turned into audio, it cannot be filtered out because the interference is at the same frequency as the desired audio signal. To effect a cure, you must locate the detection point and correct the problem there.

Defective telephone company lightning arrestors can act like diodes, rectifying any nearby RF energy. Telephone-line amplifiers or other electronic equipment may also be at fault. Do not attempt to diagnose or repair any telephone company wiring or devices on the "telco" side of your service box or that were installed by the phone company. Request a service call from your phone company.

Inspect the telephone system installation. Years of exposure in damp basements, walls or crawl spaces may have caused deterioration. Be suspicious of anything that is corroded or discolored. In many cases, homeowners have installed their own telephone wiring, often using substandard wiring. If you find sections of telephone wiring made from nonstandard cable, replace it with standard twisted-pair telephone or CAT5 cable. If you do use telephone cable, be sure it is high-quality twisted-pair to minimize differential-mode pickup of RF signals.

Next, evaluate each of the telephone instruments. If you find a susceptible telephone, install a telephone RFI filter on that telephone, such as those sold by K-Y Filters (**www.ky-filters.com**) or use DSL filters that keep the DSL data signals out of the telephones. If the home uses a DSL broadband data service, be sure that the filters do not affect DSL performance by testing online data rates with and without a filter installed at the telephone instrument. The DSL gateway may have a filtered output for the landline interface that does not include the data signals.

If you determine that you have interference only when you operate on one particular ham band, the telephone wiring system either has an "RF hot spot" at that point when excited on that band, or some cable in the system could be resonant and thus especially responsive on that band. Install common-mode chokes on the wiring to add a high impedance in series with the "antenna." A telephone RFI filter may also be needed. (See the section on DSL Equipment for filtering suggestions.)

Telephone Accessories — Answering machines and fax machines (two more telephone-related instruments that are slowly disappearing) are also prone to interference problems. All of the troubleshooting techniques and cures that apply to telephones also apply to these telephone devices. In addition, many of these devices connect to the ac mains. Try a common-mode choke and/or ac-line

Maintaining Balance with Twisted-Pair

Speaker cables made of parallel-conductor zip cord and open-wire RF feed lines are good examples of what we think of as "balanced" wiring. If the cables are perfectly balanced, common-mode signals on the cable will not affect the differential-mode signals in the cable and vice versa. This is because the balance maintains equal-and-opposite currents in each conductor. Similarly, if a radiated RF signal encounters balanced wiring, it will cause the same amount of common-mode current to flow on each conductor. Unfortunately, it's hard to maintain that exact state of balance.

If the impedance connected to each of the wires isn't the same (of either an input or output circuit), common-mode RF current will result in different voltages in those impedances. This converts some of the common-mode signal into a differential-mode signal which combines with the intended signal in the cable. RFI from this converted signal is much harder to get rid of!

Another way for cables to be imbalanced is for each of the wires to be exposed differently to the radiated RF signal. (This is also true for picking up low-frequency magnetic fields from power transformers and ac wiring, for example.) Zip-cord speaker cables and dc power cords are particularly prone to this problem. They look balanced, but there is usually a little bit of difference in the way the wires are exposed to the RF and the resulting RF current. That little bit of difference creates a differential-mode RF signal that can cause RFI.

To avoid converting common-mode signals to differential-mode, don't use unshielded cables for low-level RF and audio signals. Make sure the shields are connected properly. For unbalanced zip cord cables, replace them with *twisted-pair* cables. RF is still picked up by both conductors, but the twist ensures that both conductors pick up the *same* amount of RF.

Twisted-pair cables are easy to make: Clamp the wires in a variable-speed drill, holding the other end fixed with a vise or clamp. Slowly run the drill until the *pitch* of the twist (the number of twists per length) is one turn for every inch or two. Regular zip cord may not want to "hold the twist" so you can make your own cables using #14 or #16 AWG wire for speakers (handles most power levels, high power systems can use #12 AWG) and whatever gauge you need for a power cable. Use tape or heat-shrink tubing at the end to keep the wires together.

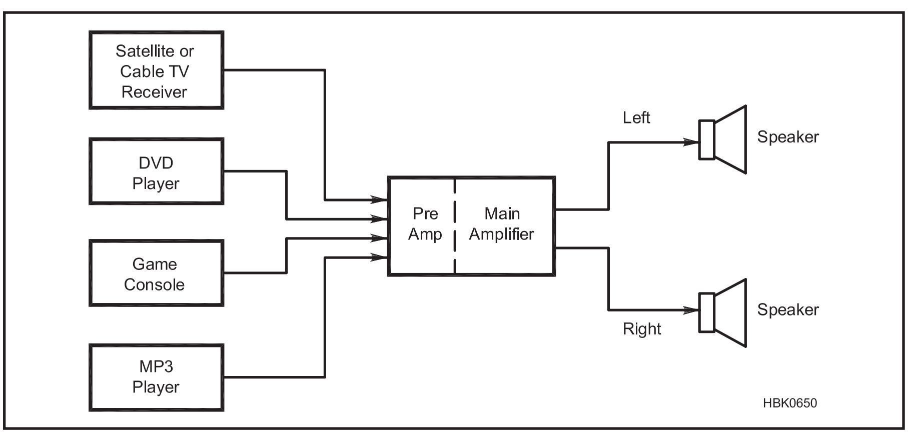


Figure 27.27 — A typical home-entertainment system.

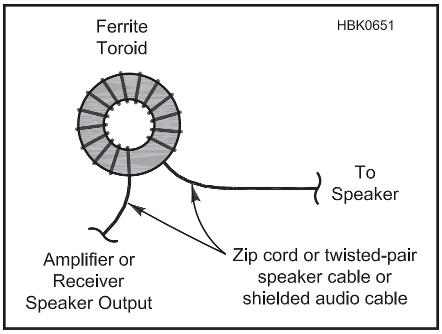


Figure 27.28 — Making a speaker-lead common-mode choke. Use ferrite material appropriate for the frequency of the RF interference.

Dummy Detectives

One particularly useful troubleshooting tool for determining where RFI is entering a victim device is called a "dummy" — a short test cable that can be inserted in a signal path. The dummy's cable shield is connected on each end of the cable but the center conductor is not connected. The dummy will allow common-mode current to flow on the shield, but will not pass a differential-mode signal. This technique was devised by Bill Whitlocak of Jensen Transformers.

Dummies are quite useful in identifying where RFI is being introduced in a signal path. If the interference goes away when the dummy is inserted, the RFI is being introduced upstream of the dummy. If the interference is common-mode, it will still be present when the dummy is inserted upstream of the victim equipment that is detecting it because the dummy's shield passes common-mode noise to the victim.

An F connector dummy is easily made with two F plugs installed on a short length of coax. A double-receptacle F "barrel" adaptor can be attached to one of the plugs to create an extension cable. At one or both of the plugs, the center conductor is snipped flush with the shield so that it does not make contact with the mating connector.

Dummies made with RCA and 1/8-in connectors (mono and stereo) are also useful for the same purpose in home entertainment systems and other consumer electronics. Use high-quality connectors, such as those made by Switchcraft and Neutrik, and use good shielded cable that fits the connector, such as RG-174 subminiature coax. Cut the center conductor of the coaxial cable so that it does not make contact with the connector pins.

filter on the power cord (which may be an ac cord set, a small transformer, or a power supply).

Cordless Telephones — A cordless telephone is an unlicensed *radio* device that is manufactured and used under Part 15 of the FCC regulations. The FCC does not intend Part 15 devices to be protected from interference. Older models that operate at 49 MHz usually have receivers with very wide front-end filters, which make them very susceptible to interference. These should be replaced with new models operating at 900 MHz and higher frequencies, which are much less susceptible to interference. A likely path for interference to cordless phones is as common-mode current on the base unit's connecting cables, which can be blocked by common-mode chokes. In addition, a telephone filter on the base unit and an ac line filter may help. The best source of help is the manufacturer, but they may point out that the Part 15 device is not protected from interference.

AUDIO EQUIPMENT

Consumer and commercial audio equipment such as stereos, home entertainment systems, intercoms, and public-address systems can also pick up and detect strong signals from nearby transmitters. The FCC considers these non-radio devices and does not protect them from licensed radio transmitters that may interfere with their operation. The RFI can be caused by one of several things: pickup on speaker leads or interconnecting cables, pickup by the ac mains wiring, or direct pickup. If the interference involves wiring connected to the affected device, common-mode chokes are the most likely solution.

Use the standard troubleshooting techniques discussed earlier in this chapter to isolate problems. In a multi-component home entertainment system (as in **Figure 27.27**), for example, you must determine what combination of components is involved with the problem. First, disconnect all auxiliary components to determine if there is a problem with the main receiver/amplifier. Long speaker or interconnect cables are prime suspects.

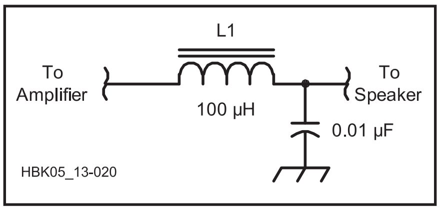


Figure 27.29 — A low-pass LC filter.

Stereos and Home Entertainment Systems — If the problem remains with the main amplifier isolated, determine if the interference level is affected by the volume control. If so, the interference is getting into the circuit *before* the volume control, usually through accessory wiring. If the volume control has no effect on the level of the interfering sound, the interference is getting in *after* the control, usually through speaker wires.

Speaker wires are often effective antennas on HF and sometimes into VHF and above. The speaker terminals are often connected directly to the output amplifier transistors. Modern amplifier designs use a negative feedback loop to improve fidelity. This loop can conduct the detected RF signal back to the high-gain stages of the amplifier. The combination of all of these factors often makes the speaker cables the dominant receiving antenna for RFI.

There is a simple test that will help determine if the interfering signal is being coupled into the amplifier by the speaker wires. Temporarily disconnect the speaker wires at the amplifier (not at the speakers) and plug in a test set of headphones with short leads. If there is no interference with the headphones, filtering the speaker wires will likely cure the problem.

Start by applying common-mode chokes. **Figure 27.28** shows how to wrap speaker wires around a large (1.4-inch O.D. or larger) ferrite core to cure speaker-wire RFI. Type #31 material is preferred at HF. (See the section on Common-Mode Chokes in this chapter.)

In some cases, the speaker wires may be picking up RF as a differential-mode signal. To reduce differential-mode pickup, replace the zip cord speaker wire with twisted-pair wire. (#14 or #16 AWG will work for most systems with higher-power systems requiring #12 AWG.) See the sidebar Maintaining Balance with Twisted-Pair to learn how to make twisted-pair cables.

Powered Speakers — A powered speaker is one that has its own built-in power amplifier. Powered subwoofers are common in home entertainment systems, and small powered speakers are often used with computer and gaming systems. If a speaker runs on batteries and/or an external power supply, or is plugged into main power, it is a powered loudspeaker. Powered loudspeakers are notoriously susceptible to common-mode interference from internally misconnected cable shields and poor shielding. Apply suitable common-mode chokes to all wiring, including power wiring. If the RFI persists, try an RF filter at the input to the speaker, such as the LC low-pass filter in **Figure 27.29**. Unshielded speakers may not be curable, however.

Intercoms and Security Systems — RFI to these systems is nearly always caused by common-mode current on interconnect wiring. Common-mode chokes are the most likely cure, but you may also need to contact the manufacturer to see if they have any additional, specific information. Twisted-pair wiring (CAT5 network cable contains four such pairs) should be used, including for audio output wiring. Wiring can often be complex, so any work on these systems should be done by a qualified sound contractor.

Public-Address Systems — Common-mode current is also the culprit here. Powered speakers are increasingly used and can be treated as described above. Work to remove interference should be done by the installing contractor and may require coordination between the amateur and contractor to characterize the interference and provide test assistance while the work is being done.

27.9.3 RFI From Computers and Other Unlicensed RF Sources

Computers and microprocessor-based devices such as video games or media players can be sources or victims of interference. These devices contain oscillators that can and do radiate RF energy. In addition, the internal functions of a computer generate different frequencies, based on the various data signals. All of these signals are digital — with fast rise and fall times that are rich in harmonics.

Computing devices are covered under Part 15 of the FCC regulations as unintentional emitters. As for any other unintentional emitter, the FCC has set absolute radiation limits for these devices. As previously discussed in this chapter, FCC regulations state that the operator or owner of Part 15 devices must take whatever steps are necessary to reduce or eliminate any interference they cause to a licensed radio service. This means that if your neighbor's video game interferes with your radio, the neighbor is responsible for correcting the problem. (Of course, your neighbor may appreciate your help in locating a solution!)

The FCC has set up two tiers of limits for computing devices. Class A is for computers used in a commercial environment. FCC Class B requirements are more stringent — for computers used in residential environments. If you buy a computer or peripheral, be sure that it is Class B certified or it will probably generate interference to your amateur station or home-electronics equipment.

If you find that a computer system is generating interfering signals, start by simplifying the problem. Temporarily remove power from as many peripheral devices as possible and disconnect their cables from the back of the computer. (It is necessary to physically remove the power cable from the device, since many devices remain in a low-power state when turned off from the front panel or by a software command.) If possible, use just the computer, keyboard, and monitor. This test may identify

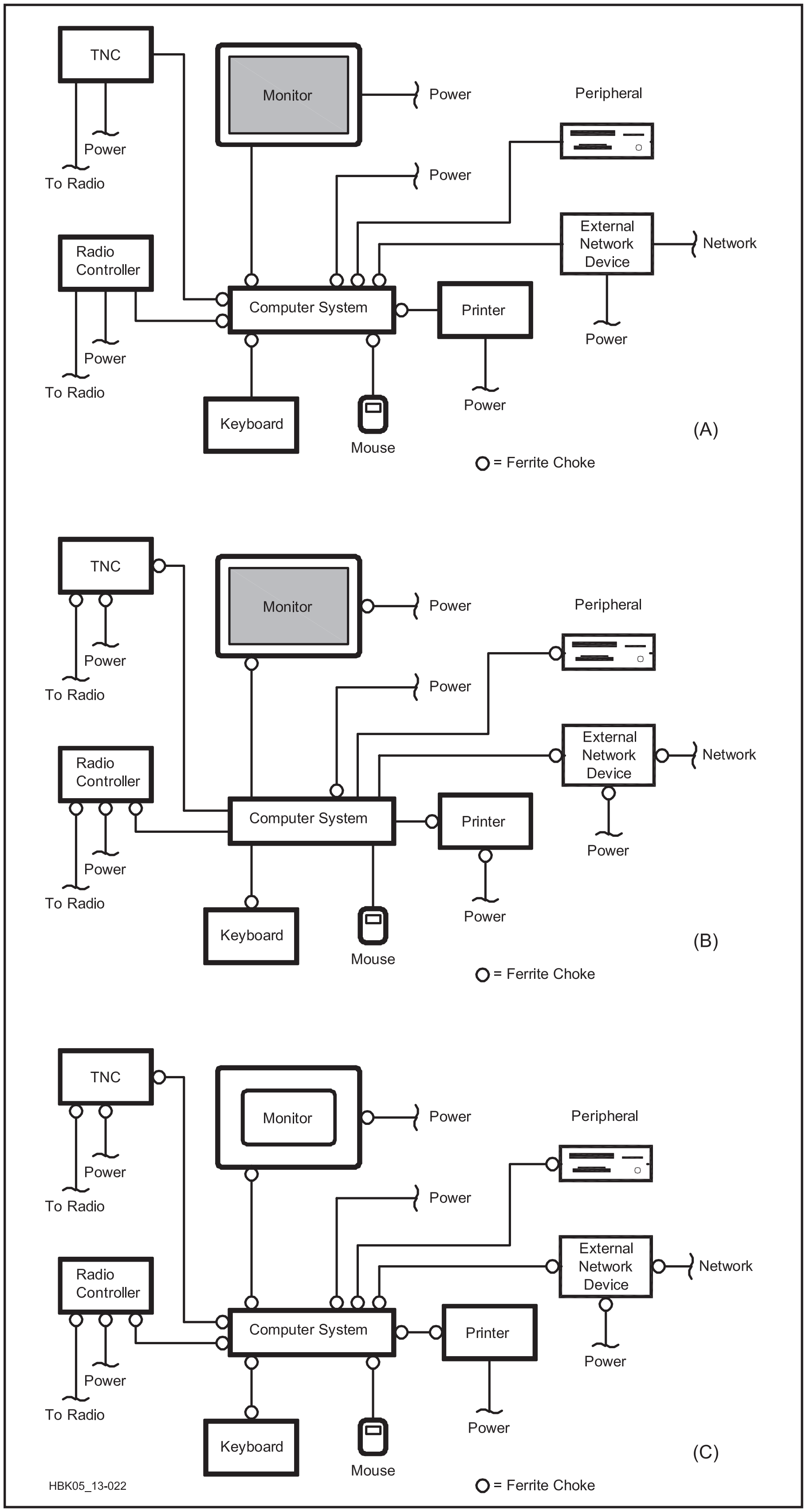


Figure 27.30 — Where to locate ferrite chokes in a computer system. At A, the computer is noisy, but the peripherals are quiet. At B, the computer is quiet, but external devices are noisy. At C, both the computer and externals are noisy.

specific peripherals as the source of the interference.

