WIRELESS MICROPHONES AND THE AUDIO PROFESSIONAL

by Jim Brown

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Jim Brown is an acoustic consultant based in Chicago, where he specializes in the design of large sound reinforcement systems for theaters, churches, stadiums, arenas, and broadcast facilities. He has also done extensive production work and mixing for broadcast, recording, and reinforcement. He received his BSEE from the University of Cincinnati in 1964, has worked in professional audio since 1970, and has been a full time consultant since 1984. His client list includes Wrigley Field, United Airlines O'Hare Terminal, Northwestern University's Football Stadium, Liberty University, Grace Cathedral (San Francisco), NBC, ABC, CBS, NPR, WTTW-TV, WGN-TV, and numerous churches and performance facilities. Jim is Vice-Chair of the AES Standards Committee Working Group on EMC, and is a Fellow of the AES. He earned FCC First Class Radiotelephone (broadcast) and Amateur Extra class licenses in 1959, and is active as W6BX and K9YC.

Introduction Wireless microphones have long since come of age – in fact, a case could be made that they are approaching senility! Once the dream of the wild-eyed producer and the nightmare of the audio professional, properly designed and implemented systems can now be used with excellent reliability. Unfortunately, far too many users try to get by with low cost systems, resulting in poor performance and questionable reliability under real world conditions.

This tutorial was first prepared in 1986 to educate relatively technical minded consumers as to the effective choice and use of wireless mic systems. Back in the 80's, nearly all systems operated on a single VHF frequency, all but the cheapest receivers had at least some ability to reject interference, and the best receivers were more bulletproof than anything sold today. In the intervening years, the laws of physics have not changed and the basic concepts remain as solid as ever, but some major changes have taken place in wireless mics. First, developments in technology have reduced the cost and increased the quality of systems that are "frequency agile" and which work in the UHF spectrum, as well as those for VHF operation. Second, frustration with the weak performance of inferior systems operating on poorly chosen VHF channels has fueled a shift to the previously empty UHF spectrum and generated a demand for frequency agile units. Third, expensive monitoring systems have been designed for clients with high budgets, mostly as a substitute for intelligent frequency selection. Fourth, both digital television and an increasingly crowded radio spectrum are putting the squeeze on the channels available for wireless mics. With all of these new stations on the air, and as religious broadcasters selfishly fill every available channel with their endless preaching, it has become very difficult to find reliable channels for wireless mics in many areas. Fifth, the vast majority of systems are missing the critical parts that would allow them to reject these strong interference sources. Sixth, a large group of television channels has been re-allocated to communications use, and broadcasters will eventually be moved off of that spectrum. Wireless mics will still be permitted there to the same extent that they are now, but operation may be difficult and unreliable. And finally, a serious assault on un-used UHF television channels, long the unofficial home of nearly all modern wireless microphones, is being waged by a coalition that includes Intel and Microsoft, hoping to make it a new home for ad-hoc computer networking.

A Wireless microphone system consists of a microphone connected to a miniature radio transmitter, and a receiver designed to receive only that signal. Some are fixed tuned - that is, they use a quartz crystal for determination of the operating channel. The only way to change channels is to return the receiver and transmitter to the factory and have new crystals put in. Most modern products are tunable -- they add a frequency synthesizer circuit to allow multiple operating channels from a single crystal. The receiver output is designed for connection directly to the microphone or line input of a mixing console. The radio transmitter and receiver combination acts as a replacement for the microphone cable. If all goes well, the console operator does not know that a radio link is involved.

Wireless Microphones Transmitters come in three basic packages. **Handheld wireless microphones** (Fig 1) have conventional microphone elements mounted to a handle into which a miniature radio transmitter and mic preamp are built. Several very good vocal performance microphones elements (and a lot more mediocre ones) are available on wireless transmitters from at least a dozen manufacturers.

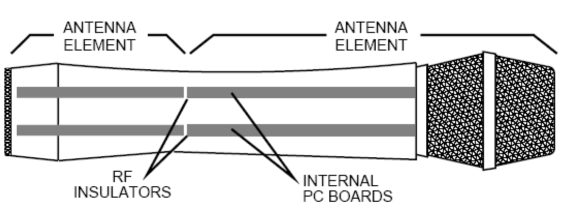

Fig 1 – A handheld transmitter

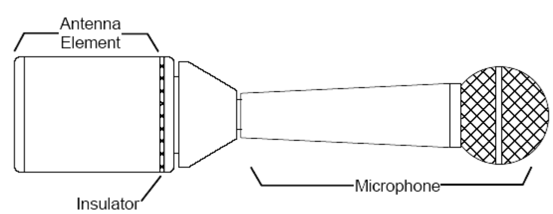

Fig 2 – A plug-on transmitter attached to a mic

Plug-on transmitters, (Fig 2) having a female XL-connector attached to a compact body that contains the transmitter, allow the greatest flexibility. Their internal battery provides phantom power to the microphone and operates the transmitter as well. A plug-on transmitter allows the use of virtually any microphone compatible with its powering circuit, as long as the mic is not so thirsty for phantom current that it drains the battery too quickly.

Body pack transmitters, (often called "lavalier" transmitters because of the mics with which they are intended to be used) allow the connection of almost any professional electret or dynamic lavalier mic. (A lavalier mic is a miniature mic designed to be pinned or clipped to an article of clothing and worn on the performer. Early lavaliers were much larger, and were worn around the neck - you've probably seen them in old TV clips.) Body pack transmitters are usually a bit larger than a pack of cigarettes, and contain the same electronics as the handheld transmitter. Non-lavalier mics and line level sources may also be used with body pack transmitters with the appropriate wiring adapters -- this can be a good way to send sound outside to an overflow system for special events.

All professional body packs are designed to provide the bias current for nearly all commonly used electret lavalier mics. The author has successfully used Sennheiser, Crown PZM, Beyer, Audio Technica, Tram, and Sony electret lavaliers with Shure, Vega, Telex, and Comtek body packs, although some models of lavalier mics are know to have RF interference problems. A given mic may need different electrical connections to different body pack transmitters. [One series of older Shure lavalier microphones is not recommended for use with wireless transmitters other than their own brand, because audio equalization was performed in the Shure power adapter for that fine mic, and the power supply is too large to be used simultaneously with the body pack.]

Wireless microphone transmitters, like all radio transmitters, are required by law to be licensed. In the United States the licensing body is the Federal Communications Commission (FCC). Only a station license is required, and it is obtained simply by filing the appropriate application with the FCC. Neither a licensed operator or a fee is required. In the US, these laws are not enforced, and the vast majority of wireless systems are unlicensed and operate illegally.

The Receiver By far, the most important single component of a wireless microphone system is the receiver. Wireless microphones should have a reliable operating range of 300 to 600 feet (100 - 200 meters) under ideal conditions, but a good receiver is required to take advantage of this range, and any interference can reduce that range significantly. The most common limiting factors in wireless microphone performance (in order of importance) are 1) Interference, 2) Reflections, and 3) Range. Wireless mics are rarely used in applications that stretch their range – interference or reflections will nearly always cause system failure first.

To understand some of the problems associated with wireless systems, we will first study Fig 3, which shows the major components of a typical wireless mic receiver. The signals picked by the antenna are sent through a broadband filter that attenuates signals far off frequency, are amplified, and fed to the first mixer. A local oscillator, followed by a frequency multiplier stage, also feeds the mixer. Operating on the "heterodyne" principle, the two signals "beat" together to produce new signals at the sum and difference of their original frequencies. The sum frequency is filtered out, and the difference signal is amplified and bandpass filtered again to remove more interfering signals. This new difference frequency is called an "intermediate frequency," or IF.

To change the operating frequency (that is, to tune in a different wireless transmitter), the frequency of the first local oscillator is changed, so that the new signal is converted to the right frequency to pass through the IF filters. A receiver that is crystal-controlled operates on a single frequency determined by what crystal is plugged into it. To change the frequency, we change the crystal. Tunable receivers use a phased-locked loop frequency synthesizer rather than a crystal; its frequency is typically changed using software or rotary switches. We'll talk more later about the advantages and disadvantages of these two types of receivers.

The heterodyne process is repeated in the second mixer. The second local oscillator always operates on the same frequency – all the tuning is done with the first oscillator. The signal is amplified and filtered some more, detected (converted to audio), and amplified to drive a mic or line level output. Why do we use these mixers to convert the signal to lower frequencies? Because those filters are the most important parts of the radio, they are expensive, and they are easier to implement at lower frequencies. They are also quite expensive to re-tune, so we set them to a single frequency and convert all of the signals we want to receive to that same frequency.

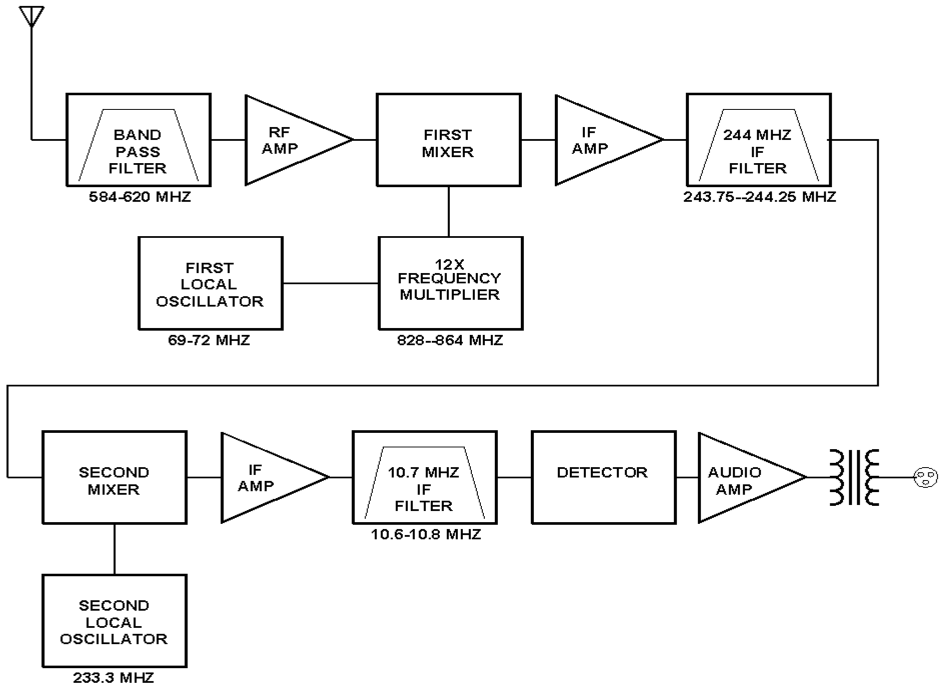

Fig 3 – Signal flow in a typical low-cost UHF wireless mic receiver

That first filter and RF amplifier after the antenna are called the "*front end*," and are critical to the performance of the receiver under the strong signal conditions that are so typical of most cities. If the *front end* is done well, the system will work well under all conditions. If it is done poorly, the receiver will be easily overloaded by nearby TV transmitters, prone to intermod and other interference, and may also do poorly with weak signals. We'll talk a lot more about these issues a bit later on.

Antenna Systems Getting the right antenna in the right place, and connecting it properly to your wireless receivers can do a lot to give your systems greater range and better reliability. Antennas should always be located close to the transmitter (i.e., the performer's mic). This gives the maximum pickup of the radio signal from the performer. Antennas should also be as far as possible from sources of interference -- other radio or TV equipment, computers, digital equipment, light dimmers, fluorescent lighting fixtures, etc. And, in general, antennas for wireless mics should NOT be high in the air -- all that does is increase the likelihood of overload and other interference from TV stations and other transmitters outside your building!

