FM Transmission Systems

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Abstract

The variables in any given FM transmission system are many. They include factors such as antenna height versus ERP, antenna gain versus transmitter power, vertical plane radiation patterns, Brewster angle, Fresnel zone, polarization, site location and topography among others. In this paper, we will examine each of these variables, the tradeoffs between cost and performance, antenna and transmission line types, installation and maintenance techniques and procedures.

1.0 Antenna Site Considerations

While few of us have much control over the location of our antenna sites, perhaps there is room for change in some situations. For the rest, the information which we present herein will help us evaluate the performance of our radio stations as a function of site location and antenna height.

Location, location, location. Those are the three most important factors in real estate, and they are equally important for radio transmission systems. This applies equally to AM, FM, TV, MMDS, cellular, PCS, two-way, paging and other RF-based services.

Ideally, the antenna for an FM broadcast station would be situated at a location that would present a clear line-of-sight to the entirety of the desired service area. The antenna would have uniform horizontal- and vertical-plane radiation patterns, and there would be no reflections from natural or manmade objects.

Unfortunately, the real world is very different from this ideal. The real world is full of obstructions, manmade and natural, that partially or fully obstruct the path from the transmitting to receiving antenna. Real-world transmitting antennas exhibit some non-uniformity in the horizontal plane, and in the vertical plane, half of the energy is radiated above the horizon into space, where it is wasted. Reflections from objects also produce amplitude variations in the received signal that cause noise and signal dropouts.

The number of variables that go into the performance of a particular antenna site is quite large, and many of these factors are beyond the broadcaster's control. Many can be mitigated, however, with good site selection, and it is on those that we must focus when searching for an antenna site.

The goal of the broadcaster is to produce a signal of sufficient amplitude to overcome noise and provide at least 20 dB of signal-to-noise ratio at as many of the receiver locations within the desired service area as possible. How much signal is sufficient to meet this goal is largely dependent upon the receiver and its antenna. In the absence of interference, a signal level of as low as 2 uV/m may be sufficient for many of today's automobile receivers. Portables may require as much as 500 uV/m. Interference from co- and adjacent-channel stations usually increases the amount of signal required for acceptable reception.

1.1 Fresnel Zone

There is no substitute for a clear line of sight between the transmit and receive antennas. This is one of the first rules in

VHF transmission. A transmitter site with a clear line of sight to virtually all the target service area is thus superior in most cases to one that is blocked by terrain or manmade obstructions to parts of the area. In some cases, simply having line of sight is not enough. In engineering our microwave and UHF STL paths, we always consider Fresnel zone clearance, knowing that a path with less than 60% first Fresnel zone clearance will be marginal. We often neglect this consideration in engineering our FM transmitting antenna locations.

For those not familiar with Fresnel zone clearances, they are circular areas surrounding the direct line-of-sight path that vary with frequency and path length. The longer the path and lower the frequency, the larger the mid-path clearance required for clear-path reception. As mentioned above, 60% first Fresnel zone clearance is all that is required to meet the clear-path reception objective, but that can be quite large at FM frequencies. The first Fresnel zone radius can be computed using the formula R = 1140 / d/f, where R is the radius in feet, d is the path length in miles and f is the frequency in MHz.

A quick example of 60% first Fresnel zone radius for a few typical broadcast situations are 267 feet for a class A, 378 feet for a class B and 463 feet for a class C1. Keep in mind that we're talking about terrain clearance at the mid-point between the transmitting and receiving antennas required to produce clear-path reception. These translate to antenna heights above ground of 534 feet, 756 feet and 925 feet respectively. With the exception of the class C, the antenna heights are well above the maximum height above average terrain (HAAT) values for the classes.

This brings us to the conclusion that height is a very significant factor in most antenna site situations. As a rule, greater height is more useful than higher power in producing higher receive signal strength, all other factors being equal.

1.2 Multipath Considerations

Multipath is a nasty word in the vocabulary of most radio engineers and station managers. It is a good descriptor of the destructive effect of the same radio signal arriving at a receive point by multiple paths. When these signals arrive in phase, all is well and the incident field strength is greater than it would be in the case of a single signal path. When they arrive out of phase, however, at least some degree of cancellation will take place, resulting in a reduced incident field strength, with complete cancellation (zero incident signal) taking place in the worst case situations.

To make matters worse, sometimes, complete cancellation can take place on frequencies close to carrier while less than complete cancellation takes place on sideband frequencies. This in many case results in a demodulated sound much more offensive to the listener than the quiet hiss of no signal. Motion in an automobile produces a constantly varying multipath situation, often causing picket-fencing (the effect of the slats in a picket fence alternately permitting and then blocking the signal), which is quite objectionable to the listener.

