20.1 Multichannel Wireless Microphone and Monitoring Systems

By Joe Ciaudelli

Wireless microphones are ubiquitous in our society. They are critical tools for content creation (e.g. movies, TV, radio), news gathering, live stage performance, sports and political events. They are also routinely used in schools, houses of worship, government facilities convention centers and corporate offices. The definition of wireless mics includes in-ear monitoring systems as well as intercom and cue systems.

Demand for wireless audio systems has been fueled by the increasing volume of content being created, higher sophistication of productions, a trend towards greater mobility on stage, the desire to control volume and equalization of individual performers, the speed required to disseminate news, and the safety that lack of cables can provide. Consequently, applications in which the number of wireless microphones, referred to as channels, being used simultaneously has increased dramatically. Note, the term channels in this context should not to be confused with TV channels in which wireless audio systems often operate within. Productions and events with large multichannel systems, greater than thirty channels, are now common. Systems of this magnitude pose a difficult engineering challenge. Careful planning, installation, operation, and maintenance are required.

Wireless systems use electromagnetic waves, instead of a cable or fiber, to transport audio information. Electromagnetic waves are produced by the vibration of charged particles. For reasons of practicality, audio systems generally use the radio frequency (RF) portion of the electromagnetic spectrum.

A wireless system requires a transmitter and complementary receiver, each having a tuned antenna, to process sound via radio frequency (RF) transmission. First, the transmitter processes the audio signal and superimposes it on a RF carrier through a process called modulation. The transmit antenna then acts as a launch pad for the modulated carrier, and broadcasts the signal over the air. The signal travels a certain space or distance and reaches the pick-up element, which is the receiving antenna. Finishing the operation, the receiver—which selects the desired carrier—strips off the signal through demodulation, processes it, and finally reconstitutes the original audio signal, Fig. 20-159. Each wireless channel operating in the same area at the same time needs to be on a unique carrier frequency.

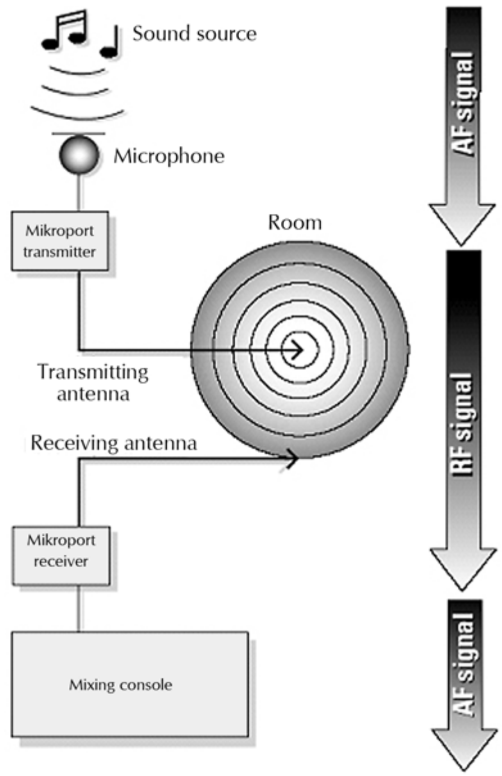


Figure 20-1. Signal path of a Mikroport system. Courtesy Sennheiser Electronic Corporation.

20.1.1 Audio Signals

Acoustic sound sources are captured by a microphone element, which transforms the mechanical sound wave to an electrical signal that the transmitter can then process. Alternately other input signals such as from electric instruments, can be fed into the transmitter.

Classically wireless microphone systems used these signals in there original analog form to modulated the carrier frequency. An analog signal is continuous and mimics the shape of a wave.

As time goes on, more digital transmission systems are employed. A digital signal is a stream of discrete numbers that represent instantaneous amplitudes of an analog signal, measured at equally spaced points in time. There are some advantages to transmitting a digitized version of an audio signal instead of its original analog form, noise being a primary one. Since analog signals can assume any value, any noise introduced is interpreted as being part of the original signal. Digital systems, on the other hand, can only understand two states numerically represented by zero and one respectively. Anything in between is disregarded. This property allows:

- Simple storage without degradation over time.
- Transmission without degradation.
- Digital Signal Processing (DSP).

Conversion of sound from the analog to the digital domain is done through the process of sampling. It must be understood that digital is an approximation. To reduce the degree of approximation, many samples of the analog signal must be measured within a short interval of time. The sampling rate must be at least twice the highest desired audio frequency. 20,000 cycles per second (20kHz) is the generally accepted maximum frequency for human hearing perception. Therefore, a sampling rate of 44.1kHz or higher is generally used for digital systems with full audio frequency response.

However, there are some trade-offs with digital systems, mainly latency, the delay between the input of a signal and its output. Each conversion between analog and digital domain takes finite time (typical for A/D and D/A: 0.1–1.5ms). Any processing, such as compression, adds more latency.

Clocking is also crucial. Digital audio is based on sampling rate and needs precise clock regeneration or master system clock for multiple devices, and/or accurate sample rate conversion.

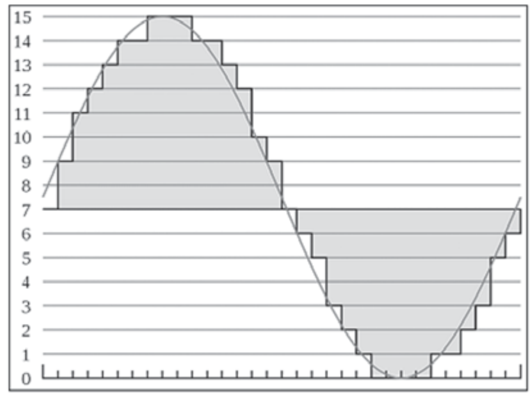
20.1.1.1 Digital Audio Representation

The A/D converter takes samples of the analog signal at discrete intervals. Based on its magnitude, each sample will be quantized to the closest available number value, Fig. 20-160.

20.1.2 Modulation

Modulation is basically adding a “code” to a carrier frequency by making a detectable change. Transmitting a signal requires three main processes:

- Generation of a pure carrier frequency.
- Modulation of that carrier with the information to be transmitted. Any reliably detectable change in carrier characteristic could translate information.
- Detection at the receiver of the signal modification in the transmitter and reconstruction of the information, also known as demodulation.



Number of samples/s = sample rate–kHz.
Number of discrete levels = 2 raised by the resolution–bit.
(4 bit = 16 level steps.)

Figure 20-2. D/A conversion. Courtesy Sennheiser Electronic Corporation.

The characteristics of a carrier signal, Fig. 20-161,that can be modified over time to convey information are:

- Amplitude.
- Frequency.
- Phase.

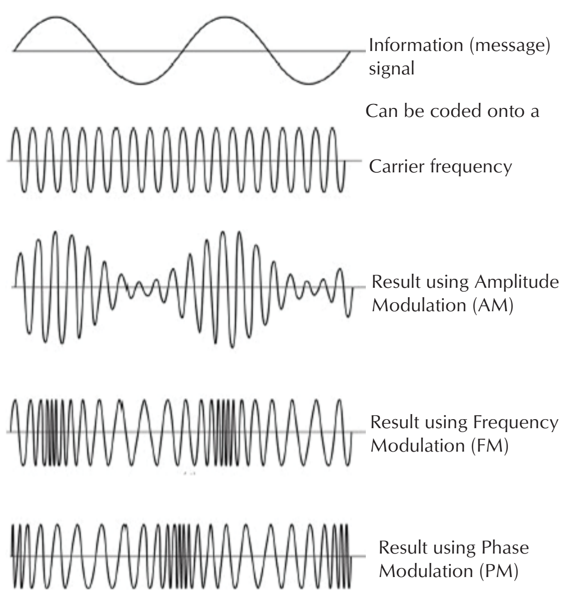


Figure 20-3. Classic analog modulation techniques. Courtesy Sennheiser Electronic Corporation.

20.1.2.1 Modulation - Analog

20.1.2.1.1 Amplitude Modulation (AM)

In AM the frequency of the carrier is kept constant and its amplitude is changed in proportion to the instantaneous amplitude of the modulating message signal.