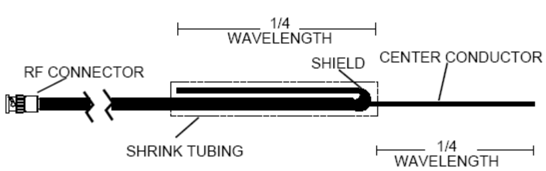

Fig 4a - This general purpose antenna is approximately omnidirectional

Figs 4a and 4b show two types of antennas that can work well for wireless microphone reception. It is generally a good idea to locate the wireless mic receiver close to the console operator, so that he or she can monitor the signal strength and be alerted to problems. In this arrangement, the best approach is to place the antenna close to the

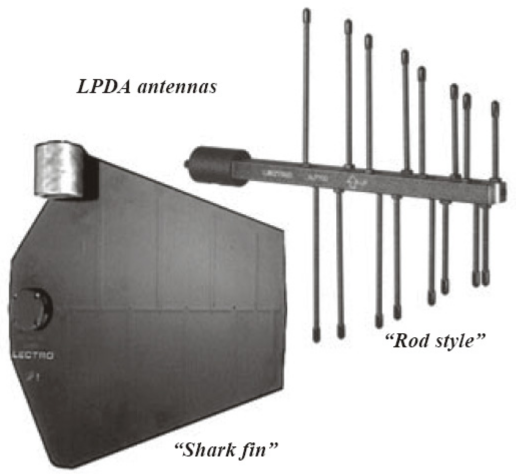

Fig 4b – Directional antennas can increase the range and reduce interference

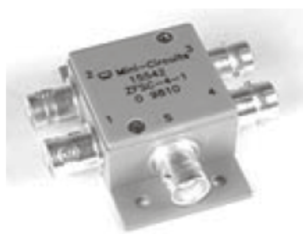

Fig 4c – A high quality passive antenna splitter

performer, and extend it to the receivers by means of good quality, low loss coaxial cable. If there is more than one receiver, use a good quality passive (non-amplified) splitter. We specify the Mini-Circuits Labs ZFSC-4-175 (718/934-4500), www.minicircuits.com, and Belden 1505A or 9100 coaxial cable. This combination will provide very good performance for cable runs of up to 200 ft and at all frequencies up to and including television channel 69. A slightly larger (RG-6) cable, Belden 1223A or 9114, will get you up to 300 ft, and an even larger one, Belden 9011, offers the lowest loss and can help with longer runs.

<u>What does all this "RG" stuff mean?</u> RG cable specs go back to military electronics in the first half of the 20th century. RG-58/U is a .2" o.d. 50 ohm cable, RG-59/U is a .24" o.d. 75 ohm cable, RG-8 is the "big" 50 ohm cable (0.4" o.d.) and RG-11 is the "big" 75 ohm cable. Later, RG-6 a slightly oversized 75 ohm cable, has become quite popular because it provides premium performance but is only slightly larger than RG-59/U. These RG-specs cover a VERY broad range of cable types. There are hundreds of RG-59 cables, some of which are optimized for video, some for low power RF, some for high power RF, some for computer data, etc. RG-59 simply defines coaxial construction, the 75 ohm impedance, and the approximate size (and even the size varies).

<u>50 Ohm or 75 Ohm Cable?</u> It has been common practice for wireless mic systems to be sold and used with 50 ohm coaxial cables. While there is nothing inherently wrong with 50 ohm cable, 75 ohm cables offer <u>far</u> better performance at <u>much</u> lower cost. Some users mistakenly believe that wireless systems are better matched to 50 ohm cable, and that they must use 50 ohm cable to prevent an impedance mismatch. In practice, this is not the case. Real world receivers vary widely in input impedance -- all that most engineers who design these systems can tell you is that they are somewhere in the 50-75 ohm range. The same is true of the antennas themselves -- their impedance is strongly affected by surrounding objects and varies with frequency. So a real world system is just as likely to be well matched to 75 ohm cable as it is to 50 ohm cable. More important, the TV antenna and cable industry have standardized on 75 ohm cables, making the quantity and quality of these cables much higher, and their prices much lower for equivalent quality.

Engineers studying transmission lines in school learn that "a high standing wave ratio increases the loss in a transmission line" and that losses will degrade the signal to noise ratio. While this true, what these textbooks fail to tell you is how <u>slight</u> this degradation is! The Handbook of the American Radio Relay League shows that even in a cable with 10 dB of loss, a 75:50 ohm mismatch will increase the loss by **<u>less than 0.2 dB, and the greater the matched loss, the less the mismatch causes the loss to increase</u>**!

<u>Which coax for wireless mics</u>? Table 1 shows <u>loss</u> and <u>cost</u> data for the <u>best</u> 50 and 75 ohm MATV cables I know of, in dB/100 ft. Prices are typical for a 1,000 ft spool from an industrial electronics vendor. (***Remember that cost is an important engineering parameter!***) And even if there is some mismatch, the extra loss it causes is much less than the advantage the 75 ohm cables start out with!

Cable	1000 ft	Diam	Impedance	200 MHz	500 MHz	700 MHz
Belden 9100 (RG-59/U)	$93.50	.237"	75 ohms	3.5 dB	5.6 dB	6.7 dB
Belden 9114 (RG-6/U)	$105	.27"	75 ohms	2.7 dB	4.35 dB	5.2 dB
Belden 9011 (RG-11/U)	$195	.40"	75 ohms	1.7 dB	2.75 dB	3.25 dB
Belden 9310 (RG-58/U)	$267	.193"	50 ohms	5.4 dB	9 dB	11.1 dB
Belden 9258 (RG-8X)	$300	.242"	50 ohms	4.5 dB	7.2 dB	9.1 dB
Belden 9913F (RG-8/U)	$774	.405"	50 ohms	2.0 dB	3.2 dB	3.9 dB
Times LMR195 (RG-58)	$320	.195"	50 ohms	5.2 dB	8 dB	10 dB
Times LMR-240 (RG-8X)	$440	.240"	50 ohms	3.5 dB	5.7 dB	6.8 dB
Times LMR-400 (RG-8)	$530	.400"	50 ohms	1.8 dB	2.9 dB	3.5 dB

Table 1 – Loss in dB/100 ft of some excellent RF coaxial cables

Reflections VHF and UHF radio signals are reflected by any metal objects in our environment. It is common for a direct signal and many reflections to be present at any VHF or UHF antenna. When these signals are precisely in phase and in polarity, they add together and all is well. If they are out of phase, significant cancellations can occur, causing distortion or noise. If they are exactly 180 degrees out of phase, in polarity, and nearly equal, there is almost perfect cancellation! The exact phase and polarity relationships between the reflections and the direct wave will vary with the travel time (and thus the distances) between the transmitter, the reflecting objects, and the receiving antenna. A performer using a wireless mic may move into and out of spots where cancellations occur. These reflection zones will be heard as distorted sound or noise bursts. If the performer is moving rapidly, the bursts will be short. If he or she moves slowly, they may move into a reflection zone and stay there! Note that these are not dead spots - there is plenty of signal, but most of it is out of phase and cancels itself out!

Diversity Reception An effective solution to the problem of phase cancellation was developed during the 1930's when such fading (caused by multiple signals over varying long paths) plagued international short wave radio transmissions. Two receivers, connected to two different antennas were used, and the operator listened to the one which received the clearest signal. This combination of two receivers and two antennas is called diversity reception. Selection of the cleanest signal is now done silently and automatically by the receiver in a circuit called a "voter". Such systems are sold in this country by Vega, Micron, Shure, Sennheiser, and Sony (Fig 5a).

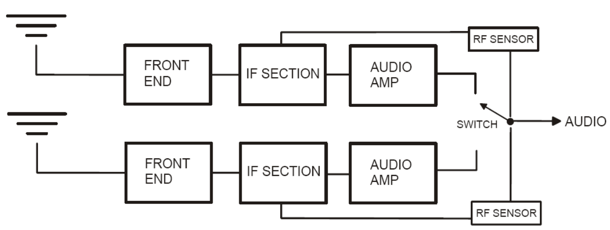

Fig 5a – True diversity with simple switching

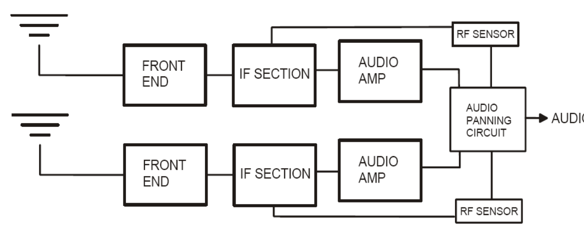

Fig 5b – True diversity with outputs combined

Lectrosonics uses an innovative method of combining the receiver outputs that provides more transparent operation, and allows the two receivers to be summed if signals are marginal (Fig 5b). This can improve weak signal performance by 3 dB, because the detected audio will add coherently, while the noise will not. The ratio of the mix is varied, favoring the receiver having the best signal to noise . Lectrosonics sells yet another variation, also shown diagrammatically in Fig 5b, that uses two transmitters (on two different frequencies) with a separate receivers for each frequency. Since their wavelengths are different, it is unlikely that a null caused by a reflection will affect both frequencies simultaneously.

A lower cost, and somewhat less effective, solution is called "switched antenna diversity". In this system, two antennas are connected to a single receiver through an electronic switching network. When a weak signal is encountered the receiver tells the switch to try the other antenna in the hope it will be better. One problem with this method is that the switcher can get overloaded, resulting either in desense or intermod. We don't like this method of diversity reception.

An interesting variation of switched antenna diversity is switched polarity diversity (Fig 5c). Reflections only cause dropouts when the two RF signals are at nearly equal levels and almost exactly 180 degrees out of phase. On a single radio channel, a polarity reversal of one of the antennas will turn that cancellation into nearly perfect addition. Lectrosonics uses this system in some of their more compact receivers, like those designed to mount on video cameras.

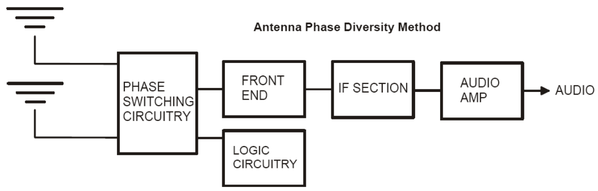

Fig 5c – Switched-antenna-polarity diversity

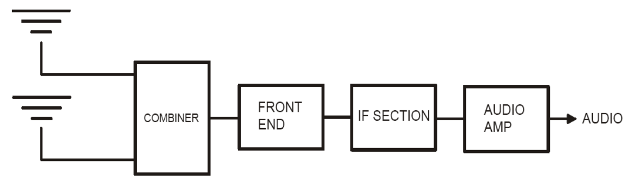

Fig 5d – Multiple antenna diversity

A very low cost method of dealing with reflections is "multiple antenna diversity." (Fig 5d) Two or more antennas are passively combined into a single receiver, and it is hoped that the statistical probability of cancellation occurring with these multiple antennas will prevent the problems associated with reflection zones. While not as effective as diversity reception, it can sometimes reduce cancellations due to reflections to the point that performance is satisfactory, and it is certainly a cost effective method. This method can also work well when talent will work in two widely separated areas, each covered by its own antenna.