The worst-case multipath scenario is where the transmitting site is located on one side of the service area and a range of mountains or high hills is located on the other. Receivers within the service area get the direct line-of-sight signal from the transmitting antenna, but they also get a reflected signal from the mountains or hills. In such a case, there will be few locations within the service area where multipath effects will not be a factor.

Perhaps the best location for a transmitting antenna in such a geographic scenario, assuming that a mountaintop location is out of the question, is on a hill near the mountain range. A directional antenna would then be used to reduce radiation toward the mountains and maximize it toward the service area. This will result in greatly reduced reflections. While it would be impossible to completely eliminate reflections, they could be reduced so that the ratio of direct-to-reflected signal at most locations throughout the service area is sufficiently high to nullify the effects of multipath.

1.3 Grazing Angle

Ground reflections play a part in the overall propagation of FM signals, particularly the vertically-polarized component. Almost all FM signal coverage lies between the horizon and 10 degrees below the horizon. This is called the *grazing angle*, and it lies between the horizontal plane from the transmitting antenna and the earth's surface. Vertically-polarized energy is attenuated considerably more than horizontally-polarized energy at angles greater than about 2 degrees. As a result, circularly-polarized signals tend to be reflected more as elliptical rather than circular. It is important in site selection to avoid grazing angles which are greater than about 2 degrees (the *Brewster angle*). Simple geometry would suggest that sites close in to the service area would be more prone to produce such high grazing angles, indicating that a more distant site may be preferable.

1.4 Vertical Radiation Pattern

We mentioned early on the vertical-plane radiation characteristics of real-world transmitting antennas. Some of these characteristics come into play when selecting a transmitting antenna site.

If a transmitting antenna is located at a considerable height above the target service area, the main elevation plane lobe may overshoot the target service area, with the energy being radiated out into space. The more bays an antenna has, the narrower the main elevation plane will be. Antennas with a small number of bays (less than four) exhibit a broad elevation plane lobe, making such overshoot of the target service area less likely.

In those situations where a large number of bays is used and the antenna is high above the target service area, it may be desirable to employ *beam tilt* to lower the beam angle slightly. Typically, just enough beam tilt is used to center the main elevation plane lobe on the distant edge of the target service area or on the horizon, whichever is closer. We will discuss beam tilt in more detail in a later installment, but mention it here because it does impact site selection.

Antennas with a large number of bays exhibit elevation plane nulls. The more bays an antenna has, the farther away from the antenna site that these elevation plane nulls hit the ground. If the area within a few miles of the antenna site is populated and it is desirable to provide service to this area, it may be desirable to employ *null fill*. A very small amount of null fill is all that is necessary to provide adequate service in these close-in areas.

2.0 Antenna Gain vs. TPO

How many bays do I need in my antenna and how much transmitter power do I need? This question often does not have a hard and fast answer. Rather, the engineer designing an FM transmission system must look at many factors to come up with the best possible combination of antenna gain and transmitter power for a given situation.

Assuming that for a given value of effective radiated power (ERP) we have a choice of between one and twelve antenna bays. If we are dealing with a class A or other relatively low power station, we can narrow the choice down to a fewer number of bays. Quite obviously one would not use a ten-bay antenna, which is over 100 feet in length, for a 6 kW ERP station. Any savings in transmitter cost would be consumed many times over by the added antenna cost and additional tower height needed to achieve the required height above average terrain (HAAT) with such a large antenna.

On the other end of the spectrum, a 100 kW station would likely not utilize a one- or two-bay antenna. Any savings in tower height and antenna cost would be more than offset by the cost of the large combined-amplifier transmitter necessary to achieve the required ERP with a low-gain antenna.

With the choices narrowed a bit, we still have a fairly wide range of choices for antenna gain and transmitter power output (TPO) to achieve the required ERP. It is at this point that other factors come into consideration.

2.1 Economic Considerations

Economics is probably the biggest factor with most stations. Without an unlimited budget, a careful analysis of the *total* cost of each possible TPO/gain combination must be made. Factors which enter into this equation include the cost of the antenna, transmission line and transmitter, tower cost (keep in mind that larger antennas require taller towers to achieve a given HAAT), and long-term *operating* cost. Operating cost should be factored in over a period of time, usually the useful life of the transmitter (say, 15 years), and added into the cost equation. For example, a high-gain antenna/low TPO transmitter combination for a class B or C station will often result in considerable up-front costs because of added tower height and the cost of a larger antenna, but the power cost savings from the lower power transmitter will offset this over a period of time. The converse is also true. The best starting point is that range of gain/TPO values that fits the budget.

Once we get past what we can and cannot afford, there are as many approaches to what is the “best” gain/TPO combination as there are engineers. Most any broadcast engineer who has been in the business awhile has an opinion on the topic. Most of these are strong opinions, usually based on personal experience in one or more situations. As such, there is a degree of validity to most such views. How, after all, can one argue with empirical data?