- Minimum required bandwidth (BW) is twice the maximum audio frequency (AF):

$$BW = 2 \times AF_{max}. \qquad (20\text{-}1)$$

- Maximum signal to noise ratio $(SNR) \approx 30\,\text{dB}\mathbf{A}$ (affected by fading).
- AF response limited by occupied *BW*.
- *SNR* dependent on signal strength and modulation depth.

Since the information is coded on the amplitude of the carrier, anything that degrades the carrier will adversely impact the desired message signal. For example, a lightening storm causes significant audible interference.

20.1.2.1.2 Frequency Modulation (FM)

In FM the amplitude of the modulated carrier is kept constant, while the frequency is varied in proportion to the instantaneous amplitude of the modulating information signal.

- Minimum required bandwidth equals twice the frequency deviation added to the maximum audio frequency:

$$BW_{min} = 2 \times (\Delta f + AF_{max}) \qquad (20\text{-}2)$$

- $SNR_{max} \approx 50\,\text{dB}\mathbf{A}$ (for typical $\Delta f = \pm 50\,\text{kHz}$) without AF processing, $\geq 100\,\text{dB}$ with dynamic processing.
- Audio Frequency (AF) response dependent on *BW*.
- *SNR* dependent on deviation Δf and received signal strength.

Since none of the message signal is coded in the amplitude of the carrier, FM is more robust and less susceptible to varying climatic conditions. This is the reason FM has classically been used for high fidelity personal and car radios. Likewise, an FM mic transmitter works like a miniature FM radio station.

20.1.2.1.2.1 FM Audio Processing

To improve the audio quality, several measures are necessary because of the inherent noise of the RF link. These techniques provide improvement of dynamic range and *SNR* of the audio signal:

20.1.2.1.2.1.1 Pre- and De-Emphasis

This method is a static measure which is used in most of the FM transmissions. By increasing the level of the higher audio frequencies on the transmitter side, the signal-to-noise ratio is improved because the desired signal is above the inherent noise floor of the RF link, Fig. 20-162.

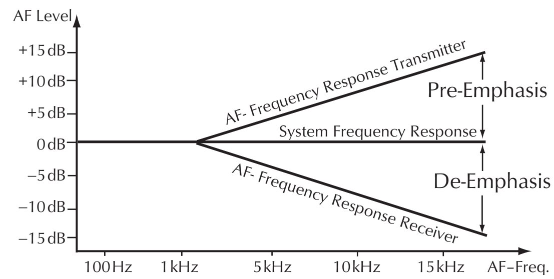


Figure 20-4. Pre-Emphasis and de-emphasis curves. Courtesy Sennheiser Electronic Corporation.

20.1.2.1.2.1.2 Companding

The compander is a synonym for “compressor” on the transmitter side, and is also a synonym for “expander” on the receiving end. The compressor raises low audio level above the RF noise floor. The expander does the mirror opposite and restores the audio signal. This measure increases the signal-to-noise ratio to CD quality level. All audio processing has consequences which are more evident with certain types of audio sources. A low level, short duration, high frequency sound, such as scissors closing, can activate the compander and a “breathing” sound can be heard which is the opening and closing of the compander circuit. Most often this is masked by typical audio input, Fig. 20-163.

20.1.2.1.2.2 Frequency Deviation

The modulation of the carrier frequency in an FM system greatly influences its audio quality. An increase in deviation yields better high frequency response and the dynamic range. The trade-off is that fewer channels can be used within a frequency range. Systems can be

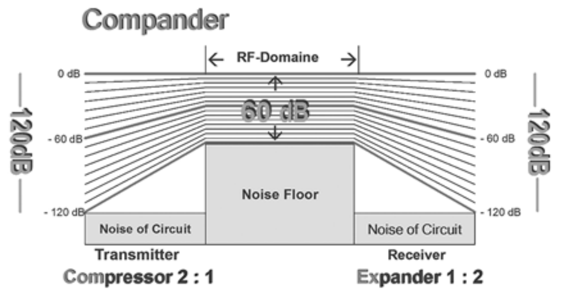


Figure 20-5. Companding curves. Courtesy Sennheiser Electronic Corporation.

categorized as wideband and narrowband. A typical wideband system suitable for high fidelity music can have a peak deviation of 56kHz. If such a system, tuned to a 525.000MHz carrier, has a loud input signal, it could modulate the carrier between 524.944MHz and 525.056MHz. In contrast, a communications grade system, like a walkie-talkie may only have a deviation of 5kHz around its center carrier. So wideband allows higher quality audio but requires a larger portion of spectrum (occupied bandwidth).

20.1.2.1.2.3 Occupied Bandwidth

The total occupied bandwidth of spectrum is largely defined by the amount of information required to transmit. A U.S. TV channel is 6MHz wide (8MHz in Europe). The volume of information sent by a high definition TV signal can occupy the whole six MHz channel. Alternately, up to four standard definition stations could share a single channel. If a channel is not being used in an area for TV broadcast, it is ideal to place wireless mics in that locally vacant TV channel. Since they are not transmitting picture or color information, and the FCC limits the bandwidth of mics to 200kHz, about eight wideband FM mics could operate within a 6MHz TV channel. If only narrowband devices are required, more than twice could be packed into that channel.

Therefore a high fidelity signal (CD quality sound) such as a mic for music applications uses a larger portion of spectrum than a low fidelity device such as a walkie-talkie (limited frequency response and dynamic range). A simple analogy can be made with shopping bags (carriers) that are placed in a trunk of a car (the trunk could represent a TV channel: a six Megahertz block of spectrum). Big bags (wideband deviation) each hold more groceries (audio information), but fewer bags will fit in the trunk which is a fixed size. Many more smaller bags (narrowband deviation) will fit in the trunk but each bag will have less groceries (information).

20.1.2.1.3 Phase Modulation

Phase and frequency are closely related since they can be considered different ways to view or measure the same signal change. Frequency modulation (FM) is that form of angle modulation in which the cycles (completed alternations) per second are varied by the information signal. Phase modulation (PM) is that form of angle modulation in which the angle is varied by the information signal. FM has generally been used for analog transmission. Phase is more often used in digital systems.

20.1.2.1.4 Modulation—Digital Systems

The promise and potential advantages of converting the natively analog audio signal to digital data prior to transmission can be summarized to:

- Lower noise.
- A compander circuit can be avoided, providing highly transparent sound without breathing effects.
- More flexibility for audio processing.
- For applications where data compression/reduction is acceptable, higher spectral efficiency.
- Transmission security (encryption).
- Error correction capabilities.
- Additional features through software/firmware updates.

The main driving force remains BEST POSSIBLE AUDIO QUALITY! (*SNR*, frequency response, immunity to interference).

20.1.2.2 Digital Modulation

With analog modulation systems, the information signal is analog, a continuous wave with infinite degrees of variation within the signals dynamic range. With digital modulation, the information signal is binary with discreet values. Technically “Digital Modulation” is a misnomer and refers to an analog carrier modulated with digital data (digital representation of an audio signal). Any modulation always changes the analog properties of the carrier. Both systems use analog carriers.

In the most basic digital message, the presence of a signal represents a binary value of “1.” Absence of the signal represents a “0.”

Simple digital modulation schemes include Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK) Fig. 20-164.

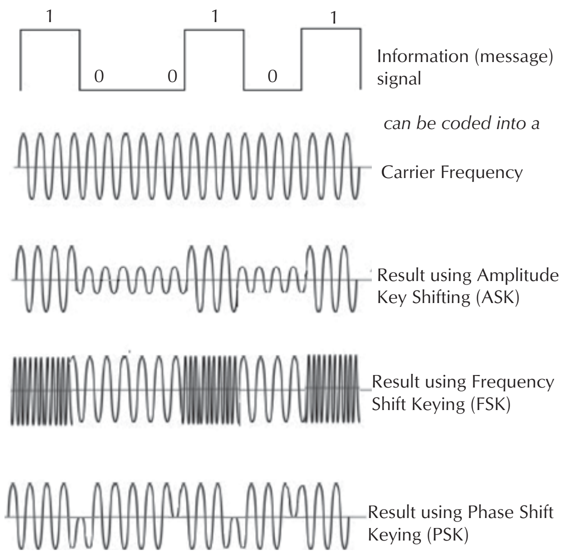


Figure 20-6. Simple binary digital modulation. Courtesy Sennheiser Electronic Corporation.