It can be difficult to determine whether peripheral connecting cables are shielded. If possible, use shielded cables for all peripherals. Replace any unshielded cables with shielded ones; this often significantly reduces RF noise from computer systems. The second line of defense is the common-mode choke. The choke should be installed as close to the computer and/or peripheral device as practical. **Figure 27.30** shows the location of common-mode chokes in a complete computer system where both the computer and peripherals are noisy. USB-power devices can also create noise from internal power supplies and are discussed in K9YC's *National Contest Journal* paper "Killing Receive Noise – Part 1 and 2," included in the online information for this chapter.

A multi-turn common-mode choke wound for the HF bands is often ineffective at VHF. When VHF antennas are located close to these devices (or if a more distant beam is pointed at them), it may also be necessary to add one or two 2-turn chokes to suppress noise on 6 meters and multiple, single-turn, clamp-on cores for 2-meter noise. The cores for the higher frequencies should always be placed closest to the noise source, and when two pieces of digital equipment are connected, each should be considered a potential source, so VHF cores may be needed on both ends.

Switchmode power supplies in computers are often sources of interference. A common-mode choke and/or ac-line filter may cure this problem. In extreme cases of computer RFI you may need to improve the shielding of the computer. (Refer to the *ARRL RFI Book* for more information about this.) Don't forget that some peripherals (such as DSL gateways) are connected to the phone line, so you may need to treat them like telephones.

WALL TRANSFORMER SWITCHING SUPPLIES

While small, low-current linear power supplies known as "wall warts" have been widely used for many years, it is now becoming common for these devices to contain switchmode or "switcher" supplies. Because they must be manufactured very inexpensively, these supplies often have little or no RF filtering at either the ac input or dc output, frequently creating significant RFI to nearby amateurs.

The least expensive course of action may be to simply replace the switchmode supply with a linear model. If the system in which the supply is used is still under warranty, the distributor or manufacturer may be able to replace it. Otherwise, a third-party linear replacement may be available with the same voltage rating and current output equal to or higher than the original supply. Adapters may be available to convert output connector styles where necessary or new connectors may be installed. Older linear-style supplies can be re-used if you are willing to splice them in to replace the switchmode model.

If replacing the supply with a linear model is not an option, you will have to apply RF filters to the supply. These supplies are rarely serviceable, so filters much be installed externally. Noise is usually radiated from the output cable, so winding the cable onto a ferrite core creates a common-mode RF choke as described in this chapter's Elements of RFI Control section. Since the wall-wart style supply plugs directly into a wall-mounted receptacle, a short ac extension cord or power strip cord can be made into a common-mode choke as well.

27.9.4 RFI to Ground-Fault (GFCI) and Arc-Fault (AFCI) Circuit Interrupters

GFCIs are occasionally reported to "trip" (open the circuit) when a strong RF signal, such as an amateur's HF transmission, is present. GFCI circuit breakers operate by sensing unbalanced currents in the hot and neutral conductors of an ac circuit. In the absence of RF interference, such an imbalance indicates the presence of a fault somewhere in the circuit, creating a shock hazard. The breaker then trips (opens) to remove the shock hazard.

An Arc Fault Circuit Interrupter (AFCI) circuit breaker is similar in that it monitors current to watch for a fault condition. Instead of current imbalances, the AFCI detects patterns of current that indicate an arc — one of the leading causes of home fires. The AFCI is not supposed to trip because of "normal" arcs that occur when a switch is opened or a plug is removed.

Under current codes, GFCI protection is required for all basement outlets, outdoor outlets, and for outlets in kitchens and bathrooms. AFCI protection is now required for all circuits that supply bedrooms and other areas of a home as well. Code requirements can vary, so be sure to check with your local building inspector for those that apply in a specific case.

RF interference to GFCI breakers is caused by RF current or voltage upsetting normal operation of the imbalance detection circuit, resulting in the false detection of a fault. Similarly, RF current or voltage could upset the arc detection circuitry of an AFCI breaker. Some early GFCI breakers were susceptible to RFI, but as the technology has improved, fewer and fewer such reports have been received. While it is possible to add filtering or RF suppression to the breaker wiring, a simpler and less expensive solution is to replace the GFCI breaker with a new unit less susceptible to RF.

The ARRL Lab has received favorable reports on the following GFCI products:

- Leviton (**www.leviton.com**) GFCI outlets which are available in both 15 and 20 A versions for 120 V ac circuits as well as cord sets and user-attachable plugs and receptacles.
- Bryant (**www.bryant-electric.com**) ground fault receptacles, which feature published 0.5 V immunity from 150 kHz to 230 MHz.
- Cooper (**www.cooperindustries.com**) GFCI products that are labeled "UL 943 compliant" on the package.

A web page on the ARRL website is maintained on GFCI/AFCI technology (**www.arrl.org/gfci-and-afci-devices**). Manufacturers seem to have largely fixed RFI issues with these devices.

27.9.5 RFI from Solar Power Installations

Solar energy is becoming increasingly popular as we transition from our dependence on fossil fuels to renewable energy sources. Residential solar installations are on the rise, especially in regions most affected by climate change. To understand how solar technology can impact an amateur radio station, it's important to first understand how energy is created from photovoltaic (PV) modules.

PV materials and devices convert sunlight into electrical energy. A single PV device is known as a *cell* or *solar cell*. (See the **Circuits and Components** chapter for more detailed information.) An individual PV cell is usually small, typically producing about 1 or 2 W of power. These cells are made of different semiconductor materials and are often less than the thickness of four human hairs. In order to withstand the outdoors for many years, cells are sandwiched between protective materials in a combination of glass and/or plastics.

To create useful amounts of power from PV cells, they are connected together to form larger units known as *modules* or *panels*. Modules can be used individually, or several can be connected to form arrays. One or more arrays is then connected to the electrical grid as part of a complete PV system. Because of this modular structure, PV systems can be built to meet almost any electric power need, small or large.

PV modules and arrays are just one part of a PV system. Systems also include mounting structures that point panels toward the Sun, along with the components that take the dc produced by modules and convert it to the ac electricity used to power all of the appliances in a home (the above excerpted from **www.energy.gov** — more on this technology can be found on the United States Department of Energy website at **www.energy.gov/eere/solar/solar-energy-technologies-office**).

Of relevance to amateur radio operators is the fact that residential solar is on the rise. According to the Solar Energy Industries Association (SEIA), in 2021 residential solar installations exceeded 1 GWdc and more than 130,000 systems in a single quarter for the first time. One out of every 600 US homeowners is now installing solar each quarter (see the SEIA Solar Market Insight Report at **www.seia.org/research-resources/solar-market-insight-report-2021-q4**).

This rise in residential solar has also brought to light an increase in RFI cases reported to the ARRL due to the various design technologies used to convert and condition the electricity produced by the panels. It should be noted that the PV cells themselves do not create RFI — they are basically large diodes — it is the power conversion process which changes the solar energy from dc to ac that creates RFI. **Figure 27.31** summarizes the different types of solar energy systems. More detail can be found at **news.energysage.com/string-inverters-power-optimizers-microinverters-compared**.

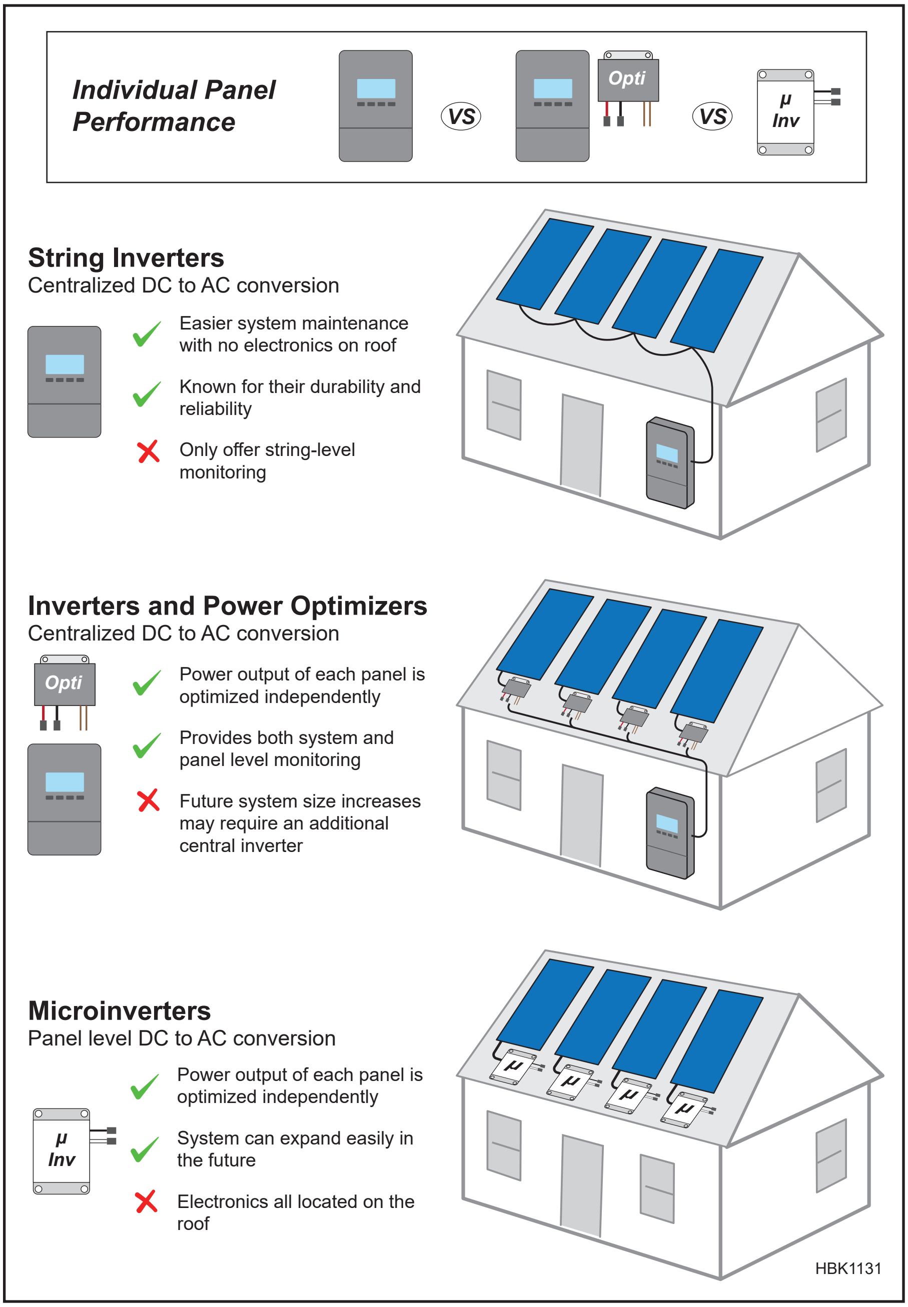


Figure 27.31 — Three common types of solar energy systems in common use today. Each type is discussed in the text.

CAUSES OF SOLAR SYSTEM RFI

RFI has been experienced by hams who have installed systems on their own homes, and by hams whose neighbors have installed systems in their homes. ARRL Lab staff have noted there are at least three basic mechanisms by which residential PV arrays can generate RFI. Some or all may be present in a given array, depending on the manufacturer's system architecture. Figure 27.31 illustrates the three basic types of arrays and power conversion that are in common use today — *string inverters*, *power optimizers*, and *microinverters*.

1. RFI from inverters. These devices are responsible for switching the high voltage dc from the array to 60 Hz phase-synchronous ac, meaning ac power in-phase with the utility ac waveform. One or more inverters may be incorporated in a given array, depending on its size. Typically, RFI from these devices is radiated by the dc wiring to the PV panels with an 18 kHz to 60 kHz fundamental switching frequency. Harmonics can extend well into the HF bands and lower VHF bands.

2. RFI from power optimizers. Power optimizers might be installed at every PV panel, or there may be a single power optimizer for several PV panels, depending on the component manufacturer and system size. Under full sunlight, power optimizers can have fundamental operating frequencies ranging from 39 kHz to 200 kHz. As with inverters, there may be harmonics extending through HF and into the lower VHF bands.

It should also be noted that when power optimizers are in the "off" or non-power generating mode, the PV array is disconnected from the ac wiring but may still generate RFI, as there is still some part of the device powered by the sunlight. RFI may be reduced significantly but it can still be noticeable.

3. Data collection and system control devices. These devices may be stand-alone or integral to other components in the PV system. They also have the least potential to cause widespread RFI, and typically only the operator of the PV array might be subjected to RFI from these components. Typical communications channels observed thus far include 60 kHz to 74 kHz and 1.8 MHz.

Vendors generally start by isolating and testing to ensure the RFI issue an amateur might be experiencing is actually being caused by the vendor's system. This can be as simple as shutting down the solar installation briefly to ensure the RFI goes away at the amateur's station. Once the vendor performs the diagnostic tests and identifies the RFI as coming from their system, solutions employed by vendors might include component changes or enhancements, addition of ferrite chokes, or modifying wiring to include twisted-pair wiring harnesses. Vendors of these systems, from local installers to component manufacturers such as SolarEdge, Enphase, and Generac, have all been cooperative in working with hams and the ARRL to work through RFI issues related to solar installations. For an example, see the PDF on a SolarEdge retrofit at the home of Paul Cianciolo, former ARRL RFI Engineer, included in online materials.

27.9.6 RFI From Grow Lights and Other Low-Voltage Lighting

There are myriad lighting types that may be in operation near amateur radio stations. While incandescent bulbs have a long history of not causing interference to amateurs, global concerns about climate change have led to a move towards renewable energy and energy efficiency, along with the need for more efficient lighting devices. Of particular relevance today are LED lighting and grow lights.

Two sets of rules apply for LED bulbs in residential environment. LED bulbs involving electronics are typically subject to Part 15 rules (described at the beginning of this chapter). If the lighting device is operated at greater than 9 kHz, it is classified as an "unintentional radiator," with limits specified in **Table 27.4**. If the device operates at less than 9 kHz, it is classified as an "incidental radiator" and has no specified emissions limits, but still has a requirement that it not cause "harmful interference," as defined by Part 15. Incandescent bulbs are an example of incidental radiators.