The underlying truth, however, is that each situation is unique with a whole set of variables that may or may not bear any similarity to experiences elsewhere. To get to the *right* answer for a given situation, one must examine each of these variables.

2.2 Terrain Effects

The first of these, and perhaps the one that has the biggest effect on performance, is the lay of the land. What is the terrain like? The ideal situation is flat, unbroken terrain in all directions from the transmitter site. The equation becomes one of simple line-of-sight. Unless there is significant population close to the tower site, there is virtually no performance difference between a high-gain/low TPO and a low-gain/high TPO. In such cases, the best combination is the most economical. Find the combination that produces the desired ERP at the desired HAAT for the lowest cost.

Add to the equation terrain features such as hills or mountains and the picture is completely different. One of the most severe cases is one where the transmitter site itself is located atop a high terrain feature with the populated area to be served at significant depression angles below. In that case, the vertical plane radiation pattern of the antenna very much comes into play. The object is no longer one of producing the maximum amount of signal on the horizon but also (and often more importantly) includes producing good field strengths much closer in.

Manufacturers provide graphs and tabulations of the vertical plane radiation patterns of their antennas. This data can be used to locate the first and second vertical plane nulls as well as the relative field at any angle below the horizon. With this data in hand, one can use the free-space loss formula along with the ERP to calculate the expected best-case field strength at any given point. The performance of one antenna can be compared to another to find that combination that will best serve the desired areas.

So far, we have discussed the two extremes, flat terrain and mountaintop transmitter site. Reality is usually somewhere in between. In these cases, where the populated area is far enough away from the transmitter site to be situated well within the main vertical plane lobe of most any antenna, are we back to a simple economic decision? Usually not.

Multipath often exists within the coverage area of an FM station. Multipath is, as its name implies, the result of the signal arriving at the receiving antenna by disparate paths. There is (usually) the direct, or line-of-sight path, and then there are any number of other paths resulting from reflections and refractions. Instantaneous phase cancellations occur at many points, producing the familiar fuzz and choppiness of multipath. Site selection is the single most important factor in preventing objectionable multipath, but antenna selection has something to do with it as well.

Consider the case where a transmitting antenna is located just outside of a metropolitan area. The tall buildings downtown are usually pretty good reflectors of RF and their tops tend to be close to the same elevation as the transmitting antenna, thus putting them in the strongest part of the vertical plane pattern. Receivers located in vehicles and homes below are at a disadvantage because they are in a weaker part of the vertical plane pattern and they are in an area where shadowing and attenuation from trees, buildings and terrain features further weakens the direct-path signal. Now factor in the relatively strong reflected signal from the downtown buildings and you have a recipe for lousy reception in the very heart of the desired coverage area.

One way to combat this is by increasing the amount of direct-path signal by employing a much broader main vertical plane lobe. This is done by using a lower gain antenna. The vertical plane main lobe from a lower gain antenna is much broader, producing stronger signals at lower depression angles that will often overcome the reflected signals so that complete cancellation does not occur.

I mentioned above that every engineer has his own opinion, usually based on some specific experience, as to the "best" TPO/gain combination to produce a given ERP. In my opinion, the most consistent reception is produced by higher TPO/lower gain combinations. More signal at lower depression angles where the receivers live is almost always a good thing.

3.0 Vertical Plane Characteristics

Consider that with an FM antenna, we achieve "gain" by increasing the number of elements in the antenna. Antenna "gain" is referenced to the field produced by a horizontally-polarized half-wave dipole in free space. A horizontally-polarized antenna with one bay, for example, would nominally exhibit a power gain of one; adding an additional element to the antenna would increase its power gain to two. Additional bays would likewise continue to increase the gain of the antenna. Circularly-polarized (CP) antennas would exhibit half this nominal gain, as half the power of the antenna is vertically polarized (i.e. a two-element CP antenna has a nominal power gain of one). As a rule, only the horizontally-polarized mode is considered when discussing antenna gain.

A single-element antenna exhibits a large vertical-plane lobe with the radiation being distributed evenly both below and above the horizon. As additional elements are added to increase antenna gain, the vertical plane lobe is narrowed, focusing the main lobe energy on the horizon. Think of a single-element antenna as a floodlight which fairly well lights up an entire room with a relatively low light intensity. Increase the "gain" of the floodlight by focusing it with a reflector, turning it into a spotlight. The same amount of light energy is emitted by the bulb, but now it produces a much greater intensity in a much smaller area. Continue to focus the light until it is a brilliant pinpoint and you have done in essence the same thing as stacking twelve or more elements in an FM transmitting antenna. There are several places where this analogy falls apart, but it illustrates the general principle.