Many properties need to be considered for a digital wireless microphone (or any other radio communications device):

- Transmitter power (emitted from the antenna).
- Range.
- Tolerance for radio-frequency noise.
- Data rate (throughput in bits/second).
- Bit error rate (fraction of bits wrongly received).
- Occupied bandwidth (in Hz).

When a system operates near its limit, any of these properties can be improved, at least in principle, *but only at the expense of others*. Reduction of occupied bandwidth, for example, requires raising the transmitter power, reducing the operating range, reducing the noise tolerance, reducing the throughput data rate, and/or accepting more errors. These limitations are fundamental to the nature of information itself, much as the conservation of energy is fundamental to physics. In the same way that conservation of energy rules out a useful perpetual-motion machine, information theory rules out a useful wireless microphone that operates in a reduced bandwidth without sacrificing other qualities.

Many of the characteristics listed above are outside the microphone manufacturer's control. Transmitter power is limited by battery life (and government rules). Needed range is set by the layout of the performance venue. Needed noise tolerance depends on the local radio-frequency environment. Data rate depends mathematically on the audio quality required (subject to compression). The acceptable error rate likewise depends on quality requirements. Radio bandwidth, as we have seen, depends on all the others.

Other services that gained spectrum efficiency when converting to digital modulation (such as cell phones and broadcast TV) did not achieve those gains from digitization as such, but from implementing compression. The two are often confused because digitization is a prerequisite to efficient compression. But the processes are distinct. And even compression does not provide an end-run around information theory. Compression reduces the bit rate, but it also impairs audio quality or adds latency. So a balance of compromises must be made.

Regulations for wireless microphones in many frequency bands restrict the maximum occupied bandwidth to 200kHz. The minimum bandwidth required for transmission is equal to the bit rate (flow of data). Data Rate/Bandwidth = bits/Hz of BW or bits/Symbol.

Typical today is A/D conversion with 24 bit resolution at a sampling rate of 96kHz, resulting in bit rate of 2.304MBit/s. To facilitate reliable transmission additional data is required for framing and coding, necessary for control and synchronization, thereby expanding the data rate by a factor of around 1.5 and resulting in gross bit rate of 3.45MBit/s. This would require over 17 bits/s/Hz, a currently insurmountable feat given the limit of the 200kHz mask.

However, superior audio quality can be achieved with a frequency response up to 20kHz and a dynamic range (*SNR*) of >100dB with an A/D conversion of 18 bits of resolution and with a sampling rate of 44.1kHz, resulting in 793.4kbit/s. Factoring the required framing and coding, yields a data rate of 1.2Mbit/s.

Simple modulation schemes like ASK, FSK, PSK offer only a fraction of the needed data rate within the permissible bandwidth (typical ≤ 150–200kbit/s). One possible option could be further processing of the digital data to result in significant data reduction or compression. Any such data processing may affect the ultimate audio quality and inevitably will introduce additional processing delays ('latency').

A more sophisticated approach is a complex modulation technique that yields greater bits/s/Hz. In digital communication, the modulated parameter takes on only a discrete set of values, each of which represents a symbol. This symbol may consist of one or more bits, or binary ones and zeros. Since the demodulator must merely identify which amplitude, frequency and phase state is most closely represented in the received signal during each symbol period, the signal can be regenerated without any distortion.

For example, simple binary phase shift keying only transmits 1 bit of information representing either a "1" or a "0". However, phase shifting of a carrier is not restricted to only two states of 0° and 180°. With Quadra-Phase Shift Keying (QPSK), four states are used, corresponding to 45°, 135°, 225°, and 315°. 2 bits are associated with each state, thus doubling the transmitted information, Fig. 20-165.

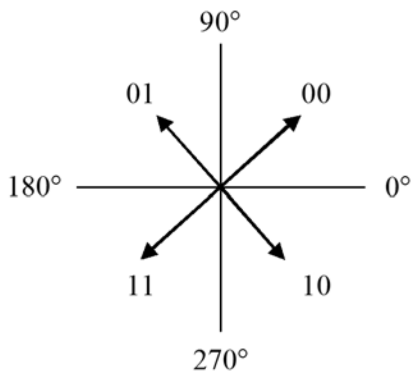


Figure 20-7. Quadra-Phase Shift Keying (QPSK). Courtesy Sennheiser Electronic Corporation.

20.1.2.2.1 QAM

It is also possible to combine phase shift keying and amplitude keying in a form of vector modulation known as Quadrature Amplitude Modulation, or QAM, Fig. 20-166.

QAM is commonly generated as a signal in which two carriers shifted in phase by 90° are modulated. The resultant sum output includes both magnitude and phase variations. The advantage of QAM is that it is a modulation of higher order, and as a result it is able to carry more bits of information per symbol. By selecting a higher order format of QAM, the data rate of a link can be increased. Table 20-3 gives a summary of the bit rates of different forms of QAM and PSK.

A simple way to view specific conditions of magnitude and phase is made possible with constellation diagrams. Constellation diagrams show the different positions for the end points of vectors from corresponding polar diagrams. Shown here are representations for different forms of Quadrature Amplitude Modulation (QAM). As the order of the modulation

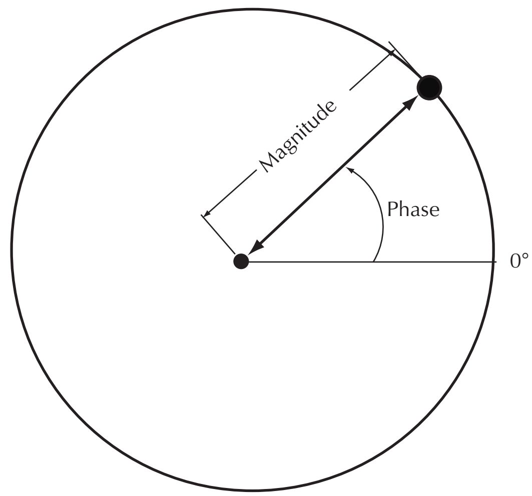


Figure 20-8. Digital (Vector) Modulation. Courtesy Sennheiser Electronic Corporation.

Table 20-1. Bit Rates of QAM and PSK

Modulation	Bits Per Symbol	Symbol Rate
BPSK	1	1 × bit rate
QPSK	2	1/2 bit rate
8PSK	3	1/3 bit rate
16QAM	4	1/4 bit rate
32QAM	5	1/5 bit rate
64QAM	6	1/6 bit rate

increases, so does the number of points (CP) on the QAM constellation diagrams, Fig. 20-167.

An alternate way to depict the constellation diagram for 64QAM shows all combinations of 4 amplitude levels with 16 discrete phase conditions, Fig. 20-168.

If each transmitted symbol represents 6 bits (64QAM), a 200 kHz wide channel can accommodate the gross data rate of 1.2 Mbit/s required for digital signals with 18 bits of resolution at a sampling rate of 44.1 kHz. The goal of uncompressed high fidelity audio with frequency response up to 20 kHz and dynamic range (*SNR*) of >100 dB is thus met!

By comparison, uncompressed digital HD Video plus audio and formatting requires a data rate of ≈ 20 Mbit/s. With 4 bits/symbol (BQAM) this signal can be transmitted over the air within the 6 MHz bandwidth of a TV-channel. This shows how the transmission of high quality uncompressed audio, considering the regulatory restraints, presents a greater technical challenge than transmission of a High Definition television signal (1080i HD video plus 5+1 audio).