For the lighting equipment, when designed to be connected to the public utility ac power line, the radio frequency voltage that is conducted back onto the ac power line on any frequency or frequencies shall not exceed the limits in Table 27.4. These limits are based on the measurement of the radio frequency voltage between each power line and ground at the power terminal using a 50 μH/50 Ω line impedance stabilization network (LISN).

Table 27.4
Part 15B Conducted Emissions Limits for Unintentional Radiators

Frequency of emission (MHz)	*Conducted limit (dBμV)*	
	Quasi-peak	*Average*
0.15 – 0.5	66 to 56*	56 to 46*
0.5 – 5	56	46
5 – 30	60	50

* Decreases with the logarithm of the frequency

The ARRL Laboratory has conducted testing on numerous lighting devices in recent years, and has concluded that at least some of these devices fail to comply with FCC standards (see **www.arrl.org/lighting-devices**). A discussion of these tests, and a broader discussion about lighting devices and RFI can be found in an article on the ARRL website at **www.arrl.org/files/file/RFI/Light_Bulbs.pdf**.

GROW LIGHTS

Large high-power grow lights in residential areas are also on the rise. These lights are typically rated at over 1,000 W (commercial lighting devices can be 5,000 W or more) and employ electronics that can act as ballasts or perform some other vital function. Grow lights (as with other lighting devices) can also incorporate switching power supplies, another potential source of RFI to amateur stations. (See **Figure 27.32A** for an example of a grow light and a pair of electronic ballasts.)

Unfortunately, these lights have proven to be a notorious source of RFI to amateur stations. Based on the distances over which the noise can propagate and tests conducted in the ARRL Lab, these devices can exceed the FCC limits by a considerable margin. Although these tests were limited to just a few samples, one light was measured to be more than 30 dB over the FCC limits.

Interference from grow lights has been shown to be problematic at distances of well over 1,000 feet from the offending device. To put this into perspective, this is over three times the distance one might expect from a compliant Part 15 or 18 device.

While grow lights may be used in other growing operations, the most recent increases in reports of RFI from grow lights can be attributed to states that have legalized or decriminalized marijuana. California and Colorado are two such states. Other uses of these lights can include growing indoor vegetables and household, ornamental, and exotic plants. It should be stressed that the mere presence of a grow light is not proof that illegal activity may be taking place in someone's home.

(A)

Figure 27.32 — A typical single LED grow light (A) and two types of electronic ballasts (B and C) that connect the lights to ac power. (Photos are courtesy Tom Thompson, WØIVJ)

(B)

(C)

IS IT RFI FROM A GROW LIGHT?

Grow light RFI tends to exhibit several unique and identifiable characteristics. Some clues as to whether or not RFI may be coming from grow lights include the following:

• Grow lights are typically controlled by a timer, cycling on and off at precise times every 12 hours or so. While this time can vary depending upon where plants are located in relation to a particular growing cycle, there should be at least a short-term, distinct pattern to the noise being generated from grow lights.

• Grow lights typically produce a broadband noise, particularly across the 40-meter band. The noise propagates over much greater distances than one might expect from devices that meet the applicable FCC limits. Once you have established a turn-on time, listen to the noise as the lamp turns on. It will generally be noisier when cold, with the RFI more focused on part of the band. This generally lasts about 5 minutes until the lamp is warm.

• The polarization is predominately vertical even though the lamp line may be horizontal.

• In the case of marijuana, the grow time is typically 6 to 8 weeks. The lights may be shut off for a few days while the plants are harvested and new ones made ready.

JURISDICTIONAL CONSIDERATIONS

Under federal law, only the FCC can create and enforce rules regarding harmful radio interference. Furthermore, as described previously in this section, both Part 15 and Part 18 of the FCC's rules unconditionally prohibit interference to a licensed radio service caused by lighting devices. This includes interference to an amateur caused by grow lights.

While the FCC may not have jurisdiction in the enforcement of drug laws, an interference complaint to the FCC may result in an investigation. Grow lights can also produce a distinctive noise signature that may result in an unwelcome calling card, depending on the type of plants involved. Although marijuana may not be illegal under some state laws, it is still illegal under federal law. Should a field investigation uncover a grow light operation involving marijuana, we simply don't know what inter-agency agreements may exist between the FCC and other law enforcement bodies. Many such growers might wish to cease operation of the offending device rather than risk a federal investigation of any kind.

APPROACHING A NEIGHBOR

As discussed elsewhere in this chapter, we typically recommend that hams discuss any RFI problems with their neighbor as a good first step. Obviously, even under the best of circumstances, the importance of diplomacy cannot be overemphasized during these discussions. It's also important never to suggest what you think the cause might be. If you're wrong, it often makes matters worse, regardless of what you suspect the source might be. Simply let the neighbor know that a source of radio frequency interference appears to be coming from their home. It can also be helpful to demonstrate the problem with a portable radio, especially one that is or looks like an AM broadcast receiver. Be sure not to turn up the radio so loud that it becomes offensive.

Obviously, depending on circumstances, approaching your neighbor in a case involving a grow light can be a potentially dangerous situation. Exercise extreme caution and good judgment in this case. For example, you may not want to directly approach a neighbor if you suspect a grow light is the source of your RFI problem. Remember that the presence of a grow light does not guarantee that marijuana is being grown. Every case is obviously different, and no two neighbors are exactly alike, but there is simply no substitute for good judgment in any situation like this.

TECHNICAL SOLUTIONS TO GROW LIGHT RFI

Technical solutions typically involve the addition of filters and chokes to the cables connected to the ballast. In the case of a grow light, this typically requires that filters be added to both the ac and the lamp side of the ballast.

See the *Grow Light Electronic Ballasts Page* by Larry Benko, WØQE (**www.w0qe.com/RF_Interference/grow_light_electronic_ballasts.html**) for details on filters being used by Larry and Tom Thompson, WØIVJ, to help in these cases. **Figure 27.33A** shows a homemade conducted RFI filter constructed by WØIVJ. The *Grow Light Ballast RFI Filter* web page, also by Tom Thompson, includes some additional filter info (**tomthompson.com/radio/GrowLight/GrowLightBallastFilter.html**).

Nanolux also sells an RF Filter Set (see Figure 27.33B, **nanoluxtech.com/rf-filter-set**) designed for single-ended lamp ballasts. Note the Nanolux web site states the following with regard to RFI from electronic ballasts:

There are two types of RFI created by electronic ballasts. Both are regulated by the FCC, but each has its own distinctive characteristics. First, there's emitted RFI, which can disrupt electronic devices within your home that run on an RF signal. Such devices include some cable boxes, internet, Bluetooth devices, and even some hydroponic controller units currently on the market.

The emitted RF filter attaches to the lamp cord, while the second type of RFI, conducted RFI, can be controlled by the conducted RF filter that connects to the power cord. The conducted RF filter protects your neighbors' and public safety communications. If conducted RFI reaches the copper wiring of your home, it will turn the house into one giant antenna. This antenna of RFI can extend for miles. It will disrupt all things operating on a radio frequency around 30 kHz. This includes your neighbor's cable, internet, and other RF devices, plus many emergency communications that run on this frequency.

Regardless of which cure you attempt, be sure to choose a filter or other components that are properly rated for the current and voltages involved.

Although common-mode chokes are another popular and effective solution in cases involving conducted emissions, the size of grow light cables and associated connectors may make them impractical without additional

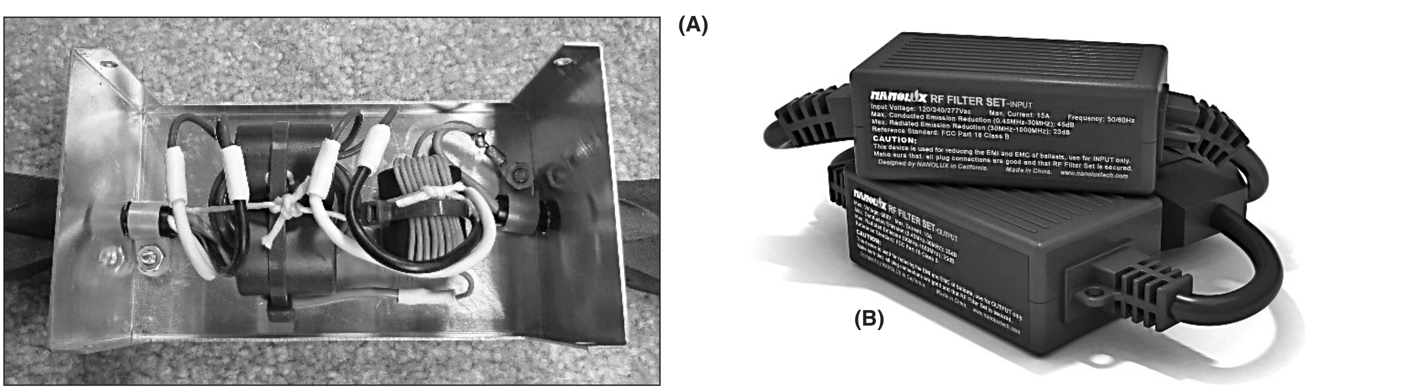


Figure 27.33 — Common-mode filter for electronic lighting ballast, designed and built by Tom Thompson, WØIVJ.

consideration. For example, you may need to temporally remove a connector or add an extension to the cable for the choke.

Keep in mind that split ferrite beads and clamp-on cores are not as effective as multi-turn toroids made of Type #31 ferrite at HF. You'll need to pass the cable end through the center hole multiple times. The most widely available and largest such toroid is 2.4 in diameter, supporting approximately eight turns of cable. The size of the cable (and connector), therefore, may prohibit or limit the number of turns that are possible with grow lights. A 4-inch diameter toroid is also available. (See the section on Common-Mode Chokes earlier in this chapter for information on ferrite materials and how to make them.) Be sure to keep the toroid as close to the RFI source as practical. Additional chokes can be placed on the cable in series.

RF Interference and the FCC

by Riley Hollingsworth, K4ZDH
(retired Special Counsel to the FCC Enforcement Bureau)

Since 1999, the FCC has worked with the ARRL in a cooperative agreement whereby the staff at the ARRL Lab takes the first cut at resolving RFI. The lab works with the complainant to make sure that the noise is narrowed down to the most probable source. The success rate with this program has been very high, and in many cases — perhaps most — the ARRL and the complainant solve the problem without any FCC involvement.

The lab can help you with the proper testing you need to do in your shack and with the documentation you need in the event the matter is referred to the FCC. I was always amazed at the number of situations in which noise that at first seemed to be power line related, was in fact (these are real examples) a nearby electric fence, a battery charger for a golf cart, an Ethernet adapter, a paper shredder, or a circuit board in a brand-new clothes washer in a room adjacent to the radio shack.

Don't assume anything. Test every possibility and document your testing. Not only will you learn a lot about the devices in your house and what causes noise and what doesn't, but good documentation will make your case stronger and easier to work. Follow to the letter the ARRL articles and website tutorials on tracking down noise in and around your shack. You can even hear noise samples on the website.

The documentation requirement is especially important if it is power line related and you have to start dealing with the power company. Take notes of every call you make, who you talked to, and when. This helps not only the power company but also the FCC in the unfortunate event that FCC action is required. In many cases, power company staff has a lot of experience running down such noise, and they take pride in locating it. In other cases, the power company has been bought, sold, or merged and does not have staff with a lot of experience in these matters. Sometimes its staff has no experience.

The cost of the equipment required to track down power line noise is less than that of two employees and a bucket truck for a day. Often the source of power line noise is a simple piece of equipment that is loose or about to fail, so finding the source helps the power company maintain its system. Keep in mind, though, that some areas are just not suitable for amateur radio. If you live next to an old substation, or a conglomeration of old poles and transformers, or an industrial area, your situation is tenuous. Whether it's our roads or power grids, lots of the infrastructure in this country is just plain old and out-of-date.

You must test diligently and document thoroughly. Never go to the FCC with a situation when you have not already worked with the ARRL and the power company.

27.9.7 RFI From Wireless Power Transfer

Wireless Power Transfer (WPT) is already widely deployed in low-power wireless chargers used to charge cell phones and similar devices. These devices use either capacitive coupling (metal plates or sleeves) or inductive coupling (coils) as the path to transfer power. There haven't been any reported cases of interference from low-power WPT chargers so far.

However, the emerging technology of WPT for much higher-powered charging of electric vehicles (WPT-EV) has the potential to cause significant interference problems. These systems are based on inductive power transfer (IPT), which uses a pair of coils close together to transfer power. The systems are controlled so that the power frequency is at or near the resonant frequency of the coupled coils, increasing efficiency. Typical resonant frequencies are from 20-100 kHz today. More about WPT-EV technologies is available at **www.intechopen.com/chapters/75267**. The current SAE standard for WPT is SAE J2954: Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology.

The largest concern for amateurs is that harmonics and noise present in a high-power system could fall into the amateur spectrum. One potential mechanism for this to happen is in the coupling between the charging power source primary coil and the vehicle's receiving secondary coil, which can form an imperfect coupling system. For example, the coils could be too far apart or misaligned, allowing energy to leak from the charging system. The vehicle may be in motion (charging coils embedded in roadways), and the charging system will have to be controlled so that power is only transferred when alignment is optimized.

The amount of stray energy is particularly important, since the estimated power transfer for a typical residential WPT-EV charger system is expected to be in range of 10-15 kW. It would not take a lot of leakage at those power levels for the spurious emissions from such a system to create interference. It should be stressed that WPT-EV is still in the experimental and prototype stages. No RFI from these systems has yet been reported. The ARRL continues to monitor WPT development through industry organizations and committees. As more information becomes available, it will be published on the ARRL's website and in publications such as this one.

27.10 Power-Line Noise

This chapter's section "Identifying the Type of RFI Source" describes power-line noise, its causes, and methods to identify it. (For more information about power-line interference, see the Reference entry for Loftness.) Many more details, including how to file a complaint, are available on the ARRL's Power-line Noise FAQ web page at **www.arrl.org/power-line-noise-faq**.

Power-line noise is a unique problem in several respects. First and foremost, the offending source is never under your direct control. You can't just simply "turn it off" or unplug the offending device. Nor will the source be under the direct control of a neighbor or someone you are likely to know. In the case of power-line noise, the source is usually operated by a company, municipality, or in some cases a cooperative. Furthermore, shutting down a power line is obviously not a practical option.

Another unique aspect of power-line noise is that it almost always involves a defect of some sort. The cure for power-line noise is to fix the defect. This is almost always a utility implemented repair, and one over which you do not have any direct control.

FCC rules specify that the operator of a device causing interference is responsible for fixing it. Whenever encountering a power-line noise problem, you will be dealing with a utility and won't have the option of applying a relatively simple technical solution to facilitate a cure, as you would if the device were located in your home. Utilities have a mixed record when it comes to dealing with power-line noise complaints. In some cases, a utility will have a budget, well-trained personnel, and equipment to quickly locate and address the problem. In other cases, however, the utility is simply unable to effectively deal with power-line noise complaints or even denies their equipment can cause RFI.

What does this mean for an amateur with a power-line noise complaint? Utilities can be of any size from large corporations to local cooperatives or city-owned systems. Regardless of the category in which your utility may fall, it must follow Part 15 of the FCC rules. Dealing with a company, co-op or municipality, however, as opposed to a device in your home or a nearby neighbor that you know personally, can present its own set of unique challenges. Multiple parties and individuals are often involved, including an RFI investigator, a line crew, and associated management. In some cases, the utility may never have received an RFI complaint before yours.