Maximum coverage is achieved by focusing the "beam" of the vertical-plane lobe on or just below the horizon. Increasing the antenna height naturally pushes the horizon out by allowing the antenna to look slightly beyond the curvature of the earth. If a tight vertical-plane "beam" of a multi-element antenna mounted on a tall tower is focused on the horizon (i.e. perpendicular to the tower and antenna), most of the energy radiated from the antenna will overshoot the target coverage area, being wasted out into space. This isn't much of a problem in cases where the antenna has few elements or is mounted below 500 feet above average terrain. However, in cases where a multi-element antenna is mounted 1,000, 1,500 or even upwards of 2,000 feet above average terrain, steps must be taken to mitigate the overshoot.

The seemingly obvious solution would be to mechanically tilt the antenna so that its vertical-plane "beam" is focused in the desired location, just below the horizon. While this technique does work, it has a serious drawback in that it only lowers the beam on the side toward which the antenna is tilted and it raises the beam an equal amount on the opposite side, in effect robbing Peter to pay Paul. In certain situations, this may be an acceptable course of action, such as where an antenna is located with all the populated area to one side, or where the antenna has a significant amount of terrain shielding on the side away from the populated area. In both such cases, the loss of signal on the opposite side would not matter.

3.1 Beam Tilt

A better way of achieving "beam tilt" is done electrically by delaying the currents to the lower antenna elements. This is easily achieved by simply inserting a "delay line" (or a short, additional length of transmission line, between the power divider and the lower antenna elements. Electrical beam tilt has the advantage of lowering the vertical-plane lobe equally in all directions. Typical values of electrical beam tilt are 0.5 to 1 degree.

Another byproduct of increasing antenna gain is that of elevation plane nulls. Any antenna with two or more elements will, in addition to the main vertical-plane lobe, have other secondary lobes both above and below the horizon. Along with these secondary lobes come vertical-plane nulls. Nulls above the horizon are of no consequence since they have no effect on coverage. Nulls below the horizon are a different story as it is below the horizon where the desired coverage area lies.

3.2 Null Fill

With an increasing number of elements, the elevation angle of the first null (i.e. the first vertical-plane null below the horizon) increases. As a result, the distance from the tower to the point on the ground where the first null lands increases. This null area, even though relatively close to the tower, is often an area of real signal problems. With virtually no direct-path signal, all the remaining signal comes from reflections and refractions and the net signal is plagued with multipath effects. If there is significant population within the null area (or if there is a major thoroughfare through the area), something must be done to mitigate these effects and make the station listenable there.

The best solution is to take steps in the antenna design to prevent the signal in the null from going all the way to zero. A very small amount of null fill, usually 5% or so, is more than adequate to provide plenty of direct-path signal to overcome all the reflections and refractions.

Null fill does not come without a penalty, however. That power put back into the vertical-plane null must come from somewhere, and it mostly comes from the main vertical-plane lobe. As such, null fill generally slightly lowers the gain of the antenna

How does one determine the distance to the first null? A quick method of determining the approximate distance is:

$$Null\ \ Radius\ \ (mi.) = \frac{Ant.Hgt.(ft)xNo.ofBays}{5280}$$

The antenna manufacturer can provide a complete vertical-plane pattern for the antenna being considered, and with this you can find not only the location of the null but its width. Overlaying that on a map can help you determine whether or not null fill is even needed.

4.0 VSWR Bandwidth

The bandwidth of a commercial FM broadcast signal, depending on whether or not subcarriers are used, is about 260 kHz. This figure is representative of a carrier modulated 110% (or 82.5 kHz deviation), the maximum allowed under 47 C.F.R. §73.1570(b)(2).

The term *VSWR Bandwidth* is generally defined as that bandwidth over which the antenna *system* has a VSWR of 1.1:1 or less (5% reflection coefficient). The antenna *system* includes the radiating elements, the interbay transmission line, matching devices and the transmission line. VSWR bandwidth is generally measured at the input to the transmission line (or the output of the transmitter).

Too often, FM antenna systems are tuned with the engineer watching the transmitter reflectometer while the tower worker adjusts the matching device on the tower. While this should result in the lowest attainable VSWR at the carrier frequency, it does not address the VSWR at the sidebands. Higher values of VSWR at the sideband frequencies or an asymmetrical passband will result in all sorts of undesirable effects.

4.1 Synchronous AM

Synchronous AM is one such undesirable effect of narrow VSWR bandwidth and/or asymmetrical passband. Consider a system which exhibits a very low VSWR on carrier and higher VSWR values at the sideband frequencies. As the carrier is modulated and power shifts to the sidebands, the perfect center-of-channel load presented by the antenna system becomes a much-less-than-perfect load at the sideband frequencies. Final amplifier tuning is no longer optimal and a significant amount of power is reflected from the antenna system back to the final amplifier. The result is a change in the otherwise constant amplitude of the FM carrier with modulation, or amplitude modulation. The phenomenon is called *synchronous* AM because the amplitude modulation occurs synchronous with the FM modulation of the carrier.