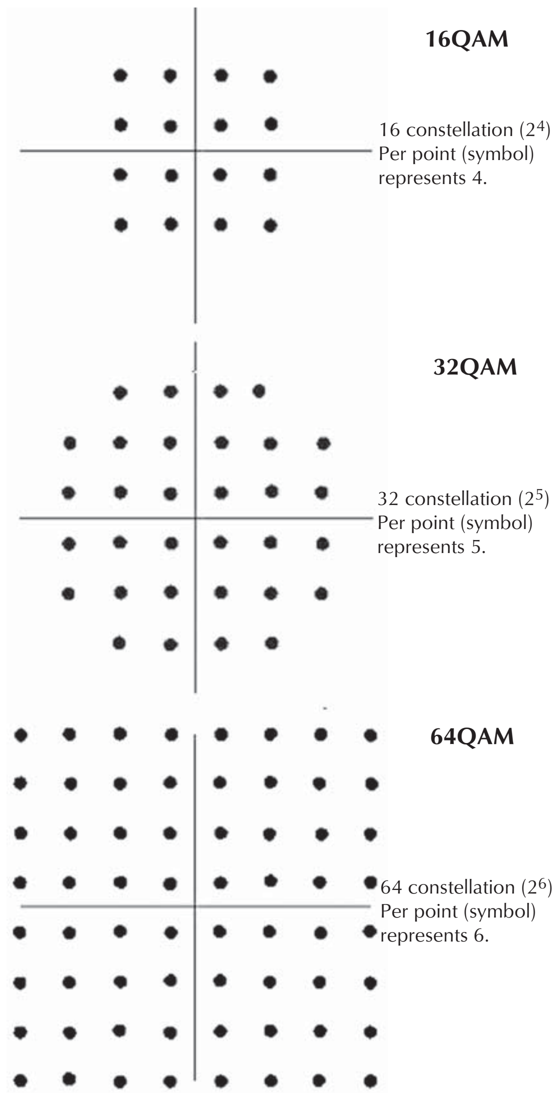


Figure 20-9. QAM constellation diagrams. Courtesy Sennheiser Electronic Corporation.

Reviewing some properties of this modulation technique:

- Constellation points (CP) are defined by discrete amplitude and phase.
- The number of CPs determines how many bits are defined by a symbol.
- The number of symbols per unit of time is limited by the RF channel BW.
- The CP is determined at specific instances of time (symbol time).

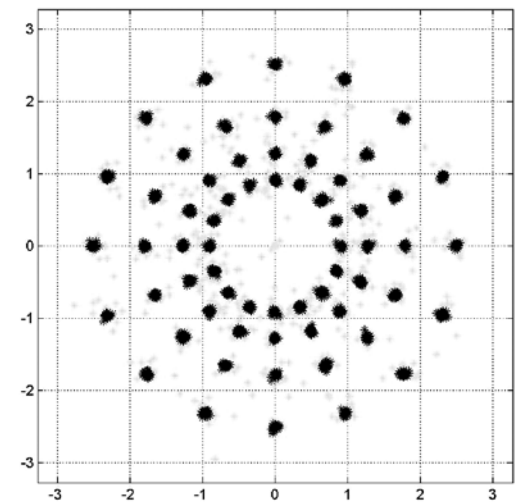


Figure 20-10. 64QAM constellation diagram. Courtesy Sennheiser Electronic Corporation.

While higher order modulation rates are able to offer much faster data rates and higher levels of spectral efficiency for the radio communications system, this comes at a price. The more bits that are represented by each symbol, the less bandwidth is required, but with a greater likelihood for bit errors and subsequent need for more transmit power. The higher order modulation schemes are considerably less resilient to noise and interference. The modulated RF Carrier (Vector) goes continuously from one constellation point to the other according to the bit sequence (symbol) to be sent. Noise and interference in the received signal make it more difficult to distinguish individual constellation points and decode the corresponding bit sequence. Lower order modulation schemes result in lower bit rate, fewer constellation points and require less carrier- to-noise/carrier-to-interference ratio (CNR/CIR) for acceptable bit error rate (BER). Figs. 20-169 and 20-170 compare the simpler QPSK with the 64QAM modulations.

20.1.2.3 Carriers Frequencies

Manufacturers have classically produced wireless microphones that can tune to a frequency within the TV band. These systems can operate on locally vacant channels (not used for over-the-air TV broadcast), often called "white spaces," per specifications outlined by government, for example, in the United States the Federal Communications Commission (FCC) regulates use of RF frequencies.

When wireless mics first became widespread in the 1980s, upper-band Very High Frequencies (VHF)

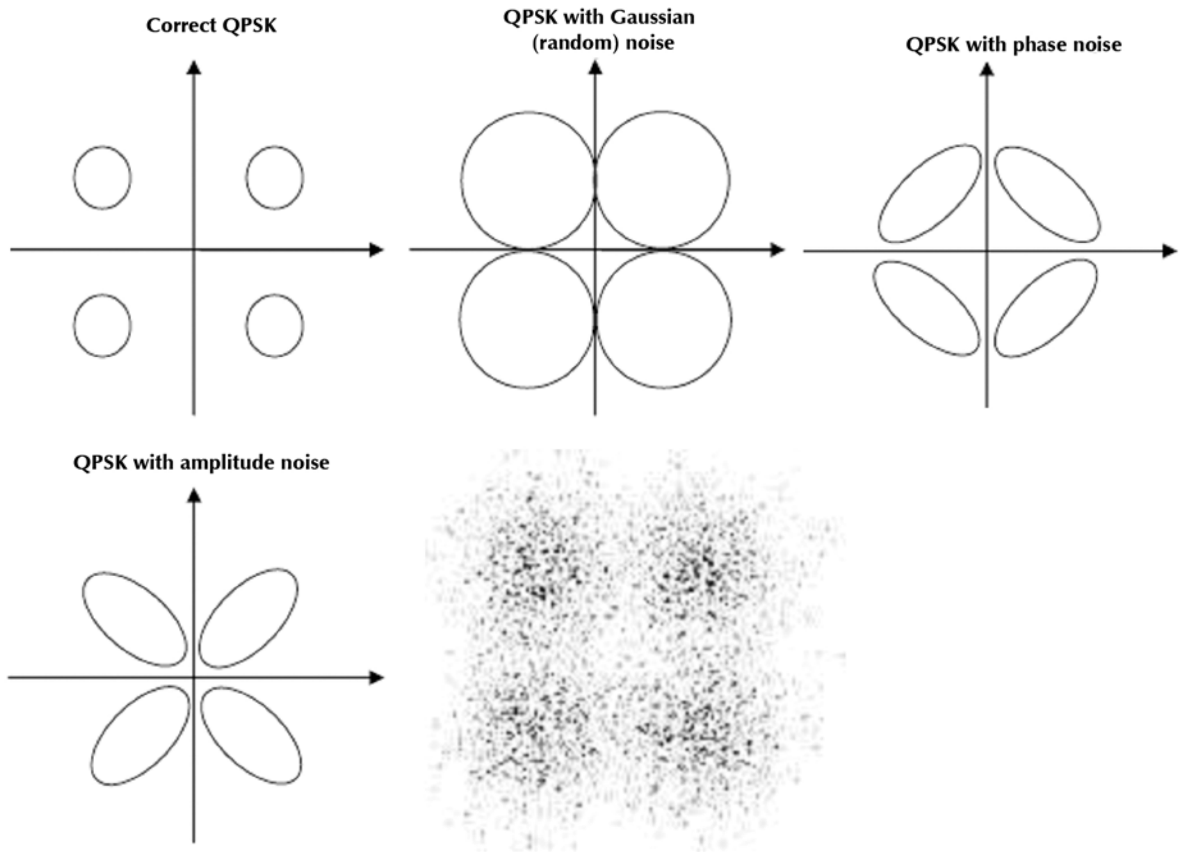


Figure 20-11. Noise in a QPSK system. Courtesy Sennheiser Electronic Corporation.

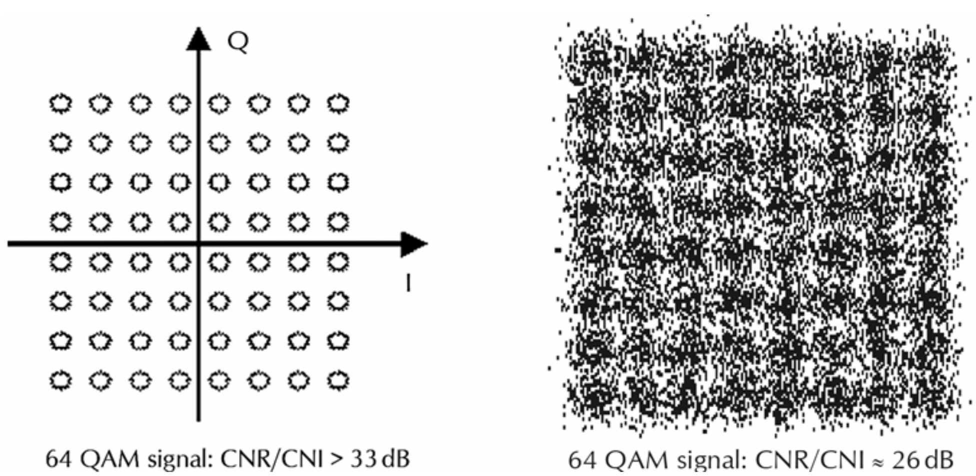


Figure 20-12. 64 QAM signal to CNR/CNI ratio. Courtesy Sennheiser Electronic Corporation.