27.10.1 Before Filing a Complaint

Obviously, before filing a complaint with your local utility, it is important to verify that the problem is power-line noise and is not caused by a problem with electrical equipment in your home. Other sources, such as lighting devices and motors, can mimic power-line noise, especially to an untrained ear. Don't overlook these important steps. Attempting to engage your utility in the resolution of an RFI problem can not only waste time but can be embarrassing if the source is right in your own home!

Utilities are not responsible for noise generated by customer-operated devices — *even if the noise is being radiated by the power lines.* They are responsible for fixing only that noise which is being generated by their equipment.

27.10.2 Filing a Complaint

Once you have verified that the problem is power-line noise (see this chapter's section on Identifying Power-line and Electrical Noise) and is not coming from a source in your home or a nearby residence, contact your utility's customer service department. In addition to your local phone book, customer service phone numbers are included on most power company websites.

It is important to maintain a log during this part of the process. Be sure to record any "help ticket" numbers that may be assigned to your complaint as well as names, dates, and a brief description of each conversation you have with electric company personnel. If you identify specific equipment or power poles as a possible noise source, record the address and any identifying numbers on it.

Hopefully, your complaint will be addressed in a timely and professional manner. Once a noise source has been identified, it is up to the utility to repair it within a reasonable period. You and the utility may not agree on what constitutes a reasonable period, but attempt to be patient. If no action is taken after repeated requests, reporting the complaint to the ARRL and requesting assistance may be in order. (Before contacting the ARRL review The Cooperative Agreement, a section of this chapter.)

It is also important to cooperate with utility personnel and treat them with respect. Hostile and inappropriate behavior is almost always counter-productive in these situations. Remember, you want utility and other related personnel to help you — not avoid you. Even if the utility personnel working on your case seem unqualified, hostile behavior has historically never been a particularly good motivator in these situations. In fact, most protracted power-line noise cases reported to the ARRL began with an altercation in the early stages of the resolution process. In no case did it help or expedite correction of the problem.

27.10.3 Techniques for Locating Power-Line Noise Sources

Radio direction finding (RDF) techniques typically offer the best and most efficient approach to locating most power-line noise sources. It is the primary method of choice used by professionals. While RDF is usually the most effective method, it also requires some specialized equipment, such as a hand-held beam antenna. Although specialized professional equipment is available for RDF, hams can also use readily available amateur and homebrew equipment successfully. The online information for this *Handbook* includes some power-line noise locating equipment projects you can build. This includes a simple and easy to build RDFing antenna, an ultrasonic dish, and attenuators.

Although it is the utility's responsibility to

Common Mistake — It's Coming from That Pole!

RFI problems from consumer devices, especially below 30 MHz, frequently involve conducted emissions. The RF in this case is generated by a consumer device in a home. It is then conducted by the house wiring, where it is radiated. In some cases, the RF can also be conducted to the service entrance of the home and out to a utility pole. In this case, the noise will peak at the pole and appear to be the source of the interference. It is not. The real source of the problem is in a residence connected to the pole.

Always verify that the actual source is not in a home connected to that pole. Frequently, the source residence will be connected to the power transformer secondary system on that pole. Also keep in mind that the hardware on a pole can make for a better "antenna." This means that noise tends to peak at poles in general. Noise also tends to peak at about every half wavelength as you traverse a power line. Be sure to use higher frequencies (i.e., shorter wavelengths) whenever possible.

Conclusion: Don't automatically assume that the source of an RFI problem is on a pole where the noise peaks. This is a common mistake made by many beginners!

locate a source of noise emanating from its equipment, many companies simply do not possess the necessary expertise or equipment to do so. As a practical matter, many hams have assisted their utility in locating noise sources. In some cases, this can help expedite a speedy resolution.

There is a significant caveat to this approach, however. Should you mislead the power company into making unnecessary repairs, they will become frustrated. This expense and time will be added to their repair list. Do not make a guess or suggestions if you don't know what is causing the noise. While some power companies might know less about the locating process than the affected ham, indiscriminate replacement of hardware almost always makes the problem worse. Nonetheless, depending on your level of expertise and the specifics of your situation, you may be able to facilitate a speedy resolution by locating the RFI source for the utility.

27.10.4 Amateur Power-Line Noise Locating Equipment

Additional information on the equipment, antennas, and techniques used to locate power line noise is also discussed in the earlier section Radio Direction Finding. Before discussing how to locate power-line noise sources, here are a few additional equipment guidelines.

Receiver — You'll need a battery-operated portable radio capable of receiving VHF or UHF in the AM mode. Ideally, it should also be capable of receiving HF frequencies, especially if the interference is a problem at HF and not VHF. Some amateurs also use the aircraft band from 108 to 137 MHz. The lower frequencies of this band can sometimes enable an RFI investigator to hear the noise at greater distances than on 2 meters or 70 cm. An RF gain control is essential, but an outboard step attenuator can be used as a substitute. A good S-meter is also required.

Attenuator — Even if your receiver has an RF gain control, an additional outboard step attenuator can often be helpful. It can not only minimize the area of a noise search but also provide added range for the RF gain control. As with other RFI sources, you'll need to add more and more attenuation as you approach the source.

VHF/UHF Antennas — You'll need a hand-held directional beam antenna. A popular professional noise-locating antenna is an eight-element Yagi tuned for 400 MHz. Since power-line noise is a broadband phenomenon, the exact frequency is not important. Either a 2 meter or 70 cm Yagi is capable of locating a power-line noise source on a specific power pole.

Although professional grade antennas can cost several hundred dollars, some hams can build their own for a lot less. See this book's online information for the article "Adapting a Three-Element Tape Measure Beam for Power-line Noise Hunting," by Jim Hanson, W1TRC. This low cost and easy to build antenna for locating power-line noise can be adapted for a variety of frequencies and receivers. Commercial 2 meter and 70 cm antennas for portable use are also suitable if a handle is added, such as a short length of PVC pipe.

Before using an antenna for power-line noise locating, determine its peak response frequency. Start by aiming the antenna at a known power-line noise source. Tune across its range and just beyond. Using minimum RF gain control, find its peak response. Label the antenna with this frequency using a piece of tape or marking pen. When using this antenna for noise locating, tune the receiver to this peak response frequency.

If you don't have a VHF or UHF receiver that can receive AM signals, see the online content for the article "A Simple TRF Receiver for Tracking RFI," by Rick Littlefield, K1BQT. It describes the combination of a simple 136 MHz beam and receiver for portable RFI tracking.

HF Antennas — Depending on the circumstances of a particular case, a mobile HF whip such as a 7 or 14 MHz model can be helpful. Magnet-mount models are acceptable for temporary use. An RFI investigator can typically get within VHF range by observing the relative strength of the noise from different locations. Driving in a circle centered on the affected station will typically indicate the general direction in which the noise is strongest. As with beam antennas, determine the peak response frequency for best results.

Ultrasonic Pinpointer — Although an ultrasonic pinpointer is not necessary to locate the pole or structure containing the source, some hams prefer to go one more step by finding the offending noise source on that structure. Guidelines for the use of an ultrasonic device are described later in this section.

Professional-grade ultrasonic locators are often beyond the budget of the average ham. Home brewing options, however, can make a practical ultrasonic locator affordable in most situations — and make a great weekend project too. See the online information accompanying this book for "A Home-made Ultrasonic Power Line Arc Detector" by Jim Hanson, W1TRC.

Oscilloscope — A battery-powered portable oscilloscope is only required for signature analysis. See the next section, Signature or Fingerprint Method, for details.

Thermal/Infrared Detectors and Corona Cameras — This equipment is not recommended for the sole purpose of locating power-line noise sources. It is rare that an RFI source is even detectable using infrared techniques. Although these are not useful tools for locating noise sources, many utilities still use them for such purposes with minimal or no results. Not surprisingly, ARRL experience has shown that these utilities are typically unable to resolve interference complaints in a timely fashion.

27.10.5 Signature or Fingerprint Method

Each sparking interference source exhibits a unique pattern. By comparing the characteristics between the patterns taken at the affected station with those observed in the field, it becomes possible to conclusively identify the offending source or sources from the many that one might encounter. It therefore isn't surprising that a pattern's unique characteristic is often called its "fingerprint" or "signature." See **Figure 27.34** for an example.

This is a very powerful technique and a real money saver for the utility. Even though there may be several different noise sources in the field, this method helps identify only those sources that are actually causing the interference problem. The utility need only correct the problem(s) matching the pattern of noise affecting your equipment.

You as a ham can use the signature method by observing the noise from your radio's audio output with an oscilloscope. Record the pattern by drawing it on a notepad or taking a photograph of the screen. Take the sketch or photograph with you as you hunt for the source and compare it to signatures you might observe in the field.

Professional interference-locating receivers, such as the Radar Engineers Model 243 shown in Figure 27.34, have a built-in time-domain display and waveform memory similar to a digital oscilloscope. This is the preferred method used by professional interference investigators. These receivers provide the ability to switch between the patterns saved at the affected station and those from sources located in the field.

Once armed with the noise fingerprint taken at the affected station, you are ready to begin the hunt. If you have a directional beam, use it to obtain a bearing to the noise. If multiple sources are involved, you'll need to record the bearings to each one. Knowing how high in frequency a particular noise can be heard also provides a clue to its proximity. If the noise can be heard at 440 MHz, for example, the source will typically be within walking distance. If it diminishes beginning 75 or 40 meters, it can be up to several miles away.

Since each noise source will exhibit unique characteristics, you can now match this noise "signature" with one from the many sources you may encounter in the investigation. Compare such characteristics as the duration of each noise burst, pulse shape, and number of pulses.

(A) (B)

Figure 27.34 — The spectrum of an unknown noise source is shown on the display of a Model 243 RFI locating receiver (A) along with a typical noise receiving antenna (B). During the RFI investigation, noise signatures not matching this pattern can be ignored. Once the matching signature originally shown in A is found, the offending noise source has been located.

Be wary of assuming that all devices have similar signatures when arcing. The fingerprint of a particular piece of hardware arcing may be quite different even for the same device on another pole.

If you have a non-portable oscilloscope, you may still be able to perform signature matching by using an audio recorder. Make a high-quality recording of the noise source at your station and at each suspected noise source in the field, using the same receiver if possible. Replay the sounds for signature analysis.

27.10.6 Locating the Source's Power Pole or Structure

Start your search in front of the affected station. If you can hear the noise at VHF or UHF, begin with a handheld beam suitable for these frequencies. As discussed previously, the longer wavelengths associated with the AM broadcast band and even HF can create misleading "hotspots" along a line when searching for a noise source, as shown in **Figure 27.35**.

As a general rule, only use lower frequencies when you are too far away from the source to hear it at VHF or UHF. Generally, work with the highest frequency at which the noise can be heard. As you approach the source, keep increasing the frequency to VHF or UHF, depending on your available antennas. Typically, 2 meters and 70 cm are both suitable for isolating a source down to the pole level.

If you do not have an initial bearing to the noise and are unable to hear it with your portable or mobile equipment, start traveling in a circular pattern around the affected station, block-by-block, street-by-street, until you find the noise pattern matching the one recorded at the affected station.

Once in range of the noise at VHF or UHF, start using a handheld beam. You're well on your way to locating the structure containing the source. In many cases, you can now continue your search on foot. *Again, maintain minimum RF gain to just barely hear the noise over a minimum area.* This is important step is crucial for success. If the RF gain is too high, it will be difficult to obtain accurate bearings with the beam.

Power-line noise will often be neither vertically nor horizontally polarized but somewhere in between. Be sure to rotate the beam's polarization for maximum noise response. Maintain this same polarization when comparing poles and other hardware.

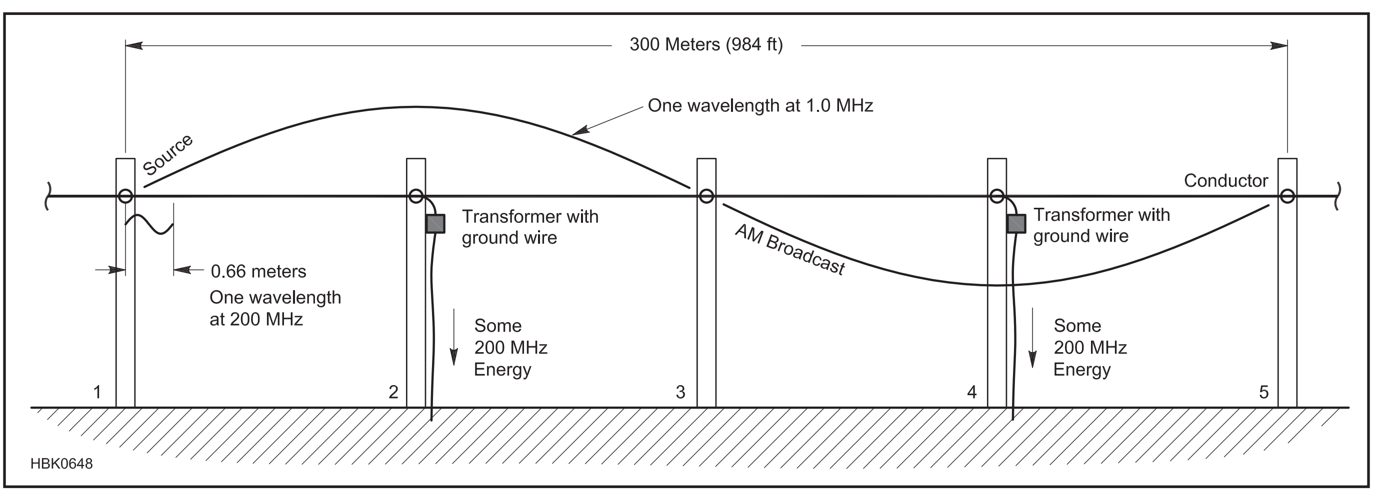


Figure 27.35 — Listening for noise signals on a power distribution line at 1 MHz vs 200 MHz can result in identification of the wrong power pole as the noise source. (From Loftness, *AC Power Interference Handbook*)

27.10.7 Pinpointing the Source on a Pole or Structure

Once the source pole has been identified, the next step becomes pinpointing the offending hardware on that pole. A pair of binoculars on a dark night may reveal visible signs of arcing, and in some cases you may be able to see other evidence of the problem from the ground. These cases are rare. More than likely, a better approach will be required. Professional and utility interference investigators typically have two types of specialized equipment for this purpose:

• An ultrasonic dish or pinpointer. The RFI investigator, even if not a lineman, can pinpoint sources on the structure down to a component level from the ground using this instrument. See **Figure 27.36**.

• An investigator can instruct the lineman on the use of a hot stick-mounted device used to find the source. This method is restricted to only qualified utility personnel, typically from a bucket truck. See **Figure 27.37**.

Both methods are similar but hams only have one option — the ultrasonic pinpointer.

CAUTION — *Hot sticks and hot stick mounted devices are not for hams! Do not use them. Proper and safe use of a hot stick requires specialized training. In most localities, it is generally unlawful for anyone unqualified by a utility to come within 10 feet of an energized line or hardware. This includes hot sticks.*

Remember that it may be interesting to you to determine what piece of equipment is generating noise, but it is the utility's job to positively complete the identification and then work on the equipment. Once you have identified the noise as coming from a particular location, be prepared to step back and let the professionals do their job.

ULTRASONIC PINPOINTER TIPS

An ultrasonic dish is the tool of choice for pinpointing the source of an arc from the ground. While no hot stick is required, an unobstructed, direct line-of-sight path is required between the arc and the dish. This is not a suitable tool for locating the structure containing the source. It is only useful for pinpointing a source once its pole or structure has been determined.