Frequency Selection Professional wireless microphone systems have traditionally operated in five portions of the frequency spectrum. In all cases, these channels are shared with other services. *The single most important factor in good wireless system operation is how well this sharing arrangement works out.* Since wireless mics are, by law, always secondary users of channels, they must, by law, accept whatever interference occurs, and not cause any. (Because of their very low transmitter power it is rare for wireless mics to cause interference to other services - I have never heard of wireless mics interfering with anything but another wireless mic.) *It is common, however for wireless mics to receive interference, and finding channels where that interference will not occur is the key to good wireless mic system performance. This is called frequency coordination.*

Low band VHF channels in the spectrum between television channels 4 and 5 (72-76 MHz) are allocated to wireless microphone use, but one of the sharing services here is common carrier paging systems. If a paging system is on your channel (or later lands there), your wireless system will hear lots of beeps, squalls, and ratchety sounding trash. The other problem with these channels is interference from computers, other digital equipment, and fluorescent lighting. *For all of these reasons, these channels can be problematic.*

A handful of high band VHF channels in the 150 - 174 MHz range are legally available to wireless mic users. Many of these channels are shared with commercial two-way radio services in nearly all cities and towns, and have little use for wireless mics. Others are channels shared with government services at locks and dams. Since there are not many locks and dams near most wireless mic users, this sharing arrangement often works well. These are the so-called "hydrological" channels, and are in the range between 169 and 172 MHz. Good receivers are required, however, because 2-way radio transmitters are very close in frequency and Channel 7 television (with much more power) is not far away. When no interference is present, these channels work well for wireless mics. The downside of the hydrologicals is that many wireless systems have been sold for only these few channels, so the chance of touring performers bringing in a system on your channel is greatly increased. *In general, these channels can be problematic unless you will be using them "in the middle of nowhere."*

Certain professional users of wireless microphones (broadcasters, and producers of programs for television and motion pictures) are permitted to operate wireless systems on High band VHF television channels (7-13) that are unused in their area. Choice of frequencies for wireless mics in this spectrum should be performed in conjunction with the frequency coordinator of the local SBE (Society of Broadcast Engineers) chapter. *Because this frequency spectrum is relatively free of interference, these channels are often good for wireless mics. One caution though -- hospitals are full of instrumentation that uses these channels to transmit patient telemetry to a central nurse's station.*

The same class of pro users who are entitled to use the VHF television channels are also permitted on unused UHF television channels (14-69). Over the past fifteen years, these channels have become quite popular with wireless mic users, and the majority of new systems operate on these channels. It costs a bit more to manufacture equipment that provides good performance at UHF, so these systems tend to be a bit more costly than equivalent VHF systems, and they tend to have higher battery drain for equivalent performance.

A few years ago, television <u>channels 60-69</u> were allocated to use by both commercial and government entities for two-way radio communications. This means that if there is no television station assigned to a given channel in your area, there may be two-way radio systems (police and fire dispatchers, trucking companies, bus companies, plumbers, etc.) on that channel. These new two-way systems will come on the air slowly over a period of years, more each year until each channel is full. The greatest impact will be in and around larger cities. Many early UHF wireless systems used these channels, and some manufacturers are still selling their stock of wireless systems manufactured for these channels to unsuspecting users, who will someday be in for a sad surprise.

A few fearless (and misguided) manufacturers have begun manufacturing systems that operate in the 2.4 GHz band that is also used by many general purpose radio systems including 802.11b networking (WiFi). Most, if not all, of these manufacturers use spread spectrum digital transmission. While spread spectrum techniques claims good coexistence with other interfering signals, the more systems of this type that are in use, the greater will be the interference between them. At least one of these systems is "not nearly ready for prime time." The vendor promises flawless interface to anything from lavalier mic elements to a guitar output, but audio performance doesn't even begin to live up to data sheet promises -- it varies from "kind of ok" to awful. *The 2.4 GHz band is a poor choice for wireless mics if WiFi systems and other consumer equipment are used within a thousand feet of so of your receivers.*

Some very low priced wireless microphone systems operate in the 49 MHz band, where they receive interference from cordless telephones, garage door openers, and other consumer devices too numerous to mention. They are also susceptible to interference from CB radio operators. Others allow you to tune them to an open spot on the FM broadcast band. *Such systems are unreliable and of poor audio quality, and should not be considered for any serious use.*

<u>The TV broadcast spectrum</u> Because the vast majority of wireless mics operate on unused TV channels, we'll use a spectrum analyzer to study how TV stations use their assigned channels. Fig 6 shows how eight UHF TV channels look at the end of a long piece of coax connected to my roof-top TV antenna.

<u>Understanding The Analyzer Screens</u> The horizontal axis is frequency (the analyzer is set for 4.8 MHz/div), and the vertical axis is signal strength. The top of the screen is set to 2 mV. The analyzer is hooked to up an antenna on the roof of my home (about 7 miles from the transmitters), and is tuned to look at TV channels 27-34. Here in Chicago, Ch 27 is unassigned, Ch 28 is analog, Ch 29 is digital, Ch 30 is unassigned, Ch 31 is digital, Ch 32 is analog, Ch 33 is unassigned, and Ch 34 is a low power analog station.

Understanding television broadcasting With analog television (the old system that most of us still watch when we're too tired to do anything useful), nearly all of the transmitted energy is concentrated around three frequencies for each channel -- the picture carrier, the color sub-carrier, and the sound carrier. TV channels in North America are 6 MHz wide. The picture carrier is 1.25 MHz, ± 10 kHz, from the lower edge of the channel, the color sub-carrier is 3.58 MHz above that, and the sound carrier is 4.5 MHz above the picture carrier. Most of the power from the video transmitter is concentrated in the lower half of the channel, and especially around the video and color carriers. Fig 8 shows these relationships.

Digital television is quite different – the energy is distributed almost equally throughout the channel. So when intermod products are produced, they also spread over entire channels. The result is broadband hash that will drastically reduce the range of wireless systems if it is strong enough. It may not sound any different from the noise that appears between stations in any radio receiver, but because its a lot stronger, it will reduce the reliable range of wireless mics. Fig 7 shows a digital channel.

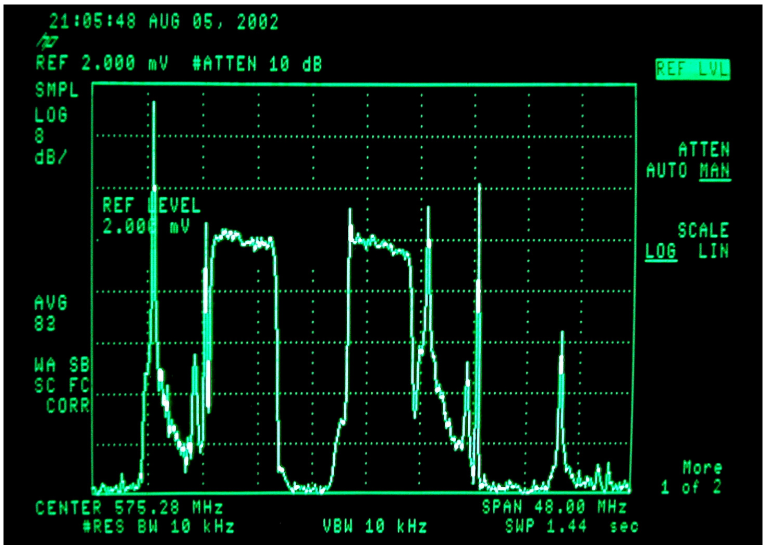

Fig 6. This spectrum analyzer's view of eight UHF TV channels clearly illustrates the nature of the interfering signals that a wireless mic system must compete with. Three analog TV stations and two DTV stations are transmitting in the eight TV channels shown in this scan. Five years ago, those digital transmitters weren't on the air!

In most localities, all (or nearly all) digital TV stations have been assigned to UHF channels, because nearly all existing VHF channel assignments were used up many years ago. This means that new and existing VHF systems are unlikely to be affected by digital television systems, and may even be the most reliable in the near future.

How much power is in these signals? The transmitter for the analog picture carrier has an effective radiated power of 3 Megawatt (3 Million watts), while the sound transmitter is 750 Kilowatt (6 dB less). Opening up the spectrum analyzer bandwidth to 3 MHz reveals that the total power in the digital signal can be comparable to that in the analog signals! We say it can be because many broadcasters are running their DTV transmitters at less than full licensed power to avoid interference to adjacent analog channels.

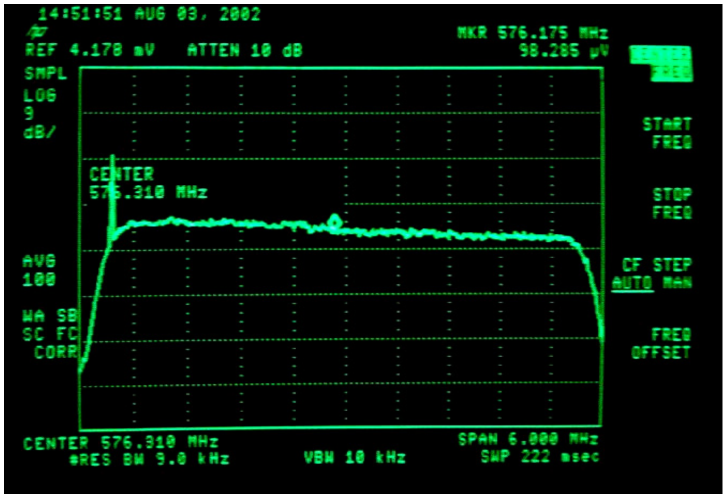

Fig 7. A 6 MHz wide view of one digital TV signal. The digital TV stations (Ch 29 and Ch 31 in Fig 6) show up as a flat trace that exactly fills their assigned channels. The high spike at the left of each DTV station is a pilot signal. Thus the digital station's power is spread equally throughout the channel.

[Effective radiated power is the transmitter's actual output power multiplied by the directivity gain of the antenna and divided by the loss in the feedline. TV transmitting antennas are highly directional vertically -- they concentrate their power in the horizontal plane (that is, relatively little signal goes straight up or down), but are usually not directional horizontally (that is, they radiate equally to all azimuths). Antenna gains are on the order of 0-18 dB.]

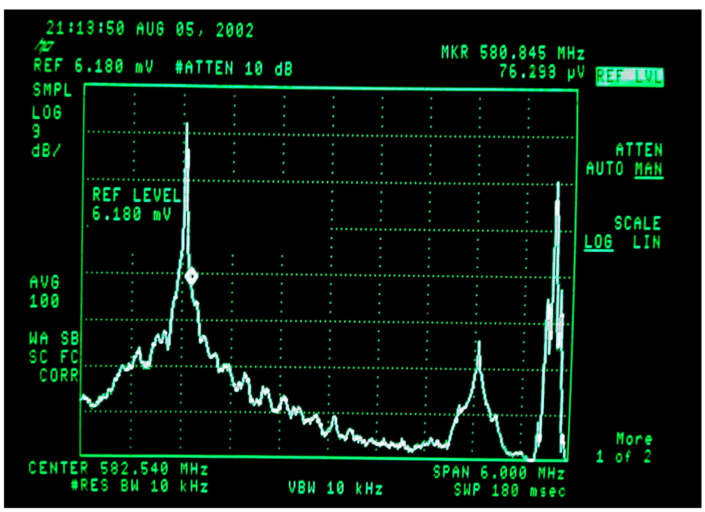

Fig 8. A more detailed view (6 MHz wide) of one of the analog signals. There are two strong spikes (their picture and sound carriers), with energy concentrated relatively close to those carriers. The tall spike at the left of the trace is the video carrier, with most of the power concentrated in sidebands relatively close to it. The tall spike at the right of the trace is the sound carrier. The bump to the left of the sound carrier is the color sub-carrier with its associated energy.

Why Wireless Mics Don't Work Well in DTV Channels

The picture carrier of the analog station is producing about 30 mv at my antenna, while the digital station's signal is giving me 2 mv throughout its channel. Doing the arithmetic, a 1 MW transmitter is putting 8,300 watts **within every 50 khz piece of the channel!** What this means in practical terms is that my 10 mw wireless mic is trying to compete with a TV transmitter on a tall building that is 830,000 times more powerful, giving the TV transmitter an advantage of 59.2 dB!

Ah, you say, but our wireless mic is much closer to our receiver. So even though the TV transmitter is so much more powerful, inverse square law (the dispersion of transmitter power with distance) will weaken the signal from that big transmitter enough that my wireless mic can be heard over it. And if the wireless receiver is inside a building with a lot of metal in its shell, the TV transmitter may be reduced in strength by a factor between 10 and 100 (10-20 dB). Sometimes these factors can be enough to allow things to work. But remember -- that broadcast transmitter is working into a very good antenna that is high and in the clear, while the wireless mic, uses a tiny antenna, much of whose radiation is soaked up or blocked by the body of the person wearing it!