(174–216 MHz) were used. Between 1990–2010, Ultra High Frequencies (UHF) ranging from 470 to 806 MHz were predominantly used. The wavelength of the carrier is inversely proportional to its frequency. Higher frequencies have shorter wavelengths, Antenna size is largely determined by the wavelength of the desired carrier. Therefore UHF systems can use smaller antennas compared to VHF, generally considered a big advantage for mic applications. UHF frequencies (450–960 MHz) have a wavelength of less than one meter. They have excellent reflective characteristics. They can travel through a long corridor, bouncing off the walls, losing very little energy. They also require less power to transmit the same distance compared to much higher frequencies, such as microwaves. These excellent wave propagation characteristics and low power requirements make UHF ideal for performance applications.

During 2010 in the United States the TV portion of the UHF was reallocated to accommodate broadband telecom services. The spectrum available for mic operation was thus truncated to 470–698 MHz. There are plans for further repacking of the spectrum. This will result in less UHF spectrum available for mics. Each nation has their own regulations so the specific frequencies available for operation vary from country to country. However, reallocation of the UHF band is the global trend. This is due to the high demand for the favorable wave propagation that the UHF range offers, such as penetration through foliage and walls. Also small antennas can be used and good range (distance) is achieved even with low transmitter RF output power (≤50 mW in the case of microphones). These advantages have spurred governments to monetize the spectrum, away from free over-the-air TV broadcast (and use by wireless mics) to telecom companies willing to pay billions of dollars for the rights to exclusive use of desired frequency bands.

Equipment is also available in frequency bands such as 902–928 MHz and 2.4 GHz which have been designated for unlicensed operation. A wide variety of non-mic wireless devices also use these bands. In areas where there is a concentration of such devices there is greater potential for interference. Even higher frequencies have been used for some applications using Ultra Wideband transmission techniques for applications such as wireless conference systems.

There is a probability that alternate ranges will become available to mic operators to help alleviate the loss of access to UHF. However, it is likely they will be available on a shared basis through the use of a priority database.

20.1.2.3.1 Spacing

In order to have a defined channel, without crosstalk, a minimum spacing of 300 kHz between carrier frequencies is generally employed for classic FM designs. A wider spacing is even more preferable since many receivers often exhibit desensitized input stages in the presence of closely spaced signals. A wider minimum spacing of 400 kHz should be used for in-ear monitors when operated in stereo. Certain digital systems with ultra-high linearity that allow equally spaced carriers (discussed below) use 500 kHz spacing.

Caution should be used when linking receivers with widely spaced frequencies to a common set of antennas. The frequencies need to be within the bandwidth of the antennas as well as any filtered antenna boosters and distribution systems.

20.1.2.3.2 Frequency Coordination

Multichannel wireless microphone systems can be especially difficult to operate, as they present several extraordinary conditions. Multiple transmitters moving around a stage together with body absorption, shadowing and polarization effects will result in wide variations of field strength seen at the receiver antenna system. This is even more challenging in a touring application since the RF conditions vary from venue to venue. In this case, the mix of frequencies is constantly changing. The daunting task to coax each of these variables makes equipment and frequency selection highly critical.

An important issue is to avoid interference from intermodulation (IM) products. Generally, one can coordinate around them or use top quality equipment that is properly configured so IM products will not be generated.

20.1.2.3.2.1 Coordinating Around IM Products

Intermodulation is the result of two or more signals mixing together, producing harmonic distortion. It is a common misconception that intermodulation is produced by the carrier frequencies mixing within the air. Intermodulation occurs within active components, such as transistors, exposed to strong RF input signals. When two or more signals exceed a certain threshold, they drive the active component into a non-linear operating mode and intermodulation (IM) products are generated. This usually happens in the RF section of the receiver, in antenna amplifiers, or the output amplifier of a transmitter. In multichannel operation, when several RF input signals exceed a certain level the intermodulation products grow very quickly. There are different levels of intermodulations defined by the number of addition terms.

In any wireless system with three or more frequencies operating in the same range, frequency coordination is strongly advised. It is necessary to consider possible IM frequencies which might interfere with the desired audio transmission. The 3rd and 5th harmonic, in particular, might raise interference issues. Considering two fundamental (wanted) signals the following signals may be present at the output of a non-linear stage:

- Fundamentals: F1 and F2.
- Second Order: 2F1, 2F2, F1±F2, F2–F1.
- Third Order: 3F1, 3F2, 2F1±F2, 2F2±F1.
- Fourth Order: 4F1, 4F2, 2F1±2F2, 2F2±2F1.
- Fifth Order: 5F1, 5F2, 3F1±2F2, 3F2±2F1.
- Additional higher orders….

As a result, the intermodulation frequencies should not be used, as those frequencies are virtual transmitters. The general rule "never use two transmitters on the same frequency" is valid in this case. However, even-order products are far removed from the fundamental frequencies and, for simplicity, are therefore omitted from further considerations. Signal amplitude rapidly diminishes with higher order IM-products, and with contemporary equipment design, consideration of IM-products can be limited to 3rd and 5th order only.

For multichannel applications (e.g., 30+ channels), the intermodulation products can increase significantly and the calculation of intermodulation-free frequencies can be done by number crunching software. By looking only at the third harmonic distortion in a multichannel system, the number of third order IM-products generated by multiple channels is:

- 2 channels result in 2.
- 3 channels result in 9.
- 4 channels result in 24.
- 5 channels result in 50.
- 6 channels result in 90.
- 7 channels result in 147.
- 8 channels result in 225.
- ….
- 32 channels result in 15,872 3rd-Order IM-products.

Adding more wireless links to the system will increase the number of possible combinations with interference potential logarithmically: *n* channels will result in two signal 3rd-order IM-products equal to:

$$(n^3 - n^2)/2 \tag{20-3}$$

The situation gets even more complicated if intermodulation among three signals is considered, which would then include the following terms for 3rd order IM:

- F1+F2–F3.
- F1+F3–F2.
- F2+F3–F1.

Equal frequency spacing between RF carrier frequencies inevitably results in two- and three-signal intermodulation products and should be avoided unless using equipment with extreme linearity (discussed below). The RF level and the proximity define the level of the intermodulation product. If two transmitters are close, the possibility of intermodulation will increase significantly. As soon as the distance between two transmitters is increased, the resulting intermodulation product decreases significantly. By taking this into consideration, the physical distance between two or more transmitters is important. If a performer needs to wear two bodypack transmitters, it is recommended to use two different frequency ranges and to wear one so that the antenna is pointing up and the other is pointing down.

With intermodulation factored in, when the number of wireless channels increases, the required RF bandwidth increases significantly, Fig. 20-171.

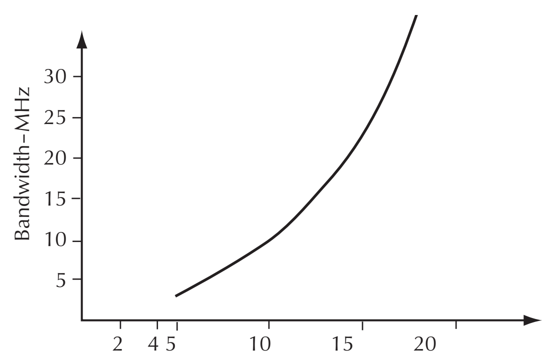


Figure 20-13. Bandwidth required for multi-channel systems. Courtesy Sennheiser Electronic Corporation.