Caveat: Corona discharge, while typically not a source of RF power-line noise, can and often is a significant source of ultrasonic sound. It can often be difficult to distinguish between the sound created by an arc and corona discharge. This can lead to mistakes when trying to pinpoint the source of an RFI problem with an ultrasonic device.

The key to success, just as with locating the structure, is using gain control effectively. Use minimum gain after initially detecting the noise. If the source appears to be at more than one location on the structure, reduce the gain. In part, this will eliminate any weaker noise signals from hardware not causing the problem.

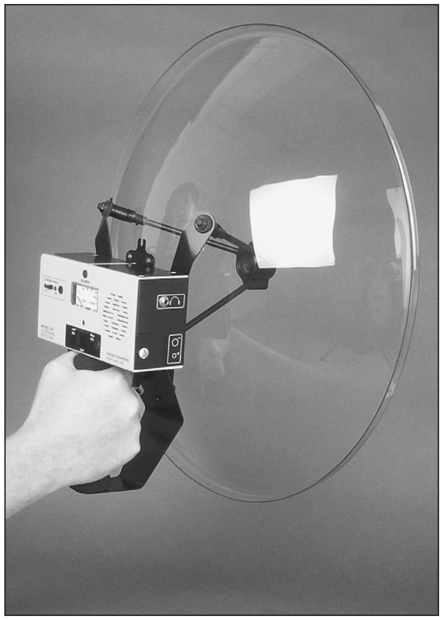


Figure 27.36 — The clear plastic parabolic dish is an "ear" connected to an ultrasonic detector that lets utility personnel listen for the sound of arcs.

Figure 27.37 — The Radar Engineers Model 247 Hotstick Line Sniffer is an RF and ultrasonic locator. It is used by utility workers to pinpoint the exact piece of hardware causing a noise problem.

27.10.8 Common Causes of Power-Line Noise

The following are some of the more common power-line noise sources. They're listed in order from most common to least common. Note that some of the most common sources are not connected to a primary conductor. This in part is due to the care most utilities take to ensure sufficient primary conductor clearance from surrounding hardware. Note, too, that power transformers do not appear on this list:

- Loose staples on ground conductor
- Loose pole-top pin
- Ground conductor touching nearby hardware
- Corroded slack span insulators
- Guy wire touching neutral
- Loose hardware
- Bare tie wire used with insulated conductor
- Insulated tie wire on bare conductor
- Loose cross-arm braces
- Lightning arrestors

27.10.9 The Cooperative Agreement

While some cases of power-line noise are resolved in a timely fashion, the reality is that many cases can linger for an extended period of time. Many utilities simply do not have the expertise, equipment, or motivation to properly address a power-line noise complaint. There are often no quick solutions. Patience can often be at a premium in these situations. Fortunately, the ARRL has a Cooperative Agreement with the FCC that can help. While the program is not a quick or easy solution, it does offer an opportunity and step-by-step course of action for relief. It emphasizes and provides for voluntary cooperation without FCC intervention.

Under the terms of the Cooperative Agreement, the ARRL provides technical help and information to utilities in order to help them resolve power-line noise complaints. It must be emphasized that the ARRL's role in this process is strictly a technical one — it is not in the enforcement business. In order to participate, complainants are required to treat utility personnel with respect, refrain from hostile behavior, and reasonably cooperate with any reasonable utility request. This includes making his or her station available for purposes of observing and recording noise signatures. The intent of the Cooperative Agreement is to solve as many cases as possible before they go to the FCC. In this way, the FCC's limited resources can be allocated where they are needed the most — enforcement.

As the first step in the process, the ARRL sends the utility a letter advising of pertinent Part 15 rules and offering assistance. The FCC then requires a 60-day waiting period before the next step. If by the end of 60 days the utility has failed to demonstrate a good faith effort to correct the problem, the FCC then issues an advisory letter. This letter allows the utility another 60-day window to correct the problem.

A second FCC advisory letter, if necessary, is the next step. Typically, this letter provides another 20- or 30-day window for the utility to respond. If the problem still persists, a field investigation would follow. At the discretion of the field investigator, he or she may issue an FCC Citation or Notice of Apparent Liability (NAL). In the case of an NAL, a forfeiture or fine can result.

It is important to emphasize that the ARRL Cooperative Agreement Program does not offer a quick fix. There are several built-in waiting periods and a number of requirements that a ham must follow precisely. It does however provide a step-by-step and systematic course of action under the auspices of the FCC in cases where a utility does not comply with Part 15.

27.11 Automotive RFI

Automobiles have evolved from a limited number of primitive electrical components to high technology, multi-computer systems-on-wheels. Every new technology deployed can potentially interfere with amateur equipment.

Successful mobile operation depends on a multitude of factors such as choosing the right vehicle, following installation guidelines, troubleshooting, and deploying the appropriate RFI fixes as needed.

A number of these factors will be covered in this section, as well as newly emerging electrical and hybrid-electric vehicles,which pose unique challenges to amateur equipment installations and operation.

27.11.1 Before Purchasing a Vehicle

When shopping for a new vehicle intended for a mobile amateur installation, begin with research. A wealth of information is available on the internet, and specifically at **www.arrl.org/automotive**, where the ARRL has compiled years of data from automotive manufacturers and other hams. Email reflectors and websites may provide information from hams willing to share their experiences concerning mobile communications in their own vehicle, which may be the very make and model you were considering.

Armed with research, your next stop is your dealer. The manufacturer of each vehicle is the expert on how that vehicle will perform. The dealer should have good communication with the manufacturer and should be able to answer your questions. Ask about service bulletins and installation guidelines. You can also ask your dealer about fleet models of their vehicles. Some manufacturers offer special modifications for vehicles intended for sale to police, taxicabs and other users who will be installing radios (usually operating at VHF and UHF) in their cars.

When shopping for a vehicle, it is useful to take along some portable (preferably battery operated) receivers or scanners and have a friend tune through your intended operating frequencies while you drive the vehicle. This will help identify any radiated noise issues associated with that model vehicle, which can be more difficult to resolve than conducted noise. If you intend to make a permanent transceiver installation, give some consideration to how you will mount the transceiver and route the power and/or antenna cables. While looking for ways to route the wiring, keep in mind that in some newer cars the battery is located in the trunk or under the rear seat, which may make power wire routing easier.

Test the car before you buy it. A dealer expects you to take the car for a test ride; a cooperative dealer may let you test it for radio operation too. A fair amount of checking can easily be performed without digging too deeply into the car. Check the vehicle for noise with a portable receiver on VHF, where your handheld transceiver will do the job nicely. On HF, you can usually locate noise with a portable short-wave receiver, or operate your HF transceiver with a portable antenna and cigarette-lighter plug. With the engine running, tune across the bands of interest. You may hear some noise or a few birdies, but if the birdies don't fall on your favorite frequency, this is an encouraging sign! Check with the vehicle completely off, with the key in the ignition, and with the vehicle running — electronic subsystems operate in different ways with the vehicle running or not running.

To test the vehicle for susceptibility to your transmitted signal, you must transmit. It is important to note that without a full and complete installation, you will not be able to fully assess the effects of full-power transmissions on a vehicle. Any testing done with temporary equipment installations cannot be considered an absolute guarantee because an installed transmitter connected directly to the vehicle's power source may cause the vehicle to act differently.

To perform transmit tests, bring your radio and a separate battery (if permitted by dealer) so you can transmit at full power while in motion without having to run cables to the vehicle battery. Use a magnet-mount antenna (several *QST* advertisers sell mounts suitable for HF) for temporary testing. (Use the magnet-mount carefully; it is possible to scratch paint if any particles of dirt get on the bottom of the magnets.) Transmit on each band you will use to see if the RF has any effect on the vehicle. Lack of response to your transmissions is a good sign, but does not mean the vehicle is immune to RF, as a permanent installation will result in different (likely stronger) field strengths and distributions in and around the vehicle and a permanent antenna more effectively coupled to the vehicle.

On both transmit and receive, you may want to experiment with the placement of the antenna. Antenna placement plays an important role in operation, and you may be able to find an optimal location for the antenna that predicts good performance with a permanent installation.

27.11.2 Transceiver Installation Guidelines

While most amateurs are familiar with the process of installing a transceiver, there are preferred practices that will help minimize potential problems. These include support from the automotive dealer, typical "best practices" installations, and consideration of special situations.

The first step is to ensure that your installation complies with both the vehicle manufacturer's and radio transceiver manufacturer's installation guidelines. Links to domestic automotive manufacturer installation guidelines are found at **www.arrl.org/automotive**. Automotive manufacturers that import vehicles for sale here do not publish installation guidelines because their vehicles are not typically used in police, fire, and taxicab applications within the US.

The installation guidelines of different manufacturers vary as to how to install a radio transceiver's power leads. Most manufacturers recommend that the positive and negative leads from the radio be run directly to the battery. This minimizes the potential for the interaction between the radio's negative lead currents and vehicle electronics. If the manufacturer recommends that both wires be connected to the battery, they will also require that both wires be fused. This is necessary because, in the unlikely event that the connection between the battery and the engine block were to fail, excessive current could be drawn on the radio's negative lead when the vehicle starter is engaged.

Some vehicles provide a "ground block" near the battery for a negative cable to be connected. On these vehicles, run the negative power lead, unfused, to the "ground block." When this technique is recommended by the manufacturer, the interaction between the power return currents and vehicle electronics has been evaluated by the manufacturer. In all cases, the most important rule to remember is this: If you want the manufacturer to support your installation, do it exactly the way the installation guidelines tell you to do it!

If no installation guidelines are available for your vehicle, the practices outlined below will improve compatibility between in-vehicle transceivers and vehicle electronics:

1) Transceivers

• Transceivers should be securely mounted in a location that does not interfere with vehicle operator controls and visibility, and provides transceiver ventilation.

• Ensure all equipment and accessories are removed from the deployment path of the airbag and safety harness systems.

2) Power Leads

• The power leads should be twisted together from the back of the rig all the way to the battery. This minimizes the area formed by the power leads, reducing susceptibility to transients and RFI.

• Do not use the vehicle chassis as a power return.

• The power leads should be routed along the body structure, away from vehicle wiring harnesses and electronics.

• Any wires connected to the battery should be fused at the battery using fuses appropriate for the required current.

• Use pass-through grommets when routing wiring between passenger and engine compartments.

• Route and secure all under-hood wiring away from mechanical hazards.

3) Coaxial Feed Lines

• The coaxial feed line should have at least 95% braid coverage. The cable shield should be connected to every coaxial connector for the entire circumference (no "pigtails").

• Keep antenna feed lines as short as practical and avoid routing the cables parallel to vehicle wiring.

4) Antennas

• Antenna(s) should be mounted as far from the engine and the vehicle electronics as practical. Typical locations would be the rear deck lid or roof. Metal tape can be used to provide an antenna ground plane on non-metallic body panels.

• Care should be used in mounting antennas with magnetic bases, since magnets may affect the accuracy or operation of the compass in vehicles, if equipped.

• Since the small magnet surface results in low coupling to the vehicle at HF, it is likely that the feed line shield will carry substantial RF currents. A large (2-inch OD or larger toroid) common-mode choke at the antenna will help reduce this current, but will also reduce any radiation produced by that current.

• Adjust the antenna for a low SWR.

27.11.3 Diagnosing Automotive RFI

Most VHF/UHF radio installations should result in no problems to either the vehicle systems or the transceiver, while HF installations are more likely to experience problems. In those situations where issues do occur, the vast majority are interference to the receiver from vehicle on-board sources of energy that are creating emissions within the frequency bands used by the receiver. Interference to one of the on-board electronic systems can be trivial, or it can cause major problems with an engine control system.

The dealer should be the first point of contact when a problem surfaces, because the dealer should have access to information and factory help that may solve your problem. The manufacturer may have already found a fix for your problem and may be able to save your mechanic a lot of time (saving you money in the process). If the process works properly, the dealer/customer-service network can be helpful. In the event the dealer is unable to solve your problem, the next section includes general troubleshooting techniques you can perform independently.

GENERAL TROUBLESHOOTING TECHNIQUES

An important aspect is to use the source-path-victim model presented earlier in this chapter. The path from the source to the receiver may be via radiation or conduction. If the path is radiation, the electric field strength (in V/m) received is reduced as a function of the distance from the source to the receiver. In most cases, susceptible vehicle electronics is in the near-field region of the radiating source, where the electric and magnetic fields can behave in complex ways. In general, however, the strength of radiated signals falls off with distance.

The best part of all this is that with a general-coverage receiver or spectrum analyzer, a fuse puller, and a shop manual, the vehicle component needing attention may be identified using a few basic techniques. The only equipment needed could be as simple as:

• A mobile rig, scanner, or handheld transceiver, or

• Any other receiver with good stability and an accurate readout, and

• An oscilloscope for viewing interference waveforms

BROADBAND NOISE

Automotive broadband noise sources include:

• Electric motors such as those that operate fans, windows, sunroof, AM/FM antenna deployment, fuel pumps, etc.

• Ignition spark

If you suspect electric motor noise is the cause of the problem, obtain a portable AM or SSB receiver to check for this condition. Switch on the receiver and then activate the electric motors one at a time. When a noisy motor is switched on, the background noise increases. It may be necessary to rotate the radio, since portable AM radios use a directional ferrite rod antenna.

To check whether fuel pumps, cooling fans, and other vehicle-controlled motors are the source of noise, pull the appropriate fuse and see whether the noise disappears.

A note concerning fuel pumps: virtually every vehicle made since the 1980s has an electric fuel pump, powered by long wires. It may be located inside the fuel tank. Don't overlook this motor as a source of interference just because it may not be visible. Electric fuel-pump noise often exhibits a characteristic time pattern. When the vehicle ignition switch is first turned on, without engaging the starter, the fuel pump will run for a few seconds and then shut off when the fuel system is pressurized. At idle, the noise will generally follow the pattern of being present for a few seconds before stopping, although in some vehicles the fuel pump will run almost continuously if the engine is running.

NARROWBAND NOISE

Automotive narrowband noise sources include:

• Microprocessor based engine control systems
• Instrument panel
• RADAR obstacle detection
• Remote keyless entry
• Key fob recognition systems
• Tire pressure monitoring systems
• Global positioning systems
• Pulse width modulating motor speed controls
• Fuel injectors
• Specialized electric traction systems found in newer hybrid/electric vehicles

Start by moving the antenna to different

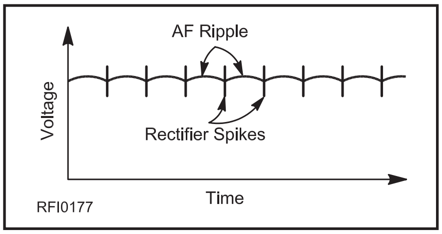


Figure 27.38 — Alternator whine consists of full-wave rectified ac, along with pulses from rectifier switching, superimposed on the vehicle's dc power voltage.