So, most of the time, guess who wins? The answer is that unless the wireless transmitter is very close to its receiving antenna, the TV transmitter will override it, and all we'll hear is digital noise. So in practical terms, the DTV transmitter severely limits the working distance of the wireless system, often to 25 feet or less.

More to the point, how can we help our wireless transmitter win? We can: 1) put the receiving antenna closer to our transmitter; 2) use a more powerful wireless transmitter (if the FCC allows it and if we can get enough battery life at the higher power level); 3) use a directional antenna that points toward our transmitter and away from the DTV transmitter; 4) move our wireless system to a channel where there is no interference. In most real world situations, #1 or #4 are the most practical solutions.

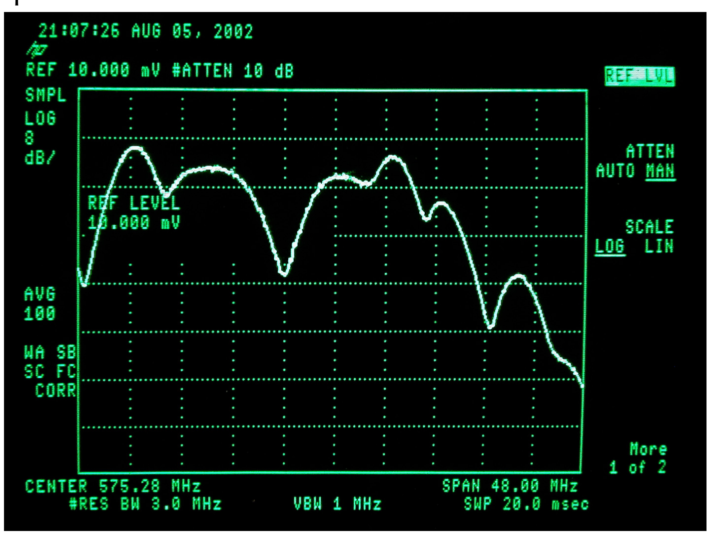

Fig 9 The same eight channels of Fig 6, but with the analyzer bandwidth set to 3 MHz.

Tunable Wireless Systems Frequency synthesizers offer an alternative to the quartz crystals used to set transmitter and receiver operating frequencies of older wireless systems. Rather than being locked into a single frequency determined by the quartz crystal in the transmitter and receiver, the synthesizer (which also uses a single quartz crystal) may be set to produce any of up to several dozen operating frequencies. The user may tune the system just like a modern digital FM tuner.

On the surface, this would appear to be the greatest thing for wireless mic operation since sliced bread. There is, unfortunately, more to getting these systems to work well than meets the eye. Careful frequency selection requires avoiding those channels where intermod products can render the systems unreliable. Synthesized systems don't always allow enough frequency choices to avoid intermod, especially when a lot of wireless systems are in use, or when the systems are used in a very difficult rf environment.

Most users are not aware of the problem until they run into interference and change one system's channel to avoid interference. What they may find is that the problematic system is now clean, but another system (or even several other systems) are now experiencing intermod caused by the transmitter they changed! We'll talk a bit more about intermod and how to predict it later on.

Synthesizers also create spurious responses (birdies), usually at frequency spacings that are equal to increments in which the system can be tuned (that is, a transmitter or receiver whose frequency can be adjusted in 100 kHz steps will probably put out trash at 100 kHz steps. Frequency synthesizers also produce a form of broadband noise called phase noise.

Battery life is the Achilles heel of tunable wireless systems, both for the transmitter and for battery-operated receivers. It is not uncommon for half of the total drain on the battery to be needed to run the frequency synthesizer circuitry! Crystal-controlled oscillators are far more efficient, so the battery life of a crystal-controlled transmitter will be nearly double that of a synthesized transmitter with the same transmit power.

The other key factor affecting battery life in transmitters is the output power. Government regulations (the FCC in the US) establish the maximum allowable output power of wireless systems at 50 mW in VHF TV channels and 250 mW in UHF TV channels. Radio systems follow inverse square law, so all other factors being equal, the range of wireless systems will increase by 1.414 when the transmitter power is doubled.

Batteries are rated in Ampere-hours (Ah) or milliAmpere (mAh) for a specified rate of discharge. Batteries are manufactured that utilize many different chemical processes, each optimized for a different purposes. A battery that backs up the BIOS for a microprocessor may need to supply only a few nA, but must last five years. So-called "standard" batteries for flashlights and radios use a carbon-zinc process, while alkaline batteries offer significantly high capacity. Both of these types have individual cell voltages on the order of 1.55 V when fully charged, decaying to about 1 V when discharged. Most rechargeable types have a much lower terminal voltage (1.2-1.3 V) at full charge, but the voltage stays much closer to that initial voltage until the battery is fully discharged.

Most users feel that 5 hours is the minimum acceptable battery life for a transmitter; that interval will get you through nearly any performance, sporting event, and even a half work day before lunch. Battery size and output voltage are also important, and most manufacturers have settled on the standard 9 volt NEMA battery. Rechargeable batteries are available in AAA, AA, C, and D configurations with excellent capacity – some as great as a non-rechargeable alkaline! Unfortunately, this is not true of the 9V NEMA battery – at the time of this writing, the capacity of rechargeable 9V batteries is significantly less than for alkaline batteries.

Wireless microphone manufacturers understand these issues, and design their equipment to work well with batteries that are widely available. A well-designed synthesized VHF transmitter should be able to achieve 8 hour battery life at the US-maximum 50 mW output, even when running with a synthesizer. UHF is another story, both because UHF transmitters are inherently less efficient, and because in the US, the FCC's maximum permitted power is more generous. Manufacturers have generally chosen to use transmitter powers between 30 mW and 50 mW so that batteries will last longer. Most Lectrosonics UHF transmitters produce 100 mW.

So summing up our discussion of tunable wireless systems, we see that 1) they drastically reduce battery life, 2) they create noise and interference that reduces their range, and 3) they require that we operate the transmitter at lower power to achieve acceptable battery life. As we will learn later when we discuss frequency coordination and the prediction of intermod and other spurious products, they also make the coordination of interference and intermod very difficult.

Interference If interference (that is, another radio transmitter or noise generated by computers or machines) is on your channel, even the best receiver cannot make your system work well. You must either eliminate the interference or change to a new channel. If the interference is close to, but not precisely on, your channel, the ***selectivity*** of the best receivers can help your transmitter thread its way through interfering signals. This is done by tuned circuits and in the best receivers, multiple helical resonators (miniature cavities that act like super-sharp tuned circuits). ***Selectivity*** is the ability of a receiver to separate your signal from others on different frequencies (channels) near your chanel.

When the going really gets tough and a very strong interfering signal is present (like a two-way radio transmitter on your block or a broadcast TV tower within a few miles), another receiver problem shows up. That first electronic section of the receiver, called the "front end," is designed to amplify (boost) the very weak signals of a wireless mic and separate it from interference on nearby channels. When presented with a very strong signal, it can be overloaded and stop working properly. One common phenomenon, called "***desensitization***", or "***desense***", occurs when the strong signal gets rectified in the RF amplifier and actually turns that amplifier transistor off. When this happens, the receiver almost stops working -- the desense acts like a gain control being turned all the way down, and shuts down the signal path! An indication of this problem is fading that occurs with the transmitter at much shorter than normal distances even though no interference is heard. These are non-destructive failures – as soon as the strong signal goes away, the receiver will resume working properly.

Computers and digital audio equipment often produce enough radio trash to seriously reduce the range of wireless mic systems. This interference can take the form of a single carrier frequency, broadband noise, or both. This equipment won't cause your receiver to go into overload, but the part of that trash that is on your channel will sound like noise, and will reduce the range of your wireless system.

Intermodulation Interference is the result of the mixing (also known as heterodyning) of two or more strong radio signals to produce radio signals on other radio channels. If one of these new signals (called intermod products) ends up on one of your wireless channels, it interferes with that wireless mic system. This intermodulation can occur in transmitters, receivers, and other radio equipment. It can even occur in nearly any metallic objects that can act like an antenna to pick up and receive these radio signals, and that have a poor electrical connection capable of rectifying these signals. And your own wireless transmitters are part of the interference mix!

What this means in practice is that if there are strong signals around your area, they can be rectified in objects like metal downspouts, building steel, rusted metal, etc., producing interference on your radio channel. Luckily the channels on which these intermod products can occur are predictable using classical (but tedious) mathematics. Computer programs are available that can be used to predict when interference can occur so that those frequencies may be avoided. Comtek has one on their website, and there's a simple one on my website in the form of a spreadsheet that illustrates the principles.

Intermodulation can also occur in your receiver (or an active antenna splitter) when it is overloaded. In this case, the front end becomes the mixer, with new interfering signals being produced by the receiver or amplifier that did not come in on the antenna. Indeed, it is quite common for any transmitter, including a wireless mic, to produce intermod when it is very close to another transmitter. Professional transmitter installations include a part called a *circulator*, installed between the transmitter and the antenna, whose function is to trap incoming signals so that they cannot produce intermod. Some "top of the line" Lectrosonics transmitters include a circulator!

But intermod is only part of the problem. There are other ways in which inadequate receiver design can allow interference to occur. Those local oscillators, and their harmonics, can leak out, mostly through the antenna jack, but also due to poor shielding. If they are on the frequency of another wireless system they can cause interference to it. And even if they stay inside the radio, they can allow "spurious responses" (that is, you can hear other stations you're not tuned to). When you realize that interfering signals can include television transmitters operating at 5 MW with an excellent antenna and the wireless mic you are listening for is using only 50 mw with a very inferior antenna, it is obvious that spurious responses of 80-100 dB below the desired signal can still cause problems.

Dealing With Overload Receiver overload problems can often be solved by reducing the signal presented to the receiver. This may seem like a contradiction - how do you improve performance by attenuating the signal? Well, remember that performance is rarely limited by system range, but rather by interference and reflections. An RF pad (attenuator) of 6 - 10 dB will often get a receiver below the overload point without letting the desired signal fall into the noise. Pads are readily and inexpensively available from your local MATV (master antenna television system) supplier. I also see them at hamfests. They come in the form of a barrel of about 0.33" o.d., usually with F-connectors on either end, and are designed for 75 ohm systems. More professional quality units have BNC connectors and are mostly designed for 50 ohm systems. Impedance makes a difference for measurements, but the difference for our purposes is insignificant. In the example that follows, we'll show how a long run of coax can attenuate interference while holding the strength of our desired signal nearly constant.

Getting Antennas Closer to the Transmitter – A Practical Example (Fig 10) Let's say we've got a mix position that's 100 ft from the stage, we want to move our antennas from the mix position to a point that's only 20 feet from the stage, it takes 150 feet of coax to get from the antenna to the mix position, and that we're working at about 600 MHz. Belden 9114 will burn about 7 dB, a 1x4 splitter will lose another 7 dB, for a total loss of 14 dB. But because the antenna is only 1/5 the distance, we gain 13 dB, so the receivers get only 1 dB less signal than before. And any interference is reduced by that same 14 dB, so we have a 14 dB improvement there. Not only that, but the digital equipment at mix positions (and in equipment racks) will often generate a lot of RF noise that interferes with wireless mics. Just by moving the antenna away from all that mess we are likely to help performance even more! What did this cost us? Well, there's $250 for the cable the splitter, and some connectors, we save the cost of three antennas, and we add the labor to pull the cable and install the connectors. Under $400, including labor, and because it's all passive, there's nothing to fail! And we've improved our freedom from overload by 14 dB!