4.2 Intermodulation/Crosstalk

Other signal problems caused by narrow VSWR bandwidth or asymmetrical passband are reduction in power amplifier efficiency, intermodulation distortion and stereo crosstalk. The greater the deviation, the worse the resulting signal degradation. Sometimes, such signal anomalies are incorrectly identified as multipath when in reality they originate in the transmitter and antenna system. Needless to say, it is highly desirable to maintain good VSWR bandwidth.

4.3 Transmission Line Effects

As mentioned above, the antenna and transmission line must be viewed and treated as a *system* rather than discrete elements, in much the same way as the phasing and coupling system along with the towers themselves are treated as a system in AM directional work. Each has an effect on the other. The longer the transmission line, the greater the effect it will have on the performance of the antenna system, and not only in the area of losses.

Long transmission lines introduce considerable phase delay in the transmitted signals. While that is not a problem with respect to the power traveling from the transmitter to the antenna, it is a problem when power is reflected back to the transmitter from the antenna. The reflected power is delayed en route back to the power amplifier, where it recombines with the energy coming out of the power amplifier. It doesn't take a lot of imagination to see how an on-channel signal with an unknown phase relationship and instantaneous deviation can muck up an FM signal.

Because of this delay effect, with long transmission lines it is even more important to maintain good VSWR bandwidth. In fact, some engineers insist on sideband VSWR of 1.08:1 or less out to 130 kHz either side of the carrier in situations where long transmission lines are employed.

I mentioned above the reflectometer method of tuning an FM antenna. A much better method employs a signal generator and impedance bridge. An even better method makes use of a network analyzer. It is only by making an impedance sweep of the entire passband and plotting the results on a Smith chart can one accurately evaluate the overall VSWR bandwidth and performance of an antenna system.

Without specialized test equipment available, it is sometimes possible to get at least a rough idea of the VSWR bandwidth of an antenna by observing the screen current in the power amplifier. Screen current in some amplifier designs is a direct indicator of amplifier loading. Modulation activity in the screen current is often an indicator that VSWR bandwidth is less than optimal. Checking synchronous AM noise is another good indicator, provided that it is known that the transmitter tuning (especially in the IPA and PA grid) has been adjusted for minimum synchronous AM.

5.0 Antenna Designs

There are numerous FM antenna designs commercially available with differing characteristics. Some commercially-available FM antenna types are the panel with crossed dipole, ring, ring-stub, slanted dipole and "rototiller."

5.1 Ring Radiator

In the early days of FM broadcasting, several variations of the ring radiator were designed for both horizontal and vertical polarization. It was found that by adding vertical stubs to the ends of the radiator, it was possible to produce elliptical polarization. It is difficult to produce true circular polarization with a ring or ring stub radiator because the axial ratio varies with azimuth. Over the years, the design has been improved by adding a second ring. One advantage of this type of radiator is its excellent circularity in free space. A disadvantage is that it is a high-Q design and is more susceptible to detuning because of icing.

5.2 Ring-Stub Radiator

A variation on the ring radiator is the ring-stub. The horizontally-polarized radiation is produced by the ring portion of the radiating element. The popular Shively 6814 is an example of a commercially-available ring-stub design.

5.2 Slanted Dipole

The slanted dipole antenna was developed in the 1970s. As its name implies, it consists of two half-wavelength slanted dipoles bent 90 degrees. The two dipoles are fed in-phase. The ratio of V-pol and H-pol radiated power is determined by the slant angle. Shunt feeding provides for equal currents in all four dipole arms, which produces excellent circularity. The Jampro PENETRATOR is an example of a slanted dipole antenna.

5.3 Rototiller

Another popular design, often called the "rototiller" because the radiating elements have a shape similar to that of the blades of a rototiller, consists of two 2 series-fed bent dipole elements, forming a space phased, circularly polarized radiator. This configuration in combination with the relatively large diameter of the radiating elements tends to produce good bandwidth and inhibit corona discharge. The Electronics Research (ERI) SHPX is an example of this type of antenna.