External disturbing sources such as TV transmitters, public safety communications, noise from digital equipment, etc., also have to be taken into consideration. Fortunately, the screening effect of buildings is rather high (30–40 dB). For indoor applications, this effect keeps strong outside signals at low levels. A significant problem can occur when poorly screened digital equipment is working in the same room. These wideband disturbing sources are able to interfere with wireless audio equipment. The only solution to this problem is to replace the poorly screened piece of equipment with a better one.

Other RF-systems which should be considered for compatibility are:

1. TV-stations “On-Air.”
2. Wireless intercoms.
3. IFBs.
4. Wireless Monitor Systems.
5. Other wireless systems.

Compatibility between components of a system is achieved if the following conditions are met: each link in a multichannel wireless system functions equally well with all other links active, and no one single link—or any combination of multiple links—cause interference.

If the transmitter of a wireless mic channel is switched off, its complementary receiver should also be switched off or muted at the mixing console. A receiver that does not “see” its transmitter will try to latch onto a nearby signal. That signal may be an intermodulation product. The receiver will then try to demodulate this signal and apply it to the speaker system.

Equipment can be designed to minimize intermodulation. A specification known as intermodulation rejection or suppression is a measure of the RF input threshold before intermodulation occurs. For a well designed receiver, this specification will be 60dB or greater. An intermodulation rejection of 60dB means that intermodulation products are generated at input levels of approximately 1mV. If high quality components are used, having an intermodulation suppression of 60dB or greater, only the 3rd order products need to be considered.

20.1.2.3.2.2 Avoiding the Generation of IM Products

Intermodulation occurs when active electronic components are driven past their linear operating range. Sophisticated high quality designs can increase the range of linearity. Highly linear designs use top grade electronic components and draw extra current providing “headroom” that prevents harmonics from being created.

Intermodulation between transmitters can be avoided through the use of circulators. An antenna is agnostic in that it will transmit as well as receive signals. If a signal is picked up by a transmit antenna it could be fed into the amplifier of transmitter’s output stage, causing intermodulation. Circulators allow a signal to be sent out of the transmitter but block unwanted signals from entering in reverse fashion.

20.1.3 Transmitter Considerations

Transmitters are available as portable devices in the form of handheld microphones, bodypacks, and plug-on transmitters, and are produced as stationary units for monitor systems.

20.1.3.1 Range and RF Power

Transmitter power is a rating of its potential RF signal strength. This specification is generally measured at the antenna output. The range of a wireless transmission depends on several factors. RF power, the operating frequency, the set-up of the transmitter and receiver antennas, environmental conditions, and how the transmitter is held or worn, are all aspects that determine the overall coverage of the system. Therefore, power specifications are of only limited use in assessing a transmitter's range, considering these variable conditions. Also, battery life is associated with RF output power. Increased power will reduce battery life with only a moderate increase in range.

Using transmitters with the right amount of RF output power is important to ensure total system reliability. There is a common misconception that higher power is better. However, in many applications high power can aggravate intermodulation (IM) distortion, resulting in audible noises.

First of all, the applied RF output power must fall within the limit allowed by each country’s regulations. In the USA, the maximum RF output power for wireless microphones is limited to 250mW for licensed professional broadcast applications and 50mW for unlicensed use. In most of the countries in Europe this figure is 50mW, while in Japan it is only 10mW. Despite the 10mW limitation, many multichannel wireless microphones are operating in Japan. This is achieved by careful attention to factors like antenna position, use of low loss RF cables and RF gain structure of the antenna distribution system.

There are indeed some applications in which more RF output power is an appropriate measure; a perfect example would be a golf tournament, as the wireless system needs to cover a wide area. The risk of intermodulation is low at this type of function since the microphones are generally not in close proximity to each other.

If transmitters with high RF power are close together, intermodulation usually occurs. At the same time, the RF noise floor in the performance area is increased. For these reasons low power transmitters (≤50mW) are recommended for multichannel stage applications.

20.1.3.2 Battery Regulation

Transmitters should be designed to provide constant RF output power and signal processing throughout the event being staged. This can he achieved through the use of a DC-to-DC converter circuit. Such a circuit takes the decaying battery voltage as its input and regulates it to have a constant voltage output. Once the battery voltage drops below a minimum threshold, the DC-to-DC converter shuts off, almost instantaneously. The result is a transmitter that is essentially either off or on. While it is on, the RF output power, signal processing, and other relevant specifications remain the same. Transmitters without regulation circuits, once the battery voltage begins to drop, will experience reduced range and audio quality.

20.1.3.3 Spurious Emissions

Apart from the wanted carrier frequency, transmitters can also radiate some unwanted frequencies known as spurious emissions. For large multichannel systems potential spurious frequencies cannot be ignored. They can be significantly reduced through elaborate filtering and contained by hermetically sealed metal compartments that shield the RF components. A completely metal RF "tight" housing for the transmitter can provide even better protection. Also, an RF tight transmitter is less susceptible to outside interference.

A metal housing not only has advantages for its shielding properties, but also its durability. These devices usually experience much more abuse by actors and other talent than anyone ever predicts, Fig. 20-172.

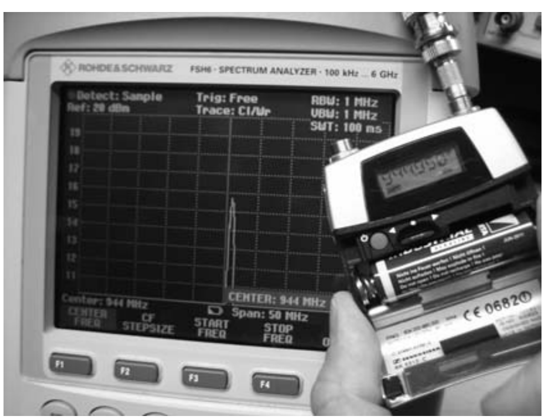


Figure 20-14. Sennheiser SK 5212 bodypack transmitter and a spectrum analyzer. Courtesy Sennheiser Electronic Corporation.

20.1.3.4 Transmitter Antenna

Every wireless transmitter is equipped with an antenna, which is critically important to the performance of the wireless system. If this transmitter antenna comes in contact with the human body, the transmitted RF energy is reduced and may cause audible noises known as "drop-outs." This effect of detuning the antenna on contact is called body absorption.

For this reason, talent should not touch the antenna while using handheld microphones. Unfortunately, there is no guarantee that they will follow this recommendation. Taking this into account, optimized antenna set-up at the receiver side and the overall RF gain structure of the system becomes critical.

This same effect can occur when using bodypack transmitters, especially if the talent is sweating. A sweaty shirt can act as a good conductive material to the skin. If the transmitter antenna touches it, reduced power and thus poor signal quality may result. In this case, a possible approach is to wear the bodypack upside-down near or attached to the belt, with the antenna pointing down. Sometimes this measure does not work because the talent will sit on the antenna. In this case, a possible solution is keeping the transmitter in the normal position and fitting a thick-walled plastic tube over the antenna, such as the type that are used for aquarium filters.

20.1.4 Receiver Considerations

The receiver is a crucial component of wireless audio systems, as it is used to capture the desired signal and transfer its electrical information into an audio signal. Understanding basic receiver design, audio processing, squelch, and diversity operation can help ensure optimum performance of the system.

Virtually all modern receivers feature superheterodyne architecture, in which the desired carrier is filtered out from the multitude of signals picked up by the antenna, then amplified and mixed with a local oscillator frequency to generate the difference "intermediate frequency." This "IF" undergoes more controlled discrimination and amplification, before the signal is demodulated and processed to restore the output with all the characteristics and qualities of the original.

Audio signal processing of an FM receiver is the mirror opposite of its transmitter. Processing done in the transmitters often include pre-emphasis (boosting high audio frequencies) as well as compression. These are reversed in the receiver by the de-emphasis and the expander circuit.

An inherent RF noise floor exists in the environment. The squelch setting should be set above this noise level. This acts as a noise gate that mutes the audio output if the wanted RF signal falls below a threshold level. This prevents a blast of white noise through the PA if the RF signal is completely lost. If the squelch setting is too low, the receiver might pick the noise floor and this noise can be heard. If the squelch setting is too high the range of the wireless microphone is reduced.