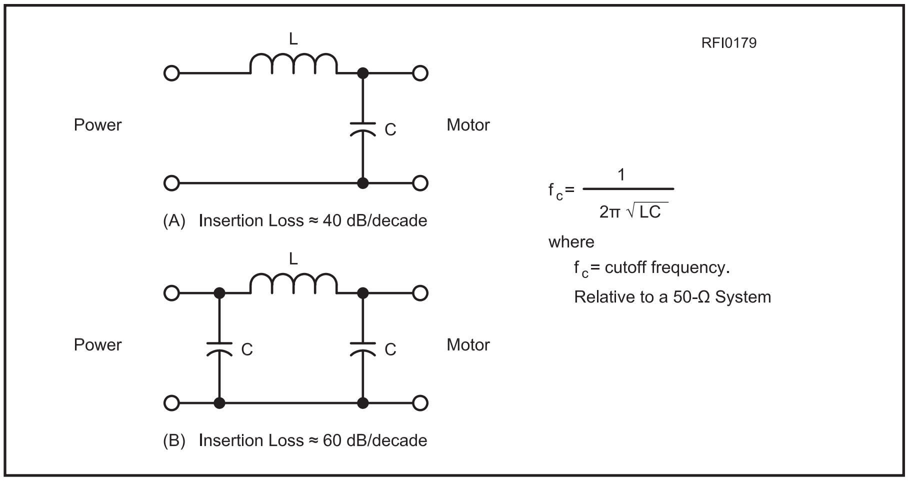


Figure 27.39 — Filters for reducing noise from dc motors.

locations. Antenna placement is often key to resolving narrowband RFI problems. However, if antenna location is not the solution, consider pulling fuses. Tune in and stabilize the noise, then find the vehicle fuse panels and pull one fuse at a time until the noise disappears. If more than one module is fed by one fuse, locate each module and unplug it separately. Some modules may have a "keep-alive" memory that is not disabled by pulling the fuse. These modules may need to be unplugged to determine whether they are the noise source. Consult the shop manual for fuse location, module location, and any information concerning special procedures for disconnecting power.

A listening test may verify alternator noise, but if an oscilloscope is available, monitor the power line feeding the affected radio. Alternator whine appears as full-wave rectified ac ripple and rectifier switching transients superimposed on the power system's dc power voltage (see **Figure 27.38**).

Alternators rely on the low impedance of the battery for filtering. Check the wiring from the alternator output to the battery for corroded contacts and loose connectors when alternator noise is a problem.

Receivers may allow conducted harness noise to enter the RF, IF, or audio sections (usually through the power leads), and interfere with desired signals. Check whether the interference is still present with the receiver powered from a battery or power supply instead of from the vehicle. If the interference is no longer present when the receiver is operating from a battery or external supply, the interference is conducted via the radio power lead. Power line filters installed at the radio may resolve this problem.

27.11.4 Eliminating Automotive RFI

The next section includes various techniques to resolve the more common RFI problems. As a caveat, when performing your own RFI work, in or out of warranty, you assume the same risks as you do when you perform any other type of automotive repair. Most state laws (and common sense) say that those who work on cars should be qualified to do so. In most cases, this means that work should be done either by a licensed dealer or automotive repair facility.

CONDUCTED INTERFERENCE

To reduce common-mode current, impedance can be inserted in series with the wiring in the form of common-mode chokes. (See this chapter's section on Common-Mode Chokes.) Wire bundles may also be wound around large toroids for the same effect.

Mechanical considerations are important in mobile installations. A motor vehicle is subject to a lot of vibration. If a choke is installed on a wire, this vibration may cause the choke to flex the wire, which may ultimately fail. It is critical that any additional shielding and/or chokes placed on wiring have been installed by qualified personnel who have considered these factors. These must be properly secured, and sometimes cable extenders are required to implement this fix.

RFI TO ON-BOARD CONTROL SYSTEMS

RFI to a vehicle's on-board control and electronic modules should be treated with common-mode chokes at the connection to the module. Some success has been reported by using braid or metal foil to cover a wire bundle as a shield and connecting the shield to the vehicle chassis near the affected module. Vehicle electronic units should not be modified except by trained service personnel according to the manufacturer's recommendations. The manufacturer may also have specific information available in the form of service bulletins.

FILTERS FOR DC MOTORS

If the motor is a conventional brush- or commutator-type dc motor, the following cures shown in **Figure 27.39** are those generally used. As always, the mechanic should consult with the vehicle manufacturer. To diagnose motor noise, obtain an AM or SSB receiver to check the frequency or band of interest. Switch on the receiver, and then activate the electric motors one at a time. When a noisy motor is switched on, the background noise increases as well.

The pulses of current drawn by a brush-commutator motor generate broadband RFI that is similar to ignition noise. However, the receiver audio sounds more like bacon frying rather than popping. With an oscilloscope displaying receiver audio, the noise appears as a series of pulses with random space between the pulses. Such broadband noise generally has a more pronounced effect on AM than on FM receivers. Unfortunately, the pulses may affect FM receivers by increasing the "background noise level" and will reduce perceived receiver sensitivity because of the degraded signal-to-noise ratio.

ALTERNATOR AND GENERATOR NOISE

As mentioned previously, brush-type motors employ sliding contacts that can generate noise. The resulting spark is primarily responsible for the "hash" noise associated with these devices. Hash noise appears as overlapping pulses on an oscilloscope connected to the receiver audio output. An alternator also has brushes, but they do not interrupt current. They ride on slip rings and supply a modest current, typically 4 A to the field winding. Hence, the hash noise produced by alternators is relatively minimal.

Generators use a relay regulator to control field current and thus output voltage. The voltage regulator's continuous sparking creates broadband noise pulses that do not overlap in time. They are rarely found in modern automobiles.

Alternator or generator noise may be conducted through the vehicle wiring to the power input of mobile receivers and transmitters and may then be heard in the audio output. If alternator or generator noise is suspected and an oscilloscope is not available, temporarily remove the alternator belt as a test. (This may not be possible in vehicles with a serpentine belt.)

IGNITION NOISE

Ignition noise is created by fast-rise-time pulses of coil current discharging across air gaps (distributor and spark plug). The theoretical models (zero rise time) of such pulses are called impulse functions in the time domain. When viewed in the frequency domain, the yield is a constant spectral energy level starting nearly at 0 Hz and theoretically extending up in frequency to infinity. In practice, real ignition pulses have a finite rise time, so the spectral-energy envelope decreases above some frequency.

It turns out that noise generated by ignition sparks and fuel injector activation manifests as a regular, periodic "ticking" in the receiver audio output, which varies with engine RPM. If an oscilloscope were connected to the audio output, a series of distinct, separate pulses would appear. At higher speeds it sounds somewhat musical, like alternator whine, but with a harsher note (more harmonic content).

A distinguishing feature of ignition noise is that it increases in amplitude under acceleration. This results from the increase in the required firing voltage with higher cylinder pressure. (Noise at higher frequencies may also be reproduced better by the audio circuits.) Since ignition noise is usually radiated noise, it should disappear when the antenna element is disconnected from the antenna mount. The radiation may be from the secondary parts of the system, or it may couple from the secondary to the primary of the coil and be conducted for some distance along the primary wiring to the ignition system, then radiated from the primary wiring.

Two main methods are employed to suppress this noise — one involves adding an inductance, and the other involves adding a resistance — both in the secondary (high voltage) wiring. This is shown in **Figure 27.40**. The addition of these elements does not have a measurable effect on the engine operation, because the time constants involved in the combustion process are much longer than those associated with the suppression components. (Note that modifying your vehicle's ignition system may be considered as tampering with your vehicle's emission control system and may affect your warranty coverage — work with your dealer or limit your efforts to changing spark plug wires or possibly shielding them.)

The resistance method suppresses RFI by dissipating energy that would have been radiated and/or conducted. Even though the amount of energy dissipated is small, it is still enough to cause interference to sensitive amateur installations. The other method uses inductance and even though the energy is not dissipated, suppression occurs because the inductor will store the pulse energy for a short time. It then releases it into the ignition burn event, which is a low impedance path, reducing the RFI.

For traditional "Kettering" inductive discharge ignition systems, a value of about 5 kΩ impedance (either real and/or reactive) in the spark plug circuit provides effective suppression and, with this value, there is no detectable engine operation degradation. (Capacitor discharge systems, in comparison, are required to have very low impedance on the order of tens of ohms in order to not reduce spark energy, so they are not tolerant of series impedance). Most spark plug resistances are designed to operate with several kV across the plug gap, so a low-voltage ohmmeter may not give proper resistance measurement results.

The term "resistor wire" is somewhat misleading. High-voltage ignition wires usually contain both resistance and inductance. The resistance is usually built into suppressor spark plugs and wires, while there is some inductance and resistance in wires, rotors, and connectors. The elements can be either distributed or lumped, depending on the brand, and each technique has its own merit. A side benefit of resistance in the spark plug is reduced electrode wear.

COIL-ON-PLUG IGNITION NOISE

Many newer spark-ignition systems incorporate a "coil on plug" (COP) or "coil near plug" (CNP) approach. There are advantages to this from an engine operation standpoint, and this approach may actually reduce some of the traditional sources of ignition system RFI. This is because of the very short secondary wires that are employed (or perhaps there are no wires — the coil is directly attached to the spark plug). This reduces the likelihood of coupling from the secondary circuit to other wires or vehicle/engine conductive structures.

There will always be some amount of energy from the spark event that will be conducted along the lowest impedance path. It may mean that the energy that would have been in the secondary circuit will be coupled back on the primary wiring harness attached to the coils. This means that the problem may go from a radiated to a conducted phenomenon.

The fix for this in some cases may actually be easier or harder than one might think. Two

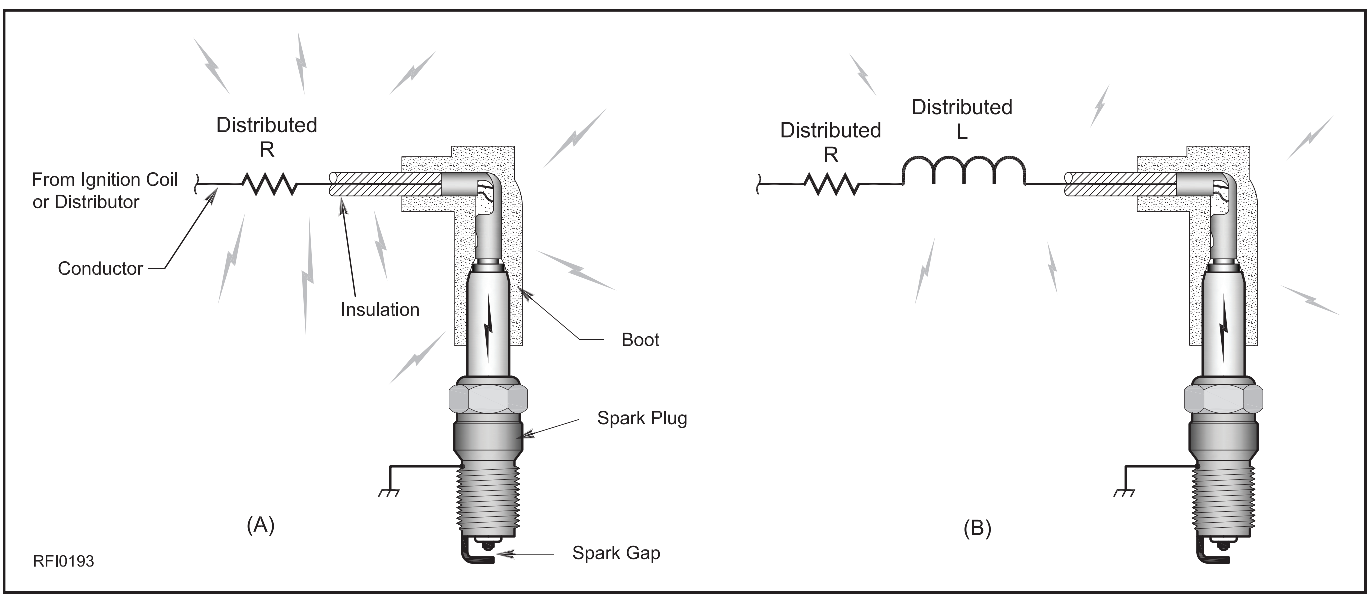


Figure 27.40 — Ignition noise suppression methods.

approaches that have been used with success are ferrite cores and bypass capacitors.

Ferrite cores are recommended as the first choice, since they require no electrical modification to the vehicle. Ferrite clamp-on split cores are added to the 12-V primary harness attached to the coils. Depending on the frequency of the noise and selection of the ferrite material, there can be significant improvement (as much as 10 dB). Key to optimizing the amount of suppression is to determine where the noise "peaks" and selecting the correct ferrite material for that frequency range (see this chapter's section Using Ferrite for RFI Suppression).

The second method is to add a bypass capacitor between the primary wire of the 12-V coil and ground in the harness near the coil assemblies (there may be two, three, or four coils). This must be done carefully because it could affect the functionality of the ignition system and — perhaps most importantly — may void the vehicle warranty. This "bypass" capacitor performs the same function that bypass capacitors in any other application perform — separating the noise from the intended signal/power.

27.11.5 Electric and Hybrid-Electric Vehicles

Electric vehicles (EV) and hybrid-electric vehicles (HEV) are quickly becoming a practical means of transportation. EV/HEVs are advanced vehicles that pose unique challenges for amateur equipment. While EV/HEVs provide improved emissions and fuel economy, they utilize switched high voltage and high current to control propulsion. The switching techniques used generate RFI within much of our frequency bands — a cause for concern, particularly for HF operation.

This section is designed to enlighten vehicle owners to the challenges and to make suggestions when installing mobile amateur equipment in an EV/HEV.

EV AND HEV ARCHITECTURE

Most EVs and HEVs have similar electrical traction system (ETS) architectures consisting of a high voltage battery supplying energy to an inverter, which controls an electric motor within a transmission connected to the drive wheels. The main difference between the two is that an HEV includes an internal combustion engine to aid in propulsion, and while a pure EV is strictly electrically powered.

The heart of the ETS is a device called an inverter. It simply converts dc voltage from the high voltage battery (typical voltage range from 42 to 350 V dc) to an ac waveform supplying the electric motor. This dc-to-ac conversion is performed by a matrix of six transistor switches. The switches chop the dc voltage into systematically varying pulses called pulse-width-modulation (PWM) to form an adjustable frequency and RMS voltage suitable to power an electric motor.

In most cases, the ac voltage from the inverter is a three-phase waveform similar to industrial applications because three-phase motors can be smaller, more efficient, and provide greater torque than single-phase motors.

IMPORTANT — Bright orange cables connect the battery pack to the inverter and the inverter to the drive motor, transferring voltage and current to and from the inverter. Because of the non-sinusoidal waveforms being transferred, these cables are shielded and terminated at each end. Under no condition should these cables be disconnected or modified, because the high voltage system depends on a delicate balance of sensors and safety mechanisms. Possible malfunction and damage to the ETS may occur if modified.

RFI FROM EV AND HEV

The inverter uses PWM to convert dc battery voltage to an ac waveform. The phase-to-phase terminal voltage appears in **Figure 27.41** as rectangular blocks with positive and negative amplitude equal to the battery voltage. For example, a 300 V dc battery pack will provide 600 V peak-to-peak at the motor terminals. In Figure 27.41, the same terminal voltage signal is sent through a low pass filter to show how PWM forms a sinusoidal waveform. Each pulse is essentially a square wave. Harmonics from these pulses fall within most of our amateur HF bands and well into VHF, affecting radio performance. This switching noise is the primary source of RFI to amateur radio equipment in electric vehicles. Because EV/HEV systems are evolving rapidly, check the ARRL's Automotive RFI web page (**www.arrl.org/automotive**) for more information.

EV AND HEV RFI REMEDIES

Troubleshooting techniques described earlier apply in diagnosing RFI from EV/HEV systems. Limited RFI remedies are available associated with components within the ETS. Work with your dealer when you suspect the ETS as the RFI source. Do not attempt to modify or repair your ETS; the dealer's service center is most qualified to inspect and repair your EV/HEV electrical traction system.