5.4 Panel Antennas

Panel antennas were developed in the 1950s specifically for co-located stations. They come in both flat and cavity-backed configurations. Both the flat frame and cavity are made of a large-diameter wire mesh with 4- to 12-inch openings, which electrically appears as a solid surface (but produces very little wind loading). Two crossed dipoles are used as the illuminating source for each panel or cavity. The two dipoles are fed 90-degrees out of phase to produce circular polarization. This type of antenna is typically side-mounted on a large-aperture tower. Because they are directional, panel antennas typically require three or four panels to be mounted around the tower to produce a circular horizontal radiation pattern; circularity on the order of 2 dB is achievable. The cavity-backed design offers better axial ratios with more controllable azimuth pattern and better bandwidth. Cavity-backed panel antennas provide a lot of control where directivity is important.

5.4 Gain

With all these designs, antenna gain is achieved by vertically stacking multiple antenna elements or "bays" at full- or half-wavelength spacing on a common feed. A single circularly-polarized bay operating by itself usually exhibits a negative gain over a half-wave dipole in free space, while two bays usually provide near unity gain. More than two bays will exhibit a positive gain, and gains of up to seven are possible with an antenna with 12 bays.

5.5 Impedance Matching

Matching is an important consideration in FM antenna arrays. The simplest and perhaps most common method uses a VSWR tuner. This matching section is inserted between the transmission line and the antenna inter-bay line and consists of variable capacitors at 1/8 wavelength spacing along the main feeder at the antenna input. This type of matching section is used on many side-mounted antennas. It is adjusted for minimum reflected power to the transmitter. The net effect of this matching scheme is to place an impedance in parallel with the antenna impedance to match it to the 50-ohm line. The disadvantages of this method are that it is bandwidth limited and it produces standing waves within the inter-bay line.

Another matching scheme involves the use of dielectric or metal slugs on the main transmission line inner conductor. This type of matching scheme produces better bandwidth, although it is more difficult to adjust.

Other more complex schemes utilize phase quaderature compensation to achieve extremely wide bandwidth. This type of matching scheme is more typically used on master antennas fed by multiple co-located stations.

5.5 Deicing

Deicing equipment, either in the form of electric heat or radomes, tends to increase the complexity, cost, required maintenance and weight of an antenna. When ice forms on an antenna, the resonant frequency of the antenna tends to go down. A narrowband antenna with even a small amount of ice will present an unacceptably high VSWR to the transmitter, possibly leading to damage not only to the transmitter but also to the transmission line the antenna itself. Deicing equipment keeps ice from forming on the radiating elements, thus preventing this detuning. Broadband antennas, while detuned by ice just as more narrowband designs are, have sufficient bandwidth that the detuning has little effect on the load presented to the transmitter.

Keep in mind that high initial cost may be offset by many years of very low maintenance costs. The converse is also true. When selecting an antenna, the best approach is to select the very best antenna that your budget can stand. After all, what other part of your transmission system has more effect on the signal you present to your audience?

6.0 Transmission Line Types

In the case of FM antenna systems, there are generally two choices for transmission line types: rigid and semi-flexible.

Air-dielectric rigid line is, as its name implies, a fixed shape that is not intended to bend. It generally comes in 20-foot flanged or unflanged sections. Sections that are intended to go on the tower are generally equipped with factory-installed EIA flanges. Sections that are used for inside RF plumbing, such as between the transmitter, RF switch or patch panel, combiner and gas barrier are often supplied without flanges. Field flanges are available which are attached by silver-soldering or with hose clamps. A wide variety of adaptors, including reducers, elbows and 45-degree sections are available to allow routing of rigid transmission line to virtually any location within a transmitter building.

Semi-flexible line, aptly named because of its somewhat limited bending capability, comes in either air-dielectric or foam-dielectric types. In the case of air-dielectric line, the inner conductor is held in place with a Teflon spiral. With foam-dielectric semi-flexible line (available in sizes up to and including 2-1/4”), a foam dielectric material completely fills the space between the inner and outer conductors, holding a more-or-less constant spacing between the two. Semi-flexible line comes on a spool in a continuous run and is generally ordered to length. An EIA flange gas-barrier or gas-pass connector is ordered for either end to complete the transmission line run.

5.1 Pressurization

Either type of air-dielectric line requires a supply of nitrogen or dehydrated air to keep the line pressurized to a few p.s.i. above ambient. The purpose of the dry air is to keep out moisture. Pressurization of the line implies that the line must be airtight.

EIA flange connectors come equipped with rubber O-rings to provide an airtight flange-to-flange seal. Connectors fitted to semi-flexible air-dielectric line are equipped with special rubber seals that provide an airtight fit between the brass connector and the copper line.

A method of getting the pressurizing air or nitrogen into the transmission line must be provided, and this generally comes in the form of a gas-barrier. The gas-barrier can either be integral in a semi-flexible line connector or a stand-alone unit with an EIA flange on either end. A fitting is provided for connecting the pressurization tubing.