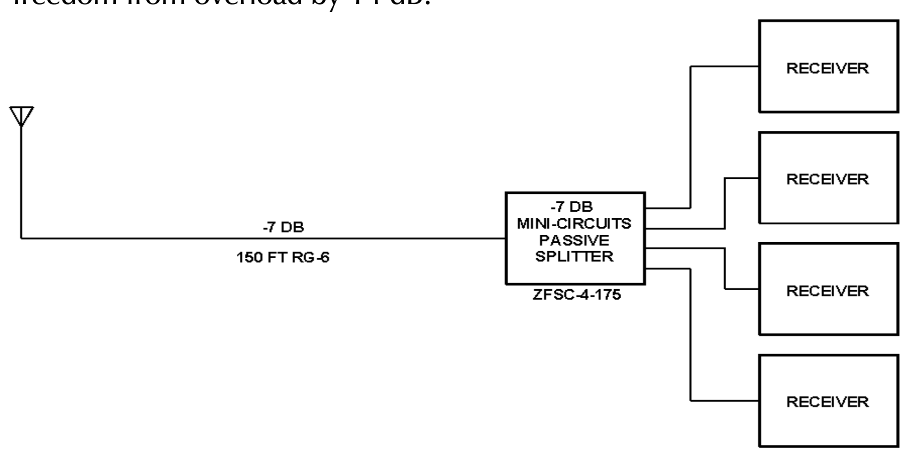

Fig 10 Moving the antenna closer to the talent puts 13 dB more signal at the antenna, but we lose 7 dB in the coax and 7 dB in a passive splitter for a net loss of 1 dB. But any TV interference (including overload or desense that it causes) is reduced by 14 dB!

How Does DTV Affect Intermodulation and Receiver Desensitization?

The answer to this question relates to the bandwidth of the input stage. If the input stage is broadband and includes the interfering signal, the total signal strength of a DTV signal integrates (sums) to be almost exactly equal to the total strength of what an analog transmitter would produce. This is because the broadband input stage sees all of the input voltage within its bandwidth and adds it together.

To reduce the overload of the input stage, we must reduce the voltage it sees. One way to do that is to attenuate (weaken) all signals (with a broadband attenuator, called a "pad"), but that will also attenuate our signal in the process. If we still have enough of our own signal, that's a reasonable solution. But that isn't always the case, especially with very strong interfering signals.

The other way to eliminate or reduce overload is to use a sharply tuned filter that allows the wireless transmitter to come through but attenuates signals on other frequencies. In other words, the receiver must be tuned to receive only the desired channel and reject other channels. Since the earliest days of radio, these tuning circuits have been critical parts of receivers, and the technology to implement them is well developed.

Over the past decade, many radio and TV receiver manufacturers, in the quest for cheaper and more compact products, have been leaving out these important components. In other words, they are selling an incomplete product, one that is missing some critical parts. If you don't use their product to listen to low power or more distant transmitters close to high power transmitters, you may never notice that the parts are missing. But if you try to listen for those small transmitters (the public stations on the FM band, for example, or those from out of town), you won't hear them -- instead, you'll hear only the big local transmitter(s) or noise.

So how much signal is hitting our wireless receiver? According to FCC data, a full power transmitter (100 KW) at 1,000 ft on channels 2-6 will generate 1.26 Vm at 1 mile for a receiving antenna at a height of 30 ft; for channels 7-13 (316 KW) the field strength is 2.24 V/m; and for channels 14-69 (1 MW) it is 3.98 V/m.

Multiple radio frequency signals combine according to the square root of the sum of the squares of the individual voltages (RSS). In a typical large US city (Chicago), the combined field strength at one mile from the two analog and one digital transmitters on "low-band VHF" channels 2-6 is 2.2 V/m; for the three analog transmitters on the "high-band VHF" channels 7-13 the total is 3.9 V/m; and for the eleven analog and nine digital UHF transmitters (channels 14-69) the total is 17 volts/meter. The combined field strength of those five broadcast signals in our spectrum analysis example is about 7 volts/meter.

TV transmitting antennas But that's only the simple analysis. An important set of "real world" fact saves us, especially on the UHF band, where transmitting antennas are highly directional in the vertical plane. Sound system designers will be able to relate to how they work – they are the radio equivalent of a simple line array like the Bose MA12 (or even two Bose MA12's stacked). Fig 11 shows several types of high gain antennas used by VHF and UHF television transmitters, and Fig 12 shows the vertical directivity of one of them.

Fig 11 – High gain antennas used by TV transmitters

So those field strengths in volts/meter were computed assuming no antenna gain, and at the elevation of the antenna. In most cities, including Chicago, they are at least ¼ mile in the air, and, the antenna system used by UHF stations is extremely directional in the vertical plane –

all the radiated power is in a narrow beam that is only a few degrees wide. Why is this done this way at UHF, and why is it not done at VHF?

Two important reasons. First, to transmit a clean TV picture with good detail, the total amplitude and phase response must be "flat," just like in audio. To achieve this, the response of the 6 MHz-wide radio channel must also be flat. It is easy to achieve flat response with a high gain antenna over a percentage bandwidth of only 1% (6 MHz on TV channel 36, 602-608 MHz), but quite difficult for TV channel 2 (54-60 MHz) where the bandwidth is 10%. In fact, the peaks and dips in Fig 12 will also translate into the frequency domain as peaks and dips. So antennas for channels 2-6 tend to use antennas with very little vertical gain – 0 to 3 dB is typical. The high-band VHF channels are somewhere in the middle – the average channel is 3% bandwidth – so stations tend to use antennas with 5-8 dB of vertical directivity. The second reason why the higher channels use more directivity is that because the wavelengths are so much shorter, it is far more practical to build high gain antennas – they are simply a lot smaller!

Since these antennas have a very narrow beam and the source of that beam is a quarter mile above ground, it shoots far over our heads and we receive very little of it on the ground directly below the antenna. In fact, thanks to the curvature of the earth and the trigonometry, a receiver near ground level doesn't get "in the beam" until it is at least 5-10 miles away from the antenna, and by then, inverse square law has reduced its field strength to the point where it is less likely to cause overload. Figs 13 and 14 show these effects.

Does this mean that we should expect <u>no</u> problems from high power UHF transmitters? No, it doesn't, but it does mean that things are not nearly as bad as simply looking at the power ratios might suggest. Fig 13 shows field strength on the ground for the antenna of Fig 6 at 500 m (1640 ft). Fig 14 shows a similar set of calculations for antennas of different gains at a height of 250 m (800 ft). Note that the higher the antenna gain, the greater the distance that is protected from overload by the high power transmitter!

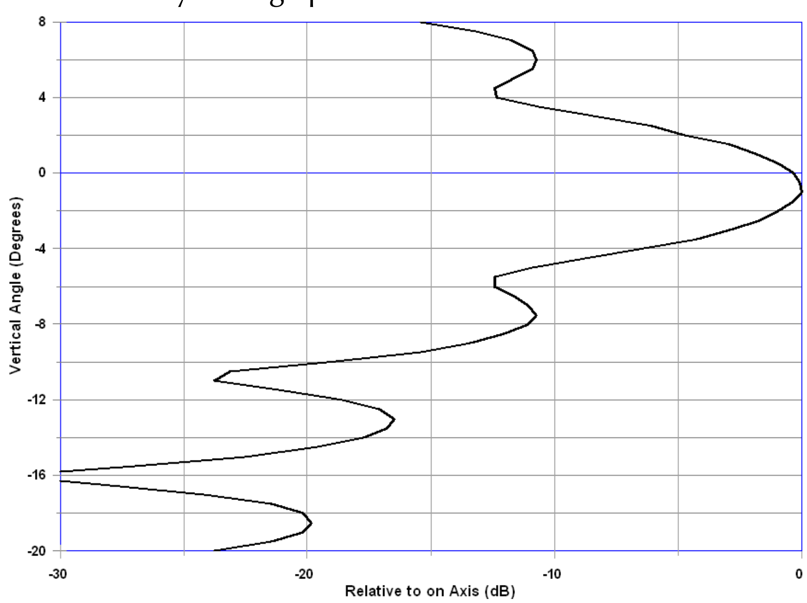

Fig 12 Vertical directivity of a typical broadcast transmitting antenna

An examination of Fig 13 and 14 makes the similarity to loudspeaker system design quite clear – the antenna is aimed to the most distant listeners (the horizon) so as to cover the most distant listeners. Closer to the antenna than about five miles, vertical directivity approximately compensates for inverse square law, and the field strength follows the inverse square law curve beyond that point. With sound systems, we aim our loudspeakers a few seats forward of the last row, loudspeaker directivity compensates for inverse square law for most of the closer seats, and sound levels follow inverse square law down beyond the aim point!

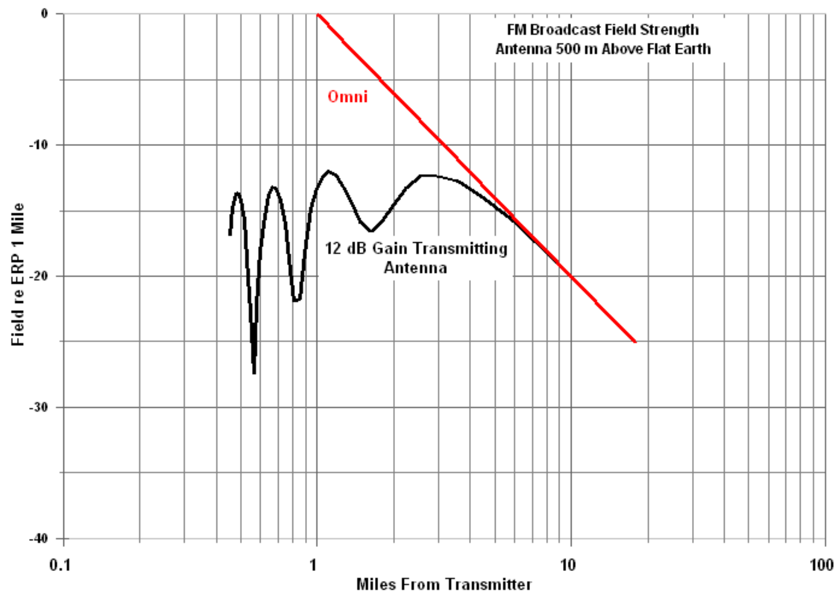

Fig 13 – Field strength on the ground for the antenna of Fig 5 at 500 m

Notice those "ripples" in the field strength curve (and the antenna's direction pattern). If you look at the response of a Bose MA12 using a high resolution measurement system like TDS or EASERA, you see the same ripples, and for the same reasons. And just as with loudspeaker systems, the phase response gets a bit messy in those ripples, which is one reason why FM broadcasters don't like highly directional antennas either – it can lead to distortion that sounds a lot like multipath distortion. In big cities, there are at least two other reasons FM broadcasters like low gain antennas. First, they want to cover people working in steel buildings close to their transmitters (downtown buildings), so they want a lot of field strength. Second, the FM antennas in major cities are often shared between a dozen or more broadcasters, and thus must be rather broadband. In Chicago, nearly all major broadcasters share four antennas on the Sears and Hancock buildings, and none of them has more than two bays (3 dB vertical directivity), and two are single bay antennas (no vertical directivity).

Studying Fig 14, we see that thanks to antenna directivity, the field strength close in under the antenna is typically 20 dB lower than if the antenna were omnidirectional. How does this impact our wireless systems? A cheap wireless receiver (that lacks those important front end tuning parts) will still get blown away within a few miles of a transmitter on an adjacent channel. A rough estimate of UHF field strength, based on the vertical directivity of typical UHF antennas is that they should be at least 20 dB lower than the simplified calculations suggested. So that 7V/m broadband RSS calculation for UHF is probably more like 700 mV/m. Similarly, since VHF high band stations (7-13) typically use antenna directivity on the order of 6-8 dB, we can expect to see a broadband RSS close-in field strength on the order of 1V/m there too.

All of this analysis seems to be confirmed by the testing reported in my AES paper on VHF and UHF interference to condenser microphones in downtown Chicago. The most severe interference by far was received from TV channels 2 and 5, and from FM broadcasters. It is also confirmed by study of the relative field strengths at the receiving antenna on the roof of my house seven miles from the transmitters, which is close to being in the main lobe of all of the antennas.