Electric vehicles also use a lot of the same type of electric motors, solenoids, switches, and control electronics as are found in non-electric vehicles. The same types of noise will be radiated from these devices, and any amateur radio equipment is essentially within feet or even inches of the noise source. One difference with electric vehicles is that adding chokes or other RFI remedies may not be permitted under the vehicle's warranty due to the more complex power and control electronics systems. If you do add components to the vehicle wiring to reduce RFI, do it in small steps, testing vehicle and noise performance along the way.

During installation, mobile equipment power cables and antenna coaxial cables should be routed as far as possible from the bright orange cables. Common-mode chokes can decrease noise on 12-V dc power cables. Additionally, antenna placement plays a critical role in mobile equipment performance. Areas such as the top of a roof or trunk sometimes provide additional shielding.

RFI to EV and HEV

While all modern vehicles have RF-sensitive electronics on board, electric vehicles have electronics that control every facet of vehicle operation, usually controlled over digital networks such as the CAN (Controller Area Network). These circuits are well filtered, which reduces the chance for stray RF to negatively affect them. However, the vehicle wiring and electronics are very close to the antennas that are radiating a strong signal. As more vehicles adopt partial or complete automated driving, RFI can present serious safety challenges!

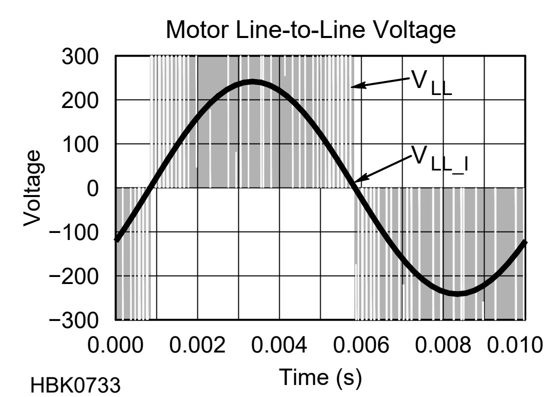


Figure 27.41 — Phase-to-phase motor terminal voltage.

Be aware that on-board electronics may be susceptible to the high levels of RF generated by amateur transmitters, regardless of the frequency of operation. Even when allowed, proper antenna installation is very important in keeping common-mode RF current pickup by cables and wiring harnesses to a minimum. Disrupting network data signals or affecting control circuit operation can have serious safety consequences.

As amateur radio and vehicles use more digital protocols and technology, it should reduce susceptibility to RFI in electric vehicles. In the interim, amateurs will have to remain cautious and be prepared to be flexible in their approach to mobile operating. Amateur operators will still have to contend with RFI, but the future may bring improvements as the digital systems become more tolerant for both the radios and vehicles.

27.11.6 Automotive RFI Summary

Most radio installations should result in no problems to either the vehicle systems or any issues with the transceiver. However, manufacturer, make, and models differ, thus introducing challenges during amateur equipment installations.

Begin by researching your vehicle of interest and visiting the dealer. Insist on transmitting and receiving your favorite frequencies as you test drive. Request information pertaining to the manufacturer's transceiver installation guidelines. If manufacturer information is not available, follow the guidelines described earlier.

After installation, RFI problems may appear. Report your problem to the dealer, because they have access to manufacturer service bulletins that may describe a repair solution. Additional troubleshooting and remedies are also described previously to assist in successful communication.

Limited RFI remedies are available associated to components within the ETS. Work with your dealer when you suspect the ETS is the RFI source. Do not attempt to modify or repair your ETS; the dealer's service center is most qualified to inspect and repair your EV/HEV electrical traction system.

Lastly, the latest version of the *ARRL RFI Book* contains additional information on RFI in automobiles. More details are given about noise sources, troubleshooting techniques, a troubleshooting flow chart, additional filtering techniques, and information on EV/HEVs.

27.12 EMC Topics

"Electromagnetic compatibility (EMC) is the ability of an electronic system to (1) function properly in its intended electromagnetic environment, and (2) not be a source of pollution to that electromagnetic environment." (Ott, page 4) This chapter's previous sections deal exclusively with the RF interference aspects of EMC — whether our signals cause RFI and whether our stations are susceptible to RFI from amateur and non-amateur sources. In this section other topics associated with EMC are discussed.

27.12.1 Standard Transient Types

A transient, by definition, "Refers to momentary over-voltages or voltage reductions in an electric power system," (CRC Electrical Engineering Dictionary) Just because a transient is momentary doesn't mean it can't cause harm. This section describes several transients that amateurs are likely to encounter and devices used to protect circuits against them.

AUTOMOTIVE TRANSIENTS

DC voltage in vehicles that use a lead-acid starter battery as the energy source varies between 10.5 V (a discharged battery) to more than 15 V during heavy charging. The typical 13.8 V ±15% input voltage specification corresponds to a fresh battery during normal charging. Numerous ac and transient signals are superimposed on that dc supply voltage – for example, the rapid current switching in the vehicle's alternator creates sharp (short-duration) transients on the power bus. If not adequately filtered by the radio, the result is a high-pitched *alternator whine* added to both receive and transmit signals that follows engine speed.

SAE (Society of Automotive Engineers) standard J1113, "Immunity to Conducted Transients on Power Leads," describes transients encountered on a vehicle's power bus such as these common occurrences:

• **Load Dump** — occurs when a loose battery connection opens up during charging and the alternator's energy is "dumped" on the power bus with no battery to hold down the voltage.

• **Alternator Field Decay** — occurs every time the vehicle is turned off and the alternator's stored energy has to be dissipated via the power bus.

• **Inductive Load Switching** — the kickback voltage from an inductive load (like an electric window motor) being turned off.

• **Mutual Coupling** — transient energy that is coupled between conductors in a wiring harness.

Table 27.5 summarizes the electrical characteristics of these transients, and **Figure 27.42** shows what they look like in time. Vehicle manufacturers build in some transient protection so that every electronic device in the vehicle does not have to protect itself against all of these transients. As explained in the Littelfuse application note *Suppression of Transients in an Automotive Environment* (available at **littelfuse.com**), vehicle electronics are already protected by a *central suppressor* in the vehicle, usually located as close to the master control computer module as possible. There are usually suppressors in other modules around the vehicle as well.

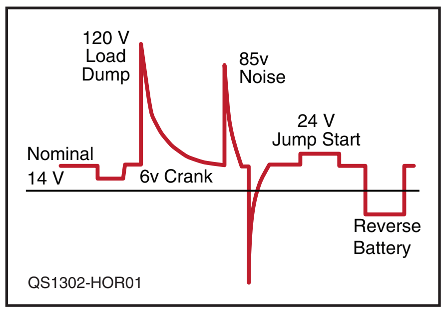


Figure 27.42 — Typical vehicle power system voltage levels for a 12-V electrical system. (Data courtesy of Littlefuse Corp.)

Table 27.5

Typical Vehicle Transients (12V System)

Type	*Voltage*	*Energy (Joules)*	*Duration*	*Occurs*
Load Dump	<125 V	>10 J	200 – 400 msec	Infrequently
Field Decay	–100 to +40V	<1 J	200 msec	At turn-off
Inductive	–300 to +80 V	<1 J	<320 μsec	Often
Mutual Coupling	<200 V	<1 J	1 msec	Often

ELECTROSTATIC DISCHARGE (ESD)

Another source of transients, especially in areas with dry air, is *electrostatic discharge* or *ESD*. A sudden discharge of static electricity by a spark, such as from walking across a carpet then touching a grounded surface, is a typical example of ESD. In fact, the standard ESD test generator uses a finger-shaped probe.

There can be enough energy in an ESD to destroy semiconductors or scramble the operation of a circuit. A typical ESD transient lasts for less than 50 µsec but can generate voltages up to 15 kV! ESD transients can appear on power and signal wiring, connectors, controls and switches, displays – anything a finger can touch, even metal enclosures. The standard ESD transient waveform is shown in **Figure 27.43**. Note the fast rise time and long decay.

Protection of circuits against ESD is discussed in a pair of application notes from Littlefuse (**www.littlefuse.com**): *ESD Protection Design Guide* and *Tips for Enhancing ESD Protection*.

27.12.2 Transient Protective Devices

There are several ways to protect electronics against transients – block them, route them away from the circuitry, and dissipate their energy as heat. The goal is to limit the remaining voltage to levels the electronics can handle. Several different types of protective components have been developed to handle transients. Available from Littlefuse, *Transient Suppression Devices and Principles*, application note AN9768 is an excellent overview of transient protection and the different types of devices that are used. A widely available and inexpensive text is *Transient Protection of Electronic Circuits,* published by Dover Press.

Vendors of protective components include Bourns (**bourns.com**), Littlefuse, TDK (**product.tdk.com**), and Vishay (**vishay.com**), who all offer selection guides and datasheets. MOV distributors such as Digi-Key (**digikey.com**) and Mouser Electronics (**mouser.com**) also provide online comparison features as well as product lines from a wide variety of vendors.

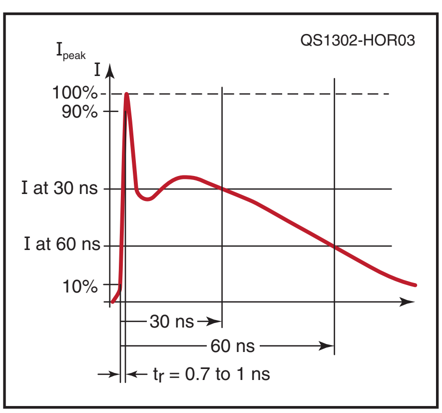


Figure 27.43 — ESD Transient waveform. (Data from standard IED 61000-4-2.)

SERIES AND SHUNT DEVICES

There are two types of transient or surge protection devices, *series-mode* and *shunt-mode,* which refer to how they are connected with respect to the equipment or circuit being protected. A series-mode protector blocks the transient from traveling to the protected equipment along the signal path by changing from a low to a high impedance state. This might be done with inductance or a switch that opens very rapidly. A series-mode protector must be able to withstand the full signal level to or from the equipment without dissipating too much energy or significantly altering the load characteristics.

A shunt-mode protector is installed between the protected conductor and a local ground system, such as a chassis connection. The protector acts as an open circuit until a threshold voltage is exceeded, then it changes to a low-impedance state to dissipate the transient energy as heat like a resistor, or direct it to ground as a switch. A shunt-mode protector "shares" the transient voltage with the protected equipment until the protector's threshold voltage is exceeded. The protected device is exposed to the transient energy until the shunt device switches to the low-impedance state.

Most protective devices used by amateurs are shunt-mode, such as lightning arrestors and spark gaps. An example of a series-mode device is a sub-miniature incandescent light bulb in the feed line to a receiver to protect it against strong signals from a nearby transmitter. Be wary of using non-linear shunt-mode devices such as diodes on any conductor that may carry significant RF voltages or currents. The resulting harmonics may cause significant RFI — see the sidebar Unbypassed Diode Junctions and RFI in the earlier section on Interference from IMD.

METAL OXIDE VARISTOR (MOV)

An MOV consists of partially conductive powder pressed into a disc or cylinder so that it is non-conductive up to its *clamping voltage*. At voltages (of either polarity) higher than the clamping voltage, its resistance drops, limiting the voltage by dissipating energy as heat. MOVs are generally connected between the circuit being protected and ground so that the lower resistance causes the MOV to absorb the transient's energy and keep voltage at a safe level. After repeated transients, MOVs generally fail in a low-resistance state.

As shown in **Figure 27.44**, the varistor consists of metal oxide grains pressed together and heated (sintered) into a disc that has electrodes and wire leads attached. An epoxy coating completes the component, which looks almost identical to a disc capacitor. The size and composition of the grains determines how the MOV behaves electrically as shown in the figure.

At voltages below the MOVs breakdown voltage, the MOV acts like an open circuit. As a transient exceeds its breakdown voltage, the MOV begins to conduct and acts as a low-value resistor. (The voltage-current graph for a fixed resistor is also shown for reference.) This allows the MOV to dissipate the transient's energy as heat. The MOV is non-polarized and acts the same with either positive or negative voltage across it.

MOVs are available with a wide range of breakdown voltages and energy ratings. Their specified operating voltage is well below the breakdown voltage, so they won't begin to conduct under normal circumstances. Their energy rating also stipulates how often the rated energy can be safely dissipated. Repeated transients, cause the MOV breakdown voltage to decrease and eventually the normal operating voltage can cause the MOV to fail at a low resistance.

The most common use for MOVs by amateurs is in ac power surge protectors and in protecting data and control lines. They are not used in high RF power environments. An MOV subjected to a very large transient may fail open-circuited so that it no longer provides any protection. Surge suppressors containing MOVs often have an indicator to show when the MOVs are no longer providing protection. Thermal fuses are included to prevent fires if the MOV fails at low-resistance.

TRANSIENT VOLTAGE SUPPRESSOR (TVS) DIODES

Essentially a heavy-duty Zener diode designed for transient suppression, the transient voltage suppressor or TVS diode (also known by the trade name Transzorb®) acts as a voltage clamp but does not dissipate the transient energy. TVS diodes offer more precise clamping action than MOVs. Unless overloaded, TVS diodes can handle repeated transients without changing their characteristics.

Transzorbs are available in both unidirectional (like a regular Zener diode) and bidirectional (two back-to-back Zener diodes in series). In the reverse direction, the Transzorb acts as an open circuit until its breakdown voltage is exceeded when it begins to conduct. In the forward direction it is a regular semiconductor diode.

The Transzorb acts faster than an MOV or GDT, both in clamping and recovery, but does not dissipate the energy of a transient. It can clamp repeated transients without the breakdown voltage changing as long as its power dissipation rating is not exceeded. Transzorbs are generally used in low-power signal applications, where more control over clamping

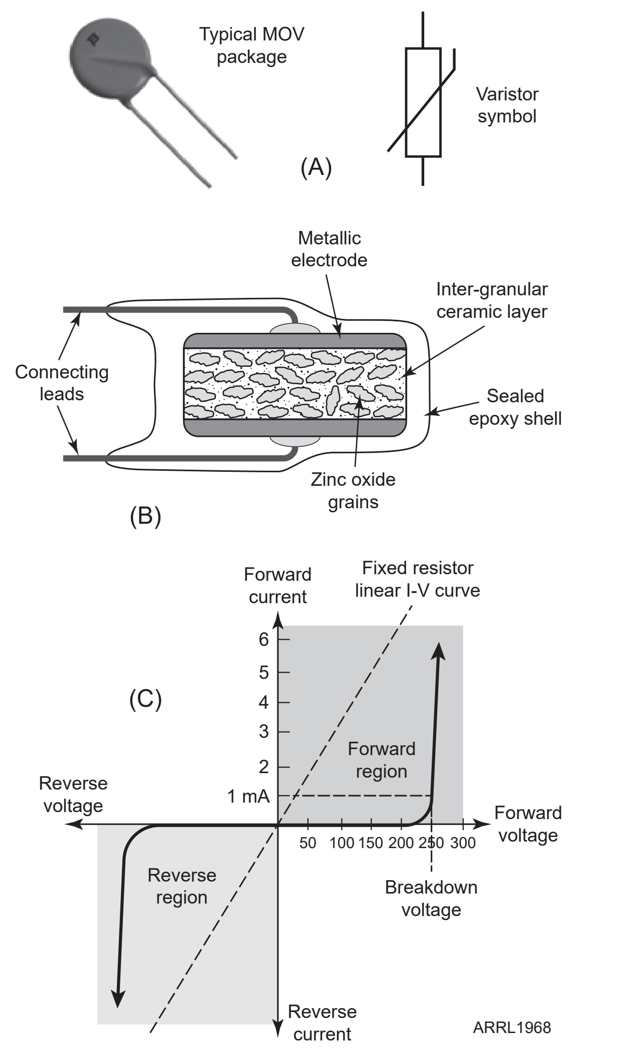


Figure 27.44 — The schematic symbol and a typical metal-oxide varistor (MOV) component (A). MOVs are made from a sintered disc of metal oxides between metal electrodes (B). The current-voltage graph in C shows the change to a low-resistance state above a threshold voltage of either polarity.