It is absolutely critical that moisture be kept out of air-dielectric transmission line. Moisture will cause oxidation in the copper, which increases attenuation at higher frequencies. Attenuation on the order of 4 dB per 100 feet has been measured in 3- and 3-1/8" semi-flexible and rigid air dielectric lines that have not been pressurized. This represents a tremendous power loss, which translates directly to signal loss.

5.2 Rigid vs. Semi-Flexible Line

There are advantages and disadvantages to both types of transmission lines. Rigid line has the advantage of lower losses. This usually amounts to a few hundredths of a dB per 100 feet over a comparable semi-flexible line. This can add up to a significant amount of power in the case of a long transmission line run.

Another advantage that rigid line has is that it is more repairable than semi-flexible. It can be removed from the tower in 20-foot sections, the inner conductor can be removed and both inner and outer can be cleaned. In the case of semi-flexible air-dielectric line, quite often a large section of the line must be removed and a replacement piece spliced in. The cutting process allows copper and Teflon shavings to fall into the line below the cut, and these shavings can accumulate in one location and produce an arc, causing further damage. Quite often, the only recourse in the case of a damaged semi-flexible line is to replace it in its entirety.

Semi-flexible line has the advantage of lower cost, sometimes as little as half the cost of a comparable rigid line. It also has the advantage of being in a continuous run as opposed to being joined with expansion connectors ("bullets") every twenty feet. Expansion, contraction and vibration of a rigid line cause chafing where the expansion connectors join the inner conductors and this often eventually results in a less than optimal connection. The I^2R loss at the connection causes heat, which further degrades the connection and eventually produces a burnout.

7.0 Transmission Line Selection

A broadcast engineer designing an FM transmission system has a number of choices for transmission line size and type. The factors that enter into this decision are transmitter power, line length and antenna gain. All three factors are somewhat variable. It is not uncommon for a given ERP and antenna gain to have the transmitter power level determined by the transmission line size and type. Changing to a larger or lower-loss line may permit the use of a smaller transmitter, somewhat offsetting the added cost of the better line. The other side of that coin is that the larger line may require a beefier tower to support it, adding cost to the project. Usually, however, the choice is a little clearer.

7.1 Power Rating

The first step in finding a suitable transmission line for a system is to determine the approximate power the line will have to carry. This is calculated by dividing the effective radiated power (ERP) in kW by the antenna power gain, or by subtracting the antenna gain in dB from the ERP in dBk and converting back to kilowatts. This calculation will yield the antenna input power, or the transmitter power output less the line loss, which is as yet unknown. While the antenna input power does not represent the total power in the line, it is a good starting point. Keep in mind that in combined systems, the power in the line is the sum of the power of each station.

Next, go to the manufacturer's catalog and find a line that exceeds the calculated line output power by a good margin, keeping in mind that the input power (which is the maximum power the line will have to carry) will be somewhat higher. While any of a number of transmission lines may have an adequate power rating, there will be few choices that offer both acceptable performance and economy. A good rule to follow when selecting a transmission line is to use the smallest line possible consistent with the required power handling capability. There are certainly exceptions, such as in the case of a very long transmission line, where it may be more important to keep losses (and thus long-term operating costs) down than the initial investment. As a rule, however, the goal should be to insure adequate performance while minimizing cost.

7.2 Line Loss

With a likely candidate selected, find the loss of the line at the operating frequency and line length. Manufacturers typically provide this information in dB per 100 feet or 100 meters. Divide the line length in feet or meters by 100 and multiply by the per unit loss to get the total line loss in dB.

7.3 System Calculation

To find the transmission line input power (or transmitter power output, TPO), add the line loss in dB to the antenna input power in dBk. Convert back to kilowatts by dividing by ten and taking the antilog. The loss of the line in kilowatts can be determined by subtracting the antenna input power from the transmitter power output. Divide the antenna input power by the TPO and multiply by 100 to calculate the efficiency of the line in percent.

Table 1 below shows an example of a system calculation. The system specifies an ERP of 50 kW, a four-bay antenna, and 500 feet of line at 100 MHz.

Table 1

ERP	50.00 kW	16.99 dBk
Antenna Gain	2.133	3.290 dB
Antenna Input Power	23.44 kW	13.70 dBk
Line Loss	0.851	0.700 dB
Transmitter Power Output	27.54 kW	13.40 dBk

Rounding in accordance with 47 C.F.R. §73.212, the *operating* TPO becomes

27.5 kW.

7.4 Safety Factors

The next question becomes one of headroom. Is a 3-inch line with a 42 kW power rating adequate? To find the answer, we must *derate* the line for VSWR. To do this, simply divide the power rating of the line by the worst-case VSWR. A good number to use to account for possible icing of the antenna is 2:1. In our example, the derated average power capability of the line for 2:1 VSWR is 21 kW. Is this reasonable for a 27.5 kW input power?