20.1.4.1 RF Signal Level

Varying RF signal strength is mainly due to multi-path propagation, absorption and shadowing. These are familiar difficulties also experienced with car radios traveling within cities.

Audible effects due to low RF signals, known as drop-outs, can occur even at close range to the receiver, due to multi-path propagation. Some of the transmitted waves find a direct path to the receiver antenna and others are deflected off a wall or other object. The antenna detects the vector sum, magnitude and phase, of direct and deflected waves it receives at any particular instant. A deflected wave can diminish a direct wave if it has different phase, resulting in an overall low signal. This difference in phase is due to the longer path a deflected wave travels between the transmitter and receiver antennae and any phase reversal occurring when it hits an object. This phenomenon needs to be addressed in an indoor application since the field strength variation inside a building with reflecting walls is 40dB or more. It is less critical outside.

RF energy can be absorbed by non-metallic objects resulting in low signal strength. As stated previously, the human body absorbs RF energy quite well. It is important to place antennas correctly to minimize this effect.

Shadowing occurs when a wave is blocked by a large obstacle between the transmitter and receiver antennas. This effect can be minimized by keeping the antennas high and distance of ½ wavelength away from any large or metallic objects.

These problems are addressed by a diversity receiver. A diversity system is recommended even if only one channel is in operation. Large multichannel systems are only possible with diversity operation.

There are a variety of diversity concepts available. Antenna Switching Diversity uses two antennas and a single receiving circuit. If the level at one antenna falls below a certain threshold it switches to the other antenna. This is an economical architecture but it leaves the chance that the second antenna could be experiencing an even lower signal than the one that falls below the threshold level. Another approach is switching the audio signal of two independent receiver units where each receiver unit is connected to its own antenna. This is known as TRUE diversity. This technique improves the effective RF receiving level by greater than 20dB. With a true diversity system, frequent switching between the two antennas is a desired result.

The minimum distance between the two diversity antennas is very often an issue of debate. A minimum of 1/4 of a wavelength of the frequency wave seems to be a good approach. Depending on the frequency, 5–6 inches is the minimum distance. In general, a greater distance is preferred.

20.1.5 Antennas

The position of the antenna and the correct use of its related components - such as the radio frequency (RF) cable, antenna boosters, antenna attenuators, and antenna distribution systems—are the key to trouble-free wireless transmission. The antennas act as the "eyes" of the receiver, so the best results can be achieved by forming a direct line of sight between the transmitter antenna and receiver antenna of the system.

Receiving and transmitting antennas are available as omni-directional and directional variants. For receiving, omni-directional antennas are often recommended for indoor use because the RF signal is reflected off of the walls and ceiling. When working outside, a directional antenna is most often a good choice since there are usually little to no reflections outdoors, and this directivity will help to stabilize the signal. In general, it is wise to keep an "antenna tool box" that contains both omni-directional and directional antennas for use in critical RF situations, since they transmit and receive signals differently.

Omni-directional antennas transmit or receive the signal by providing uniform radiation or response only in one reference plane, which is usually the horizontal one parallel to the earth's surface. Within that plane, the omni-directional antenna has no preferred direction and cannot differentiate between a wanted and an unwanted signal.

If a directional antenna is used, it will transmit or receive the signal in the path it is pointing towards. The most common types are the yagi antenna and the log-periodic antenna, which are often wide range frequency antennas covering the whole UHF range. In an outdoor venue, the desired signal can be received and an unwanted signal, from a TV station for example, can be rejected to a certain degree by choosing the correct antenna position. A directional antenna also transmits or receives only in one plane, like an omni-directional antenna.

Several types of omni-directional and directional antennas also exist for specific conditions. The telescopic antenna is an omni-directional antenna and often achieves a wide range (450–960 MHz). If telescopic antennas are in use they should be placed within the line of sight of the counterpart antenna. They should not, for example, be mounted inside a metal flight case with closed doors as this will reduce the RF field strength from the transmitter and compromise the audio quality.

System performance will be raised considerably when remote antennas are used. A remote antenna is one which is separated from the receiver or transmitter unit. These antennas can be mounted on a mic stand or similar support. This will improve the RF performance significantly. However, when using remote antennas, some basic rules need to be considered. Placing antennas above the talent increases the possibility the transmitter and receiver remain within line of sight, ensuring reliable transmission. If a directional antenna is used, the position of the antenna and the distance to the stage is important. One common set-up is pointing both receiving antennas toward the center of the stage. Once again, a line of sight between the receiver and transmitter antennas is best for optimum transmission quality.

Directional and omni-directional antennas do have a preferred plane, which is either the horizontal or vertical plane. If the polarization between the transmitter and receiver antenna is different, this will cause some significant loss of the RF level. Unfortunately, it is not possible to have the same polarization of the antennas all of the time. In a theatrical application, the antenna is in a vertical position when the actress or actor walks on the stage. The polarization of the transmitter may change to the horizontal position if a scene requires the talent to lie down or crawl across the stage. In this case, circular polarized antennas can help. These kinds of antennas can receive the RF signal in all planes with the same efficiency.

Because the polarization of the antenna is critical and telescopic antennas are often used, it is not recommended to use the receiver antennas strictly in a horizontal or vertical plane. Rather, angle the antennas slightly as this will minimize the possibility that polarization would be completely opposite between transmitter and receiver.

One last note: The plural form for the type of antenna discussed in this article is "antennas." Antennae are found on insects and aliens.

20.1.5.1 Antenna Cables and Related Systems

Antenna cables are often an underestimated factor in the design of a wireless system. The designer must choose the best cable for practical application, depending on the cable run and the installation. As the radio frequency travels down the cable its amplitude is attenuated. The amount of this loss is dependent on the quality of the cable, its length and the RF frequency. The loss increases with longer cable and higher frequencies. Both of these effects must be considered for the design of a wireless microphone system, Table 20-4.

RF cables with a better specification regarding RF loss are often thicker. These are highly recommended for fixed installations. In a touring application, in which the cable must be stored away each day, these heavier cables can be very cumbersome.

As any RF cable has some RF attenuation, cable length should be as short as possible without significantly increasing the distance between the transmitter and receiver antennas. This aspect is important for receiving applications but is even more critical for the transmission of a wireless monitor signal.

Table 20-2. Different types of RF cables with various diameters and the related attenuation for different frequencies. (Source: Belden Master Catalogue)

Cable Type	Frequency MHz	Attenuation db/100 ft	Attenuation dB/100 m	Cable diameter in/mm]
RG-174/U	400 700	19.0 27.0	62.3 88.6	0.110/2.8
RG-58/U	400 700	9.1 12.8	29.9 42.0	0.195/4.95
RG-8X	400 700	6.6 9.1	21.7 29.9	0.242/6.15
RG-8/U	400 700	4.2 5.9	13.2 19.4	0.405/10.3
RG-213	400 700	4.5 6.5	14.8 21.8	0.405/10.3
Belden 9913	400 700	2.7 3.6	8.9 11.8	0.405/10.3
Belden 9913F 9914	400 700	2.9 3.9	9.5 12.8	0.405/10.3

In a receiving application, it is important to consider losses from the cable as well as from any splitter in the antenna system during the design and concept stage of a wireless microphone system. If the losses in the system are small, an antenna booster should not be used. In this case, any drop-out is not related to the RF loss in the antenna system; instead, it is more often related to the antenna position and how the transmitter is used and worn during the performance. An antenna booster is recommended if the loss in the antenna system is greater than 6dB.

If an antenna booster is necessary due to long antenna cable runs, it should be placed as close as possible to the receiving antenna. Antennas with a built-in booster are known as active antennas. Some of these have a built-in filter, only allowing the wanted frequency range to be amplified. This is another measure to reduce the possibility of intermodulation of this amplifier.

Two antenna boosters should not be used back-to-back when the RF cable run is very long. The second antenna booster would be overloaded by the output of the first amplifier and would produce intermodulation.

Special care must be taken when using an antenna booster if the transmitter comes close to the receiver antenna. The resulting strong signal could drive the antenna booster past its linear operation range, thus producing intermodulation products. It is recommended to design and install a system such that the transmitter remains at least 10 feet from the receiver antenna at all times.