Lightning and EMP

While there are some similarities between the lightning and *electromagnetic pulse* (EMP) events, lightning is comparatively slow. EMP events create large voltage transients or gradients that act 10 times faster (or more) than lightning. The damage from both can be similar but protection techniques are different. You can read about EMP in the *QST* articles by Dennis Bodson, W4PWF, which are online in the ARRL's *QST* archives.

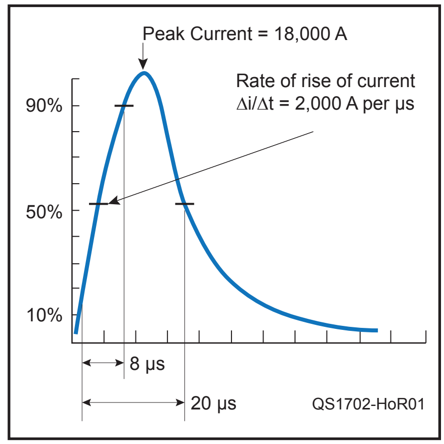


Figure 27.45 — The IEEE 8/20 model waveform for a typical lightning pulse.

action is required, and repeated transients are expected.

DIODE CLAMPING AND RC FILTERING

Most effective for ESD and fast transients, clamping diodes route energy away from the protected circuit into the power supply, where it is absorbed by the filter components. This limits the circuit voltage to one forward voltage drop beyond the power supply voltage.

RC low-pass filtering is useful for both RFI and ESD. Inserted in series with an input circuit, the RC filter consists of a series resistor followed by a capacitor to ground. The filter attenuates RF voltages above its cutoff frequency and smooths out transient voltages, dissipating some of the energy as heat.

RC filters are particularly useful in high-impedance inputs for which the additional series impedance of the filter does not cause significant errors. However, the shunt capacitance across a high-impedance input may affect high-frequency performance considerably. Be sure to consider the effects of any protection circuit on the protected circuit's behavior.

27.12.3 Lightning

Lightning and protection against it are also discussed in the chapters **Assembling a Station** and **Safe Practices**. The ARRL publication *Grounding and Bonding for the Radio Amateur, 2nd Edition* offers an extensive discussion on lightning. You can also find practical information at **www.arrl.org/lightning-protection**.

A typical lightning strike is composed of three to four impulses per strike. Peak current for the first pulse averages around 18 kA (98% of the strikes fall between 3 kA to 140 kA at their peak). For the second and subsequent impulses, the current will be about half the initial peak. The typical interval between impulses is approximately 50 msec. **Figure 27.45** shows a typical impulse, referred to as the *IEEE 8/20 model waveform*. Remember, this is an *average* and fully half of lightning strikes have more energy than this waveform!

Voltages created by this current pulse can be enormous and depend on the resistance (R) and inductance (L) through which the current flows. According to Faraday's Law, the faster that current changes (Δi / Δt, where the symbol Δ means "the change in") through an inductance, the higher the voltage that is created. Higher current through a resistance also means higher voltage, per Ohm's Law. The combination is stated as:

$$V = I \times R + L \times \Delta i/\Delta t$$

While the majority of lightning's energy is pulsed dc, there is a substantial amount of RF created by the fast rise time of the pulses. A typical lightning strike rise time is 1.8 µsec. That translates into a radiated RF signal peaking at 139 kHz. Rise times can vary from a very fast 0.25 µsec to a very slow 12 µsec, yielding an RF range from 1 MHz down to 20 kHz. When lightning "attaches" to the *air terminal* (where the leader channel reaches the grounded object), the rise time for current can be as short as 10 nsec. The result is that lightning's energy extends upward in frequency to 10 MHz and higher.

An indirect or nearby strike can generate fast-rising transients with energies equal to or larger than the automotive inductive transient and with voltages nearly as high as an ESD pulse. Protection for ac power circuits is usually provided by *surge suppressors,* which consist of multiple power outlets in a single enclosure (aka "power strips) protected by MOVs. Protection ratings are specified in joules (J) or watt-seconds. Surge suppressors used in the home or amateur station should meet the UL 1449 safety standard. Older and non-rated units may fail gradually in ways that can create a fire hazard and should be discarded.

27.12.4 Gas Discharge Tubes (GDT)

Several examples of *gas discharge tubes* (GDT) used by amateurs are seen in **Figure 27.46**. The photograph of a GDT shows the shape and placement of the metal electrodes. They are typically made of tungsten or some other tough metal that can withstand repeated short arcs. The schematic symbol includes a small dot next to the electrodes. This indicates the presence of gas. A proprietary combination of gases is used, along with electrode spacing, shape, and material to control the *breakdown* or *sparkover voltage*. This is the voltage at which the GDT "fires" (an arc forms between the electrodes), limiting the voltage in the feed line. GDTs are available with breakdown voltages of less than 100 V to several kV. The GDT is connected across the protected signal or feed line so it acts as a shunt-mode device.

After the GDT fires, the voltage across the arc is limited to about 10 – 15 V, depending on the model and the current level of the arc. Once the transient energy is discharged, the arc is extinguished or *quenched* and the GDT returns to an open state. As long as the maximum current is not exceeded or the electrode surfaces are not damaged, the GDT will continue to provide the rated protection.

The GDT is a type of *crowbar* protection. From the Littlefuse GDT catalog, "A crowbar device limits the energy delivered to the protected circuit by abruptly changing from a high impedance state to a low impedance state in response to an elevated voltage level. Having been subjected to a sufficient voltage level the crowbar begins to conduct. While conducting, the voltage across the crowbar remains quite low (so) the majority of the transient's power is dissipated in the circuit's resistive elements and not in the protected circuit or the crowbar itself. This allows the crowbar to be able to withstand and protect loads from higher voltage and/or higher current levels for a greater duration of time than clamping devices." A typical GDT limits the voltage across the electrodes to 15 V or so, which is well within the safe voltage range for nearly all radio equipment.

There are several types of packages as shown in the figure. The GDTs used in commercial lightning protectors for coaxial cables are removable cartridges available from the protector vendors and manufacturers. Amateur applications are considered "low to medium voltage" for rotator or antenna switch control lines and "high voltage" for feed lines. Because GDTs rarely fail shorted, they are recommended over MOVs for protecting rotator control lines.

GDTs are used in *lightning arrestors* (See the chapters **Assembling a Station** and **Safe Practices**) that are inserted in feed lines and attached to a protective ground system. The GDT is usually a cartridge-style component that can be inspected and replaced, if necessary. Because the GDT is voltage-sensitive, it is important to specify an arrestor as being rated for low-power (typically 150 W) or full-power operation.

Axial wire lead GDTs are also available for PCB and terminal-strip use. Testing a GDT requires a special *hi-pot* (short for "high-potential") tester that limits current through the device being tested for insulation breakdown. Motor rewinding shops often have this type of equipment and can test a GDT, but it is usually more cost-effective to replace the GDT if you think it has been damaged.

APPLYING GDTS

As you can see in Figure 27.46, there are many different styles of GDT packages. The *leaded* and *cartridge* packages are the most common in amateur stations. GDTs are rated by breakdown voltage and ability and energy handling ability. The Littlefuse CG-series is suitable for most amateur applications.

At RF and especially in circuits that must withstand transmitter output voltages, a cartridge style GDT is used. **Figure 27.47** shows a typical lightning protector with UHF connectors for attaching to feed lines. The GDT is connected between the shield and center conductor of the feed line, with the protector body also mounted on a grounded metal mounting bracket. Several *QST* advertisers offer these protectors for either low power or for full legal limit operation.

Because SWR affects maximum voltage in the feed line, the lightning arrestor's power rating must specify the maximum SWR for that rating. For example, the Alpha-Delta TT-series specifies power rating with a maximum SWR of 3:1. From the Alpha-Delta datasheet:

200 W models: 200 W RF at a VSWR of 3:1 generates a voltage of 173.2 volts. The gas tube in this model is rated at 350 volts.

2 kW models: 2 kW RF at a VSWR of 3:1 generates a voltage of 547.7 volts. The gas tube in this model is rated at 1,000 volts.

Don't confuse the SWR rating for power with the maximum SWR that results from inserting the arrestor in the line — that specification will be much lower.

For protecting dc or low-frequency control and telephone lines, the leaded package is the most common. These components can be connected to screw terminals or barrier strips. For rotator control lines, measure the RMS voltage from the control box and multiply by 1.414 to get peak voltage to ground. (2.8 for peak-to-peak) Add another 10-20% to provide margin and determine the required breakdown voltage.

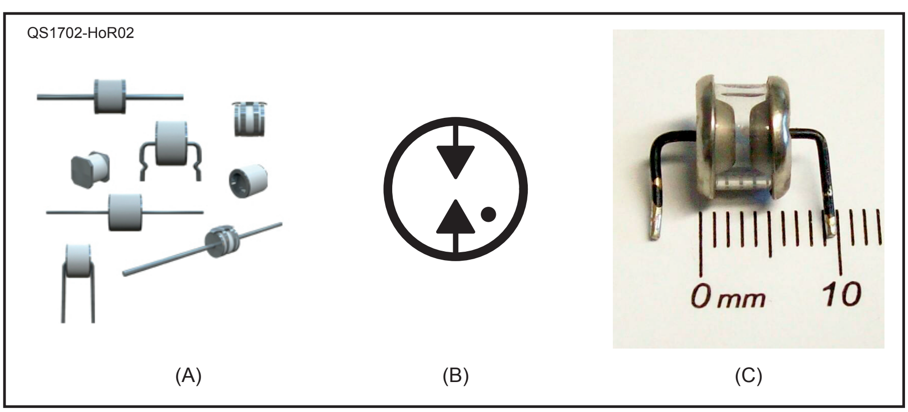


Figure 27.46 — Typical gas discharge tube components (A), the GDT schematic symbol (B), and a close-up photograph showing the electrode shape (C). (Photo provided by Ulfbastel via Wikimedia Commons)

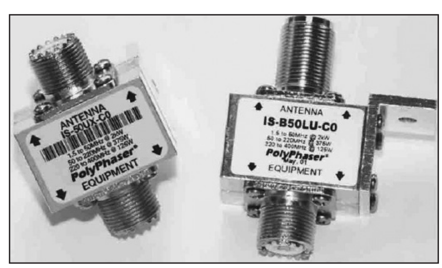
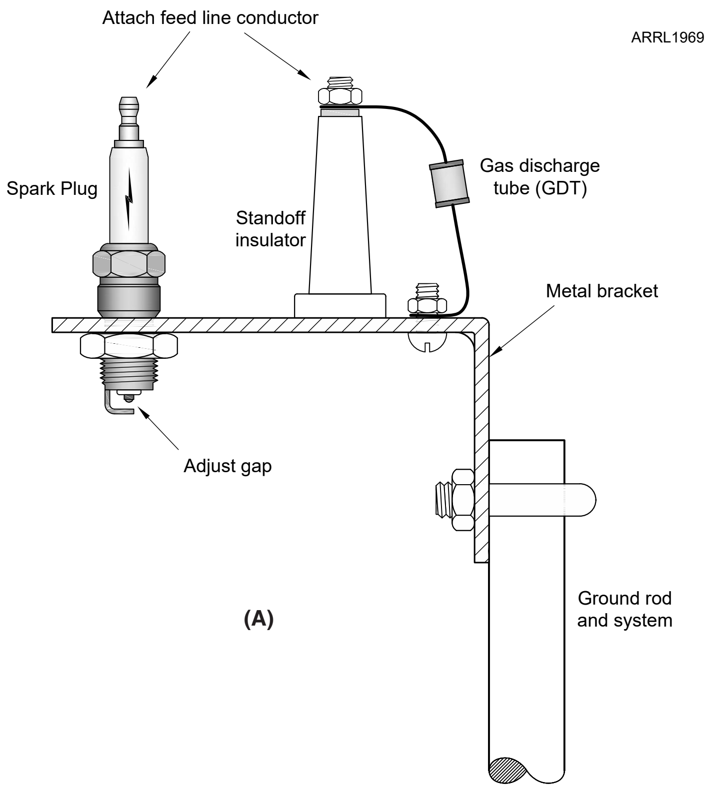


Figure 27.47 — A pair of coaxial lightning arrestors (aka lightning protectors) manufactured by Polyphaser — the IS-50UX and IS-B50LU.

Remember that telephone line ringing voltage can be as high as 150 V_{PK-PK}.

When using GDT-based protectors you must provide a good lightning protection ground system for full protection, including a lightning protection plan and bonding for all protected equipment. (See the section on Grounding and Bonding in the chapter on **Assembling a Station**.)

You should also be aware that there are two basic versions of commercial lightning protectors: one that passes dc current and one that does not. If you plan on using a remote device such as a preamp or antennas switch that requires feed line power, be sure not to purchase the dc blocking version. A call to the vendor will help you make the right choice.



(A)

(B)

(C)

Figure 27.48 — Pipe spark gap constructed by Tom Rauch, W8JI (A) and a wire-and-clamp spark gap constructed by the author (B). Spark plugs (C) can be mounted on a grounded bracket and adjusted to the desired breakdown voltage. [Photo B courtesy Tom Rauch, W8JI]

27.12.5 Spark Gaps

A similar type of crowbar device is a *spark gap* or *air gap protector*. Again, from the Littlefuse catalog, "An air gap protector consists of two conductive surfaces with spacing between them that will permit an arc when a specified potential is placed across the surfaces. The air gap is not a sealed device and therefore it must operate at atmospheric pressure and under the effects of the environment." A spark gap can also provide protection by limiting maximum voltages on towers or antennas or feed lines.

Spark gaps can be easily made from common materials and ARRL publications have many examples, including the use of automotive spark plugs for open-wire feed lines. Two examples are shown in **Figure 27.48**. Spark gaps are nothing more than metal surfaces, one connected to a ground system, that are spaced just far enough apart that normal transmit signal voltages do not cause an arc between them.

With dry air having a breakdown voltage of about 3 kV/mm, a 3 mm separation will arc over at about 9 kV. Once the arc starts, the voltage across it is very low until the current is discharged and the arc is extinguished. Be aware that the breakdown voltage may vary significantly based on the environment at the time of use, such as during rain or fog.

The spark gap in Figure 27.48A, made by W8JI, consists of a simple piece of copper pipe that is connected to a tower ground system. The pipe is positioned close to the base of the non-grounded tower section. The separation is about 1/8th inch (approximately 3 mm).

An alternate method in Figure 27.48B was constructed by NØAX and uses #2 AWG tinned copper wire. One piece of wire is connected to a listed ground clamp on the tower leg above and the other below a fiberglass insulator section. The wire position and spacing can be adjusted by loosening the clamp screws or just bending the wire.

Another option shown in Figure 27.48C is to mount a conventional spark plug or GDT across a stand-off insulator to a grounded bracket and attach the protected conductor to its top terminal with a short flexible lead. The spark plug gap is easily adjusted to the desired width using a feeler gauge. Do not use resistor-type spark plugs.

Debris or water in the spark gap will reduce its breakdown voltage. Arrange the conductors so that water flows away from the gap and does not pool or gather in the gap. Keep the gap from becoming an attractive nesting site for insects. Regular inspection and cleaning of the gap is a good idea as well.

27.13 References and Bibliography

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