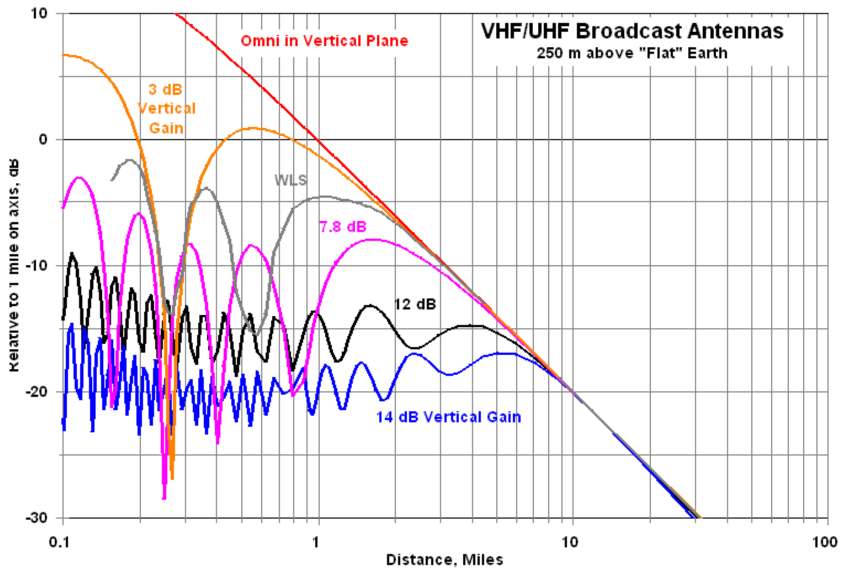

Fig 14 – Field strength on the ground vs. vertical gain for antennas at 250m

How does this affect the receiver? It is the total voltage at the receiver input that causes desensitization by rectification at the input stage. The instantaneous voltage on any given frequency will determine the strength of the intermodulation product from combining signals. Digital signals will certainly contribute to intermodulation distortion, but their product will be broadband noise that is lower in strength for any given interfering signal on any given wireless mic frequency. That's the good news. The bad news is that the noise will be spread over a wide spectrum, and will be contributed to by multiple transmitters on either side of the wireless channels.

The result is that intermodulation caused by digital transmitters will likely be every bit as bad as that from analog signals, but because it is broadband noise, it may never be identified as having resulted from intermodulation! And the overall effect on wireless mics will be to reduce their transmitting range.

Intermodulation occurs outside our equipment -- in non-linear junctions in building structure, etc. -- and inside our equipment (due both to the non-linearity of semiconductor devices, and to overload). We have no control over the intermod that happens outside our equipment, but we can control what happens inside our equipment with careful front end filtering (i.e., between the antenna and the first electronic stage) to eliminate interfering signals before they can produce intermod in our equipment.

There are at several good strategies for front end filtering. **Broadband** filters can be tuned to accept only signals within two or three adjacent 6 MHz UHF TV channels that we know to be free of interference. **Single TV channel** filters, set to a bandwidth on the order of 3-6 MHz, can be used to squeeze a half dozen wireless systems into a single empty channel surrounded on both sides by local transmitters. Single-channel fixed filters are relatively inexpensive, although no wireless mic manufacturers have yet figure that out and used them in their products. Narrowband filtering is quite expensive, especially if it has to track a frequency-agile transmitter. This author is aware of only two manufacturers, Lectrosonics and Sennheiser, who currently manufacture systems that have narrowband filters, and only the most expensive Sennheiser products do.

If we go back and study that first spectrum analyzer view of those eight UHF channels (Fig 6), we see two television channels that are not in use (around the 4th and 8th divisions of the frequency axis). These would appear to be good places to put wireless microphones, and they are – if we use receivers that include those narrowband filters. But a receiver that doesn't contain those parts, or one that has only a wideband filter in the front end, is likely to be "blown away" by the broadcast transmitters on both adjacent channels. Fig 3 illustrates the problem. This receiver is designed to tune over a 40 MHz range, and the front end filter is 40 MHz wide! That's fine if you'll be using the receiver in rural Idaho, but you may find it next to useless in most major cities.

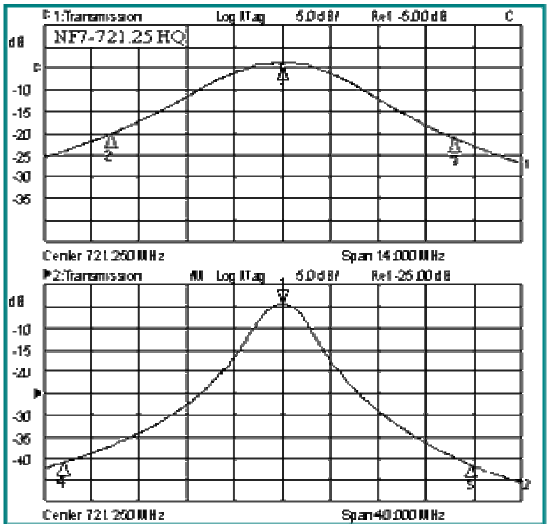

Fig 15 – An inexpensive narrowband filter (about $180). Filters like this should be built into wireless receivers, but rarely are.

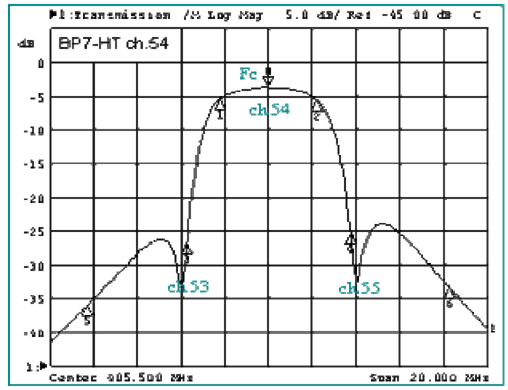

Fig 16 – This larger and more expensive multi-stage filter (about $450) has both wider bandwidth and better rejection of adjacent transmitters. [The channel identification references CATV channels, not broadcast channels] These filters are from Tin Lee Electronics (www.tinlee.com)

The good news here is that you can add these filters outboard – simply connect them between the antenna and the receivers! If you're using an antenna splitter to feed four receivers for frequencies within that filter's bandwidth, put the filter between the antenna and the splitter. For example, let's say we have wireless transmitters on 675.5 MHz, 676.150 MHz, 676.65 MHz, and 677.55 MHz. A narrowband filter (Fig 15) tuned to 676.5 MHz and a bandwidth of 2 MHz would pass all four of those signals but provide some rejection for the signals on either side. The more costly (and larger) filter of Fig 16 would allow us to use more of the empty channel for our wireless systems, even fitting in as many as eight frequencies, and providing much greater rejection of the adjacent signals. Fig 17 shows how these filters might be used.

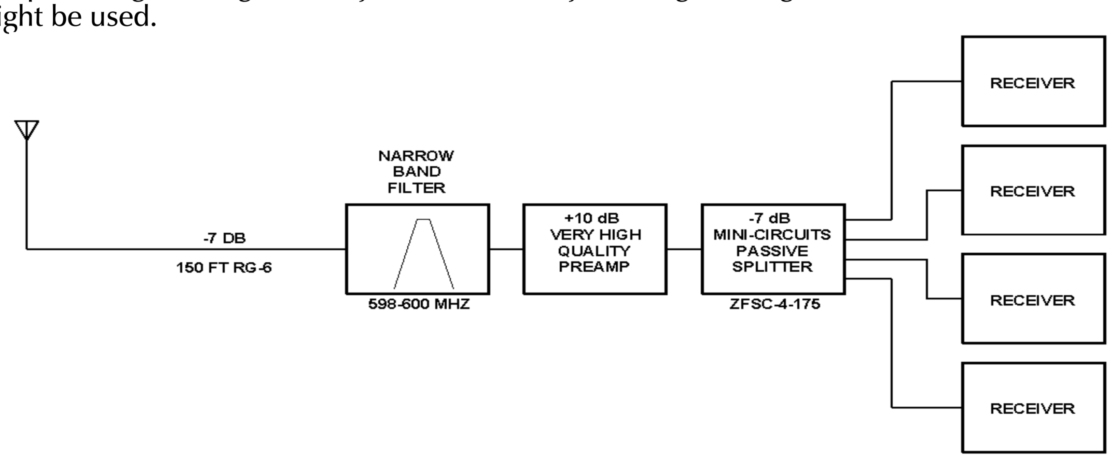

Fig 17 – A narrowband filter rejects strong signals on adjacent channels

A tuned cavity is a passive, electromechanical resonator. Cavities have very high Q and can have very low insertion loss (less than 0.25 dB), and their physical size is directly related to the wavelength to which they can be tuned.

[The Q of a resonant circuit is defined as the ratio between the reactive and resistive components at the resonant frequency. The bandwidth (BW, or Δf) of a circuit is defined as the difference between the half power points (-3 dB) on either side of resonance. BW = f_R/Q.]

Cavities that cover the UHF spectrum are of a very manageable size; cavities for the VHF spectrum are much larger. The cavity shown in Fig 18 is designed for use in two-way radio systems that work in the 400-470 MHz spectrum. It has a Q of 450, which results in a -3 dB bandwidth of only 1 MHz, and it can handle 100 watts. A bandpass cavity has two coupling loops, one at an input and one at an output. Signals at the resonant frequency are coupled through the cavity, others are rejected.

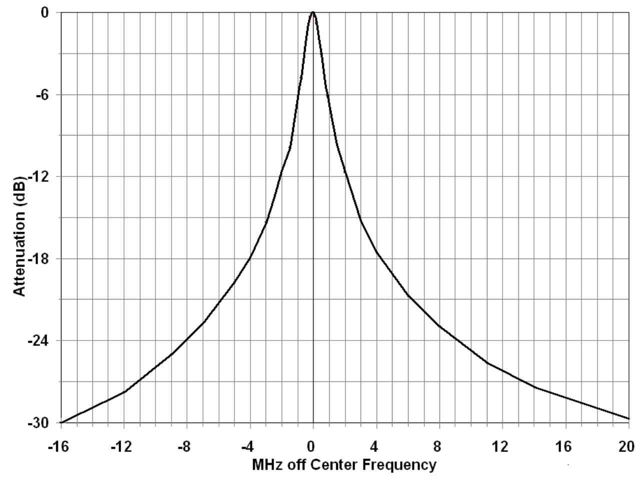

Fig 18 – A 450 MHz cavity and its response

Receive-only systems can utilize similar components called helical resonators and ceramic resonators. These much smaller components are designed for receiving systems only – they cannot handle power. Helical resonators have considerably lower Q (broader bandwidth) and more insertion loss (typically 1 dB/pole). They can be cascaded to achieve relatively narrow bandwidth, but at the expense of considerably insertion loss (a 6-pole filter might be more narrow than a cavity, but would have about 6 dB insertion loss. Both types of filters are essentially fixed tuned devices – their resonant frequency is determined during manufacture. Some helical resonator designs include a variable capacitor that can move their resonant frequency very slightly (a few percent).

<u>Finding A Good Channel To Use</u> If you are not experienced in choosing wireless mic channels (and even if you are), contact someone who is, and who understands VHF/UHF spectrum usage in your geographical area. Talking to the SBE (Society of Broadcast Engineers) frequency coordinator is a good place to start. He can usually be found by calling the chief engineer of one of the better broadcast stations in your area. When you think you have found a channel, listen to it on a scanner or other receiver that will tune to it. And make sure to do so during busy periods when the maximum interference is likely to be present (and when you would be using it).

Especially when many wireless systems will be used, or when wireless will be used in an area where many other strong signals are present, be sure to use a good computerized intermodulation prediction program. The likelihood of problems increases exponentially with the number of strong radio signals present (including your systems and other strong radio and TV transmitters). Once again this is a job for the professional.