The answer to that question is determined by estimating the risk of the VSWR ever getting to that point. Are the protective circuits in the transmitter reliable? Are there deicers or radomes on the antenna, and are they effective and reliable? In most cases, you can count on your protective and deicing systems to do the job.

It is not wise, however, to put your eggs all in one basket. An outboard VSWR or reflected power monitoring device is a good investment to protect your very expensive transmission line. The trip point of the device should be set below the level that would exceed the rated average power of the line with full transmitter power output. In our example, the line is rated at 42 kW. Divide that by the TPO of 27.5 kW to find the maximum VSWR that will derate the transmission line to the TPO. In our example, this VSWR is 1.53:1. The idea is to make sure that in the worst case — with the transmitter running at full power and some sort of antenna problem — the line will be protected.

8.0 Transmission Line Installation

Little thought is given to proper transmission line installation in many cases. A bag of cable ties or a box of Wraplock in the tower rigger’s pouch is deemed sufficient to secure the line to the tower. Most radio engineers have seen transmission line installations where little more than electrical tape or cable ties was used to secure the line.

While such inexpensive measures will work in the short term, over a period of time, trouble will likely come as a result. Cable ties deteriorate with exposure to sunlight and extreme temperatures, becoming brittle, breaking and falling off. Thermal expansion/contraction as well as other differential motion between tower and line can cause Wraplock to chafe against the outer jacket, often resulting in the outer jacket and eventually the outer conductor being cut through. Once this happens the inside of the line is exposed to the elements.

8.1 Installation Hardware

Transmission line manufacturers offer a wide array of mounting hangers, brackets and hardware that are designed to protect lines from differential motion problems and keep them working properly for many years. In addition to the hardware, line manufacturers publish specifications for mounting hardware, including recommended spacing between hangers for different wind load and radial ice values. The published values are not simply theoretical numbers or designed to promote the sale of hardware. They have been derived from extensive empirical data — including wind tunnel testing — and are based on the EIA RS-222 standard (Structural Standards for Steel Antenna Towers and Antenna Supporting Structures).

8.2 Environmental Factors

Where a tower is located has an impact on the installation of a transmission line on the tower. Values of *design basic wind speed*, the maximum wind speed at a height of 10 meters over open terrain, are published for counties and states in EIA TIA-222-E. This is a good place to start when considering what hardware to use in a particular installation.

The maximum amount of radial ice accumulation is another factor that must be carefully considered when designing a transmission line installation. Some locations, particularly those in the southern tier of states, are especially prone to ice storms and large accumulations of ice on tower structures and attachments. Warm, moisture-laden air rides up and over cold surface air and falls as rain. When the supercooled raindrops impact the surface and objects on the surface, they instantly freeze. It is not uncommon to have 1” or more of radial ice build up on a tower structure, its antennas and lines in such circumstances, greatly increasing the dead weight and cross-section (and thus wind loading) of the tower, antennas and lines.

With the design basic wind speed and maximum expected amount of radial ice in hand, the manufacturer’s installation charts can be consulted to determine the type of hanger which should be used and the recommended maximum hanger spacing for a particular line. The quantity of hangers can then be calculated.

8.3 Installation Methods

The next step is to determine how the hangers will be attached to the tower structure. Many towers provide mounting tabs to which hangers can be directly bolted. This is the simplest means of attachment, and provides for very secure mounting.

Another means of mounting utilizes hose clamps or some other means of leg attachment. The hose clamp, sometimes called a “round member adapter,” clamps to the tower leg and to the hanger itself through a slot in the hanger. When utilizing this attachment method, especially with larger diameter transmission lines, some means must be provided to get around the flanges where tower sections mate. Specially made standoff kits are available from line manufacturers to provide a means of getting the line securely past flanges without allowing the line to chafe against the flanges.

Hoisting grips are “Chinese handcuff” devices that are designed to securely attach to a transmission line and pull it up the tower without stretching or distorting the line. Typically, one hoisting grip should be used every 200 feet to spread out the load. This helps keep the weight of the line on the load line and off the line itself. Once the line is in place on the tower, the hoisting grips are secured to the tower to provide permanent vertical support.

8.4 Grounding

It is very important to “ground” a transmission line to the tower at both top and bottom and in some cases at several locations along the line’s length. When lightning hits the tower, high-level currents will flow down the tower in all the available parallel paths, including in the outer conductors of transmission lines. Because copper has a lower DC resistance than the steel of the tower, greater currents are prone to flow in the transmission line outer conductors than in the tower steel. This will often result in significant potential developed between the transmission line outer conductor and the tower itself, resulting in arc-through of the transmission line outer jacket and pitting of the transmission line outer conductor. In extreme cases, the pitting will actually penetrate the outer conductor, opening the