Also, signals that come from over-the-air (OTA) TV broadcast—such as a Digital Television (DTV) signal—are unwanted signals that may contribute to intermodulation products in any amplifier stage of your system. Outboard narrowband filters are available that are tunable to a 6MHz (one TV channel) bandpass. This provides added safety when operating on a vacant TV channel in between active TV signals.

This will often work for fixed installations because it is less likely that the RF environment will change. This is especially the case where the RF environment is congested with many TV stations or other wireless systems are operating in the vicinity, such as a broadcast production studio in a major city.

20.1.5.2 Splitter Systems

Antenna splitters allow multiple receivers to operate from a single pair of antennas. Active splitters should be used for systems greater than four channels so that the amplifiers can compensate for the splitter loss. Security from interference and intermodulation can be enhanced by filtering before any amplifier stage. As an example, a thirty-two channel system could be divided into four subgroups of eight channels. The subgroups can be separated from each other by highly selective filters. The subgroups can then be considered independent of each other. In this way, frequency coordination only needs to be performed within each group. It is much easier to coordinate eight frequencies four times than to attempt to coordinate a single set of 32 frequencies, Fig. 20-173.

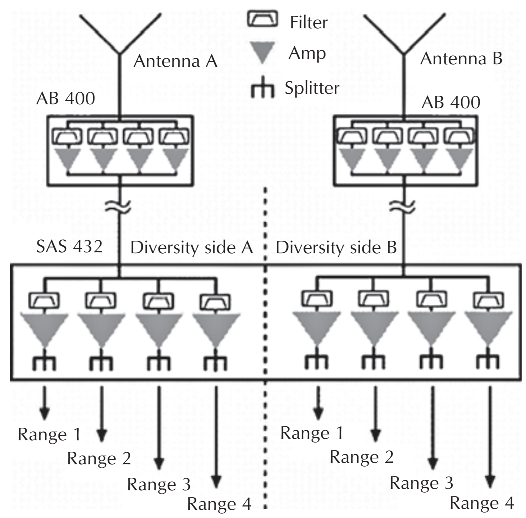


Figure 20-15. Diversity antenna set-up with filtered boosters, long antenna cables, and active splitter with selective filtering. Courtesy Sennheiser Electronic Corporation.

20.1.6 Wireless Monitor Systems

Wireless monitor systems are essential for stage-bound musical productions. Perhaps the biggest advantage of a wireless monitor system is the ability to use an individual monitor mix for each musician on stage. Furthermore, a wireless monitor system significantly reduces the amount of, or even eliminates, monitor speakers in the performance area. This results in lower risk of feedback, and a more lightweight, compact monitor system.

Some special precautions must be taken before using wireless monitor systems. In most cases, this signal is a stereo signal. This multiplexed signal is more sensitive to drop-outs, static and multipath situations. For long range applications, mono operation can improve system performance.

If wireless microphones and wireless monitor systems are used in parallel, those systems should be tuned to separate frequency bands at least 4MHz apart, more is even better. Also, the physical distance between any transmitters and the in-ear receiver on a performer should be maximized. This will reduce the risk of blocking—an effect that desensitizes a receiver and prevents the reception of the desired signal. Therefore, if a bodypack wireless mic transmitter and a wireless monitor receiver are both attached to the same talent, those devices should not be mounted directly beside each other.

When musicians use the same monitor mix, one transmitter can be used to provide the radio frequency (RF) signal to more than one wireless monitor receiver. If individual mixes are desired, each mix requires its own transmitter operating on a unique frequency. To avoid intermodulation disturbances, the wireless monitor transmitters should be combined, and the combined signal should then be transmitted via one antenna. Active combiners are highly recommended. Passive combiners suffer from signal loss and high crosstalk. An active combiner isolates each transmitter by around 40dB from the others and keeps the RF level the same (0dB gain), thus minimizes intermodulation. Again, intermodulation is a major issue within the entire wireless concept. When using stereo transmission, it is even more critical.

When considering an external antenna, one important factor must be taken into consideration: the antenna cable should be as short as possible to avoid losses via the RF cable. A directional external antenna is recommended to reduce multipath situations from reflections, and it will have some additional passive gain that will increase the range of the system.

If remote antennas are used for the wireless monitor transmitters as well as wireless mic receivers, those antennas should be separated by at least 10 feet. "Blocking" of the receivers, as discussed above, is thus avoided. Furthermore, the antennas should not come in direct contact with the metal of the lighting rig. This will detune the antenna and reduce the effective radiated wireless signal.

20.1.7 System Planning For Multichannel Wireless Systems

When configuring a multichannel wireless microphone system, several factors are essential for reliable operation. First, you must understand the environment in which the system will be used.

1. Location. The coordinates of a venue can be determined by using mapping tools on the internet, such as Google Earth. If you figure out the coordinates of the venue, you can simply plug this information into the Federal Communications Commission (FCC) homepage at http://www.fcc.gov/fcc-bin/audio/tvq.html. The result shows all transmitters licensed by the FCC in this area. Valuable information can also be found within an FCC approved TV White Space database, including Spectrum Bridge: http://whitespaces.spectrumbridge.com/whitespaces/home.aspx; or Key Bridge Global: https://keybridgeglobal.com/whitespace/. Most importantly, these databases will indicate any TV channels that are reserved for wireless microphone use at a specific location. All approved databases share the same information. Note, some channel reservations may be limited to certain dates and times. This information will allow the designer of the wireless system to plan which vacant TV channels can be used for wireless audio devices. If there is a TV transmitter close to the location of the wireless microphone system (<70 miles), this TV channel should generally be avoided. Operators running a large number of mics can apply to reserve locally vacant TV channels for their events through the database system, making those channels unavailable to other white space devices. Licensed operators, such as broadcasters can make reservations directly into the database. Unlicensed operators first need to apply for approval with the FCC. Once one knows which TV channels may be used in the area, the designer can use another software tool that calculates the IM-free frequencies and displays possible set-ups.

2. Quantity and Frequency Coordination. Determine how many wireless microphones, wireless monitor systems, intercoms, etc. are required or in use for your job. With the information you gathered from step one, you can begin the system design. You now have the available TV channels and the number of wireless systems you want to use.

With this know-how you can start the frequency coordination of your system inside the vacant TV channels. This is supported by software that is available from various companies. The key here is to prevent intermodulation products (unwanted frequencies generated by harmonic distortion) from interfering with the wanted frequencies of your wireless systems.

A test at the venue is also necessary. If you have the chance, scan the location with a spectrum analyzer, Fig. 20-174. With this tool, you can verify that the information from the internet is correct. Alternately, you can scroll through the tunable frequencies of your wireless receivers to scan the RF activity in the venue. Many receivers also have an auto scan function to find open frequencies. This cross-check is necessary to find out whether other wireless devices are in use that you do not have on your list, which could interfere with your signals during operation.

3. Tune Your Components. Set your individual transmitters and corresponding receivers to their coordinated frequencies. Switch on all components and perform a final test of compatibility. Physically space

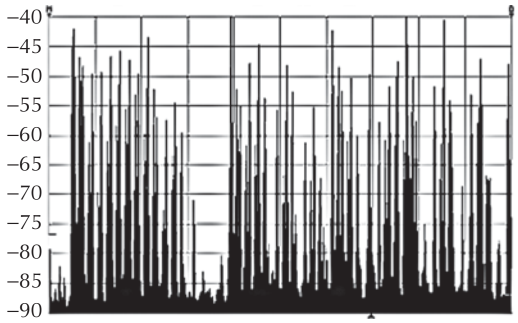


Figure 20-16. Plot of the RF spectrum in Athens outside the Olympic Stadium (450-960 MHz). Courtesy Sennheiser Electronic Corporation.

the transmitters a couple feet apart and at least ten feet from the receiving antenna. Listen for any interference. Once again, compatibility is confirmed when each link in a multichannel wireless system functions equally well with all other links active and, no single link—or any combination of multiple links—cause interference.

20.1.8 Conclusion

Large multichannel wireless systems demand excellent planning, especially in the initial phase, and good technical support. Observing all the above mentioned items, reliable operation of a system can be achieved, even under difficult conditions.

With gratitude for contributions by Volker Schmitt, Gerrit Buhe, and Peter Arasin.