Several models of pseudo-communications quality receivers manufactured for the ham radio and hobbyist market cover VHF and UHF TV channels, and can scan and operate under computer control. For some of them, software is available to log the frequencies that are received. The major shortcoming of these receivers is their relatively poor freedom from overload and rejection of spurious responses. In other words, they may hear stuff that isn't really there. In general, the models that are larger and more expensive are likely to be the better performers – the circuitry that rejects interference is both physically large and expensive. The ICOM PCR-1000 is a fair performer; their model R7000 should be better. Products like the Kenwood TH-F6A, Icom IC-Q7, and Yaesu VX-7 ham "talkies" can tune these channels and have scanning capability, but their image rejection and overload characteristics are poor and so is their sensitivity.

Intermodulation products are really the combined result of two related mechanisms.

1. When any waveform is passed through a non-linear device, harmonics of the components of the original waveform will be produced.
2. When two sine waves are combined in a non-linear device, intermodulation will result. Those components will be new sine waves at frequencies equal to the sum and difference of the original sine wave frequencies.

If we introduce two sine waves at frequencies A and B into our non-linear device, mechanism #1 will produce harmonics at frequencies 2A, 2B, 3A, 3B, 4A, 4 B, and so on. Mechanism #2 will produce new sum and difference frequencies A+B, A-B, 2A-B, 2A+B, 2B-A, 2B+A, 3A+2B, 3A-2B, 3B-2A, 3B+2A, 4A+3B, 4A-3B, 4B-3A, 4B+3A, and so on. We only care about those products that are close in frequency to the transmitter we want to receive. Products that are wildly different from the receive frequency will be filtered out by the front end of even the poorest receivers. Thus, we can immediately ignore all of the harmonics themselves and the sum frequencies. The products that will cause us grief are those on **difference** frequencies.

Intermod prediction is really a very simple process mathematically. All that is needed is a simple spreadsheet that computes the sum and differences of all the possible combinations between the frequencies and throws up a red flag when one of those intermod products is on a frequency that we need to receive. There's one very important "gotcha" though – the number of calculations (and the possibilities for interference) increases exponentially with the number of transmitter frequencies, and, we must include any strong broadcast carriers in our calculations! In general, you should always check the closest/strongest broadcast carriers.

A spreadsheet to predict intermod products for up to four mics and two broadcast carriers can be found on my website. Some notes about the spreadsheet. Cell B3 sets the bandwidth in MHz that should be protected from intermod products. 0.1 MHz (100 kHz) is the default, and is fairly conservative. To use the spreadsheet, enter some frequencies you think might work in cells D4 – G4, and list the strongest close broadcast carriers in cells H4 and I4. The intermod products will show up in column B, and if one of them interferes with one of the chosen frequencies, you'll see the word "TILT" under that frequency. To see the mix that produced the product, look in column A.

When the spreadsheet predicts interference, try shifting one mic at a time up or down in frequency in 25 kHz steps until there no problems are predicted.

Some general guidelines about frequency selection.

1) Give the filters in your receiver as much frequency spacing as practical between your transmitter and strong interference. If you only have a 6 MHz channel to work with, put the lowest and highest wireless channels at least 2 MHz away from the adjacent sound and picture carriers, except that if you are working with a filter like Fig 10, you can work a bit closer (1.5 MHz).
2) Don't put your transmitters closer together than about 300 kHz so that they don't interfere with each other directly.
3) Try to achieve irregular spacing between your transmitters. Regular spacing is far more likely to cause intermod to land on your channels.
4) If you need more wireless channels than you can squeeze into one TV channel, find

another empty channel and repeat the process.

5) If you have decent front end filtering, whether within the radio or with outboard filters, you can generally ignore transmitters in one TV channel when computing intermod in another channel.

6) Don't assume that you're the only game in town. Check with the SBE frequency coordinator, and with other potential wireless users in your immediate vicinity (like the theater or church next door). You shouldn't need to look further than about 1,000 ft, except at a sporting or major news event where there may be broadcasters doing wild and crazy things (like running a lot more power with a lot of channels). But remember – they are allowed to be there, while you're probably bootlegging, so they have the right of way!

7) Check the FCC website, http://www.fcc.gov/fcc-bin/audio/tvq.html to learn what TV stations are in your immediate area. You are prohibited from using any channel that is in use by a licensed broadcaster within a certain distance (usually about 50 miles) of your transmitter. Once on the website, enter the latitude and longitude of where you will be using wireless, and a radius of 85 km.

8) FCC rules require that wireless systems use frequencies that are divisible by 25 kHz. To minimize synthesizer noise, most wireless mic manufacturers allow frequency to be set in increments of 100 kHz or more.

Data sheets are full of specifications that rarely mean much, but leave out specifications that are relevant. Here are some definitions of some terms and specifications commonly used to describe wireless systems.

Selectivity This defines the bandwidth of the front end and the IF. *Selectivity* is provided by filters, both in the front end and in the IF. A very good front end will be at least 20 dB down ± 6 MHz either side of the frequency to which it is tuned to prevent overload of the RF amp stage and mixer. A better one will be half as wide. Additional selectivity (filters) in the IF separate one wireless transmitter from another, and separate wireless transmitters from noise on adjacent channels.

Sensitivity: This specification describes the ability of the receiver to receive weak signals – it defines the smallest signal that can be detected **if no noise or interference is present**, and is expressed in several different forms. The most meaningful is SINAD, which is defined as

$$\text{SINAD} = \frac{(\text{Signal}) + (\text{Noise}) + (\text{Distortion})}{(\text{Noise}) + (\text{Distortion})}$$

`

SINAD is measured by running the system at full deviation with a weak RF signal and measuring the level at receiver output, giving (S + N + D). Then, with the transmitter still running, the audio signal is subtracted, to measure (N + D). This measurement is the most meaningful way to express sensitivity, because it effectively removes the compander from the circuit (whose problems can be obscured by the other forms of sensitivity measurement).

Sensitivity is also specified as an input voltage (at the antenna terminal) that provides a specified signal to noise ratio or "xx dB quieting." These forms of the specification fail to show the limitations of the companding system, which is why they are poor indicators of receiver performance. A low number is generally good, but if it's too low, especially on a low cost receiver, the input stage has is likely to be very prone to overload.

Spurious response: A tendency of the receiver to hear signals on a channel it is not tuned to. This should expose problems with oscillator harmonics, and spurious noise from the synthesizer.

Image, image response: The susceptibility of a radio receiver to signals on the "other side" of the local oscillator. Image responses will be displaced from the desired signal by 2X the IF frequency.

Intermediate frequency (IF): The frequency to which all signals are converted for amplification, filtering, and detection.

Local oscillator: An oscillator within the receiver whose frequency is displaced either above or below the desired signal by a spacing equal to the intermediate frequency. This oscillator "beats" with the desired receive signal to produce a difference signal at the intermediate frequency (IF).

Third order intercept: A measure of how much signal a receiver can handle before it produces intermodulation on its own. This is defined as the input level of an interfering signal required to produce 3^{rd} order intermodulation distortion equal to its own signal strength (that is, the intermod is equal in amplitude to the interference that produces it). Usually expressed in dBm. A value of -15 dBm is mediocre, the best receivers can achieve +10 dBm.

Blocking dynamic range (BDR): A measure of how much signal a receiver can handle before it starts to desense. A large number is better. I've never seen this data for wireless receivers.

High side injection: The local oscillator is <u>above</u> the receive frequency.

Low side injection: The local oscillator is <u>below</u> the receive frequency.

Oscillator harmonics: Most local oscillators start with a clock that runs at a relatively low frequency, then use a harmonic of that frequency to beat with the incoming signal. It is possible for one of those harmonics to interfere with a desired signal if it is not carefully filtered or shielded within the receiver.

Oscillator leakage: Some poorly designed receivers allow one or more of the oscillator harmonics to leak outside the box, usually via the antenna connector due to poor filtering, but also due to poor shielding. A good receiver will keep this leakage low, but it will not be zero, so a good antenna splitter should prevent back-feed from one output port to another. The Mini-Circuits splitters provide at least 20 dB of isolation between ports.

Port isolation: For an antenna splitter, the amount by which a signal injected at one output port (typically due to oscillator leakage) that is attenuated at another output. Usually specified in dB.

<u>Problems At Short Range</u> When your wireless system experiences noise and dead spots within 50-200 feet of its receiver, something's wrong. If it's a good system and all your connections are good, you are probably receiving interference. Interference may not necessarily be heard as noise – it may simply make your system have poor range or dead spots. Again, there may be plenty of signal from your transmitter, but it may be getting overwhelmed by the noise. Look for interference sources (noted above) around your antenna. Move the interference source away from the antenna or move the antenna away from the interference source and closer to the performer's mic. Or do both. One of those talkies listed earlier makes a fine "probe" when looking for interference sources.

If this doesn't make things better, suspect desense. Receivers for channels A and B can be overloaded by a transmitter for channel C within 10-30 feet. This is more often a problem with cheapies, but I've seen it with a few good systems too. Try taking the antenna off the receivers that are having problems and using a paper clip or short piece of wire instead. If reception improves, you're experiencing overload. As a permanent fix, insert a 10 dB pad or passive splitter (described above) between the antenna and the receiver.

Extending Range Most good wireless systems should be good for at least 300 ft if there's nothing in the way and nothing to interfere with them. When it is necessary to extend the range of a wireless system beyond 500-1000 feet, several tools are available. Wireless receivers operating in or near TV channels work very well with antennas designed for the MATV service. A good multi-element antenna having 8 dB of gain can double the working distance. Raising the antenna height can also help considerably (if it doesn't increase interference). With some receivers a low noise pre-amplifier will also help extend the range. And, when you are going for long range, use the lowest loss cables you can find. *But try all of these things cautiously if you are in a strong signal area - all of these techniques can cause receiver overload if they increase the strength of the interference!*

Improving Audio Performance – Companding All analog wireless microphone systems use fixed pre-emphasis and de-emphasis to reduce noise, just like that used in FM broadcasting and analog tape recording. In addition, most wireless mic systems also use noise reduction systems (known generically as *companders*). They *comp*ress the audio level before transmitting and ex*pand* it again in the receiver. When this is done well, the audio is not changed by the total process, but noise in the radio link is greatly reduced. dbx and Dolby noise reduction are other examples of compansion systems. Most of the better quality wireless systems use companders, and are capable of dynamic range on the order of 105 dB. Some brands and models work much better than others. This is another area where low cost systems tend to be inferior -- their cheapie compansion circuits produce very audible pumping.

All analog wireless microphones, including those using compansion, must also use peak limiters to prevent over-modulation according to FCC rules. While these limiters can help improve the signal to noise ratio, it is important that they be adjusted so that they are not overused. Most wireless mic transmitters have preamp input gain control accessible as a screwdriver adjustment which can be accessed through a hole in the transmitter case. It should be adjusted so that peak limiting is not audible in normal operation. Excessive peak limiting will be audible as a pumping of background room noise and, in severe cases, as a loss of high frequencies (the latter is caused by the pre-emphasized highs being limited more severely than the rest of the audio).

Digital/Analog Hybrid Lectrosonics offers a conventional analog wireless system that uses DSP to transmit audio as digital data over the radio link, then convert it back to analog audio in the receiver. No analog signal processing or compansion is used – the DSP does it all.

Evaluating Audio Signal processing Audio signal processing as always been a weak spot for wireless mic systems, but some systems do offer superior performance. Several simple tests can expose common problems. One is to simply rattle a ring-full of keys at varying distances from the mic, while listening critically to the output of the mic in headphones. Start about a foot from the mic, gradually moving to about ten ft away. Any un-natural sounds here mean that the mic will likely have problems with sibilance and high frequency transients in music. Repeat this test while someone talks into the microphone, paying careful attention to what the voice sounds like.

Another useful test of compander action is to carefully generate a low frequency transient near the microphone that isn't very loud, and listen for audible "whooshing" or "breathing." This test must be performed in a relatively quiet space, and you need to listen at fairly high levels with headphones. One way to generate the transient is to lay the mic on a table, then gently bump the table with your fist (the "meaty" part of your hand, not a knuckle). Try this with multiple positions of the fist and intensity of the bump.

It's also useful to compare (A/B) the wireless mic system with a microphone of the same type that has a wired connection to the mix console. For any comparative test, it's critical that levels be very carefully matched – it is well known that a signal that is slightly louder will often be perceived as "better." It's also important that the microphones be in polarity when you do the listening test. To set levels, temporarily reverse the polarity of one microphone and set their relative gains for maximum cancellation while someone talks into the mics. It's ok to tweak the EQ a bit to maximize the cancellation. [The cancellation test will produce flanging if the wireless system has any latency. In this case, tweak the gain for maximum audible cancellation (flanging). it might also be possible to compensate for the latency by putting the talker slightly closer to the wireless mic] Once levels are matched, restore the mics to the same polarity for the listening tests.

Digital And Analog Tone Squelch Two-way radio systems have long used sub-audible tones and digital codes to allow one receiver to recognize one transmitter and reject all others. These systems have been applied to wireless mics with varying degrees of success. The advantage is that if their own transmitter is overridden by another signal using no code (or a different code), you won't hear the interfering signal. The disadvantage is that you won't hear your wireless mic transmitter either. In other words, an interference event which would have been a burst of noise becomes dead silence (or it the squelch isn't fast enough, a burst of the interfering signal followed by silence).

Wireless Intercom Systems A wireless intercom system consist of two or more wireless mic systems wired for two-way communication between two or more crew members. In these systems, the base station functions as a repeating transmitter, picking up transmissions from each remote (or "walkaround" belt pack) and retransmitting them on a channel where all remotes can hear. The base station is also usually tied into a conventional wired intercom so that everyone on the selected channel can hear the wireless users. The wireless intercom can be set up so that all remotes are on the same channel and operate "push-to-talk", or may be on individual channels and operate "full duplex" (i. e. listening and talking at the same time). In either variation, everyone hears everyone else, rebroadcast through the base station.

The range of these systems is roughly comparable to that of wireless mics. Frequency coordination is critical, since these systems can use up frequencies very quickly (including those you'd like to use for wireless mics). Receivers are generally not as good, particularly in the area of overload performance, but noise that would not be tolerated with wireless mics is more acceptable in intercom operation. System costs are about the same as an equal number of wireless mic transmitters and receivers.

Problems with surrounding objects An interesting operational problem with wireless systems occurs when there are intermittent metallic connections in the immediate vicinity of the wireless mic transmitter. When such intermittent connections exist, a static-like noise is heard in the receiver output. One condition that can cause this is the performer wearing costumes containing conductive materials. The exact mechanism causing the problem is not clear, but several are possible. If rapidly changing reflections are produced by the metal object, they could be detected at the receiver as amplitude or phase modulation. Intermodulation could also be taking place.

Multipath (Reflections) A thread several years ago on the Theater Sound Mailing List caused me to write this explanation of multipath and some common interference phenomena that occur with wireless mics. The thread started when someone asked about using wireless mics on a theatrical production where the set would include a large, complex framework made out of aluminum. By the time it was over, several myths had arisen and been dispelled.

JB: Any conductive object can pick up radio waves (act as a receiving antenna) and re-radiate them (act as a transmitting antenna). Here's what happens.

A radio wave is an electromagnetic field -- i.e., the simultaneous combination of an electric (voltage) field and a magnetic field at right angles to each other. An antenna is simply a conductive object this is producing or receiving that field. An electromagnetic field causes current to flow in a conductive material. And the closer the size of the conductive object is to a multiple of a quarter wave length of the radio signal involved, the more current will flow.

When radio frequency current flows in a conductive object, that current sets up a new radio signal (another electromagnetic field) which is then radiated by that object back out into space. If there is nothing non-linear happening, this new field is directly related to the original field that produced it, and it will be indistinguishable from the original field. But at any point in space, a radio antenna will pick up both fields, and those fields will have traveled different distances to get to the antenna. Because of the different distances, the travel times will also be different. This will put the original field out of phase with the new re-radiated copy of itself. The total voltage the antenna sees is the sum of that produced by the two fields. (Note that this is different from polarity, which is a reversal of the field or the voltage, and this difference is why it is so important to say polarity when you mean polarity!).

If we move the antenna, the time relationships will change. This is exactly what you hear when you drive down the road and hear "multi-path" distortion of an FM signal -- at some points the reflection is precisely in phase (zero degrees, or a multiple thereof), at some points it is precisely 180 degrees out of phase (or an odd multiple thereof), and at every other point is some random number of degrees out of phase. [Another time you'll hear this is when you're listening to a distant FM station and an airplane flies through the path between you and the station. You'll hear slow additions and cancellations as the phase relationship between the direct and reflected signals change with the plane's position.]

When the two signals are precisely in phase, they add together perfectly, and the result is equal to the sum of the two fields. When they are precisely 180 out of phase, they subtract from each other. If they are precisely equal, they cancel each other. If they are not, the result is simply less signal. Something similar happens when they are a random number of degrees out of phase -- there is a partial addition or partial subtraction, depending on the phase relationship, and that phase relationship changes as the antenna is moved. Exactly the same thing happens when you move the transmitting antenna (i.e., the wireless mic).

> *>This vibration, with a pure piece of metal, not only sends off frequencies at*
> *>400Mhz, but it sends 800Mhz, 200Mhz and so on.*

JB: NO, NO, NO. It re-radiates exactly what it receives.

> *>But since we aren't dealing with a pure piece of metal, the frequencies it sends off*
> *>are insane. If there is a bar of metal attached to another bar of metal, it can vibrate*
> *>that one too.*

JB: There is no "vibration." New frequencies are produced by poor electrical connections that cause ***rectification***, not metal alloys. Some connections of dissimilar metals can cause rectification too. When this happens it causes intermodulation distortion (see above).

Paul Peterson noted:

> *>I've heard several designer's mention RF interference when there's pieces of metal*
> *>rubbing or scraping together. In one case, the metal pins in an actor's recon*
> *>structed knee created interference every time he flexed his knee.*

JB: What's happening here is pretty complex. Those pieces of metal are simply re-radiating the radio signal as in the above discussion. But when they rub together, their length changes, and so does their electrical conductivity (at the connection). That change produces a change in the strength of the re-radiated field, and that change can be detected as amplitude modulation of the signal. That change in amplitude is what you are hearing as noise.

And Paul Johnson correctly observed

> *>diversity systems with close spaced aerials give marginal diversity performance.*
> *>The problem seems to be reflections. If you just connect one aerial and wander*

>over the set, the signalstrength varies far more than a non-metalic set. Watch out
>for strange nulls. Spacing the receiving aerials to both sides of the stage pretty well
>cured the problem.

JB: Note that all of these effects are VERY dependent on the size of the conductive objects and the openings between them. If the objects are large enough in comparison to a wave-length, there can also be significant shielding effect -- i.e., the large object prevents signals from getting past it. The large framework which is the basis of this thread could do that. But if the openings are large in comparison to a wavelength, it will act less like a barrier. For that reason, UHF mics, which use shorter wavelengths, might be expected to perform better than VHF mics.

My advice: Definitely use diversity receivers and good, well separated antennas. Try both VHF and UHF systems, and see which works best. As with any multiple wireless show, be careful about frequency coordination for intermod. And don't play cheap if you want a reliable show.

Some one asked:

>I've heard about the polarization of radio waves. Could you explain that and how
>it affects wireless systems?

JB: A vertical antenna sends out vertically polarized waves, and receives vertically polarized waves better. Likewise, a horizontal antenna sends and receives horizontally polarized waves. [This isn't an on/off relationship, it's a continuously variable function -- the received signal strength is multiplied by the cosine of the angle between the antenna's polarization and the angle of the radio wave. When the angle is 0 degrees, the cosine is 1, and when it's 90 degrees the cosine is 0.] But the antennas in wireless transmitters are typically the arm of the performer holding a handheld transmitter, and the cable connecting the lavalier mic to the body pack. It's hard to say what the polarization of the radio waves will be that are transmitted by these antennas! Moreover, any time a radio wave bounces off of any object, its polarization may be changed. ***Thus we must think of the polarization of our wireless systems as random.***

>What should be the orientation of the receiving antennas, especially with a diver
>sity system?

JB: This is generally much less important than having them well located (and in a diversity system, well separated). If you must put both diversity antennas in the same spot, do put them at right angles to each other (for example, one 45° in one direction, one 45° to the other). This is the best way to deal with the randomly polarization of the transmitter. If the antennas are separated, I'd go with whatever orientation provides optimum directivity to the area where transmitters will be.

SUMMARY AND RECOMMENDATIONS

- It costs money to build wireless systems that are good sounding and reliable under real world conditions. $800 - $1,400 should be a minimum "street" price for wireless systems. Stick with major manufacturers like Comtek, Shure, Telex, and Lectrosonics. All are designed and manufactured in the US. Buying cheaper systems is asking for trouble, either now, or in the future.
- The more wireless mics you plan to use at one time, the more you should plan to pay for them. If you're in a small town, need only two or three wireless, and there are no other churches (or interference sources) nearby, you'll have a good chance of being happy with something in the $800 range.
- The bigger the city, the more the mics you need to use, or the closer you are to big TV transmitters, the more likely you are to need mics that cost $1,200 - $2,000 per channel.

- When buying a crystal-controlled system, never accept any manufacturer's "stock" frequencies. This will make it far less likely that a touring sound company will bring in a system that wipes out one of yours!
- Always have frequency coordination done by a professional who understands the radio environment in your area. These professionals should know the television transmitters in your area and exactly how close their transmitters (not their studios) are to your facility.
- Avoid amplified antenna splitters, amplified combiners, or antenna pre-amplifiers.
- When you buy electronic equipment that will be used anywhere near your wireless mics (computers, monitors, mice, digital audio and video, ballasts for fluorescent lighting, etc.) insist that it be FCC Class B approved, and make sure the interconnecting cables are shielded. And don't believe it's Class B unless you see the sticker on the product. (The more lax FCC Class A standard allows equipment to put out much more radio trash).
- Keep antennas away from computers, digital equipment, dimmers, fluorescent lighting, other radio equipment, and accessories for all of the above. When you buy lighting equipment, insist that it conform to FCC Part 15 Class B or FCC Part 18 Residential Use.
- Locate antennas "low to the ground" and close to the performer.
- If you use transmitting antennas (for wireless intercom, hearing impaired systems, or two-way radio) DO locate them high and in the clear, and keep them away from your receiving antennas.
- Use good quality coax (see Table 1) and passive antenna splitters (Mini-Circuits Labs ZFSC-4-175).
- Avoid UHF channels 60-69, which will be plagued by interference from new two-way radio systems in a few years.
- Make sure you understand how local TV stations affect the radio environment in your area, and consider buying good VHF systems when you need more wireless mics.
- If your systems are unreliable within about a 300 ft range, something is wrong, probably interference or intermod. Work on finding the source of the problem by moving your antenna away from known interference sources. Also check the FCC website to make sure that there is no TV station using that channel in your area. (But expect wireless systems to lose range when going through walls which contain a lot of metallic elements -- it's normal for this kind of construction to block the signal.)

Acknowledgements: Thanks are due to Gordon Moore and the people at Lectrosonics for paying attention to my suggestions, building great products, and doing their best to move the ball forward. If there are better wireless systems in the world than their top systems, I don't know what they are. There's also an excellent tutorial on their website that goes into even more depth that this one on some aspects of wireless mics, and I haven't found a single lie in it! Pretty good for a manufacturer of wireless mics! Thanks also to Ray Rayburn for his thoughtful review of this manuscript and his suggestions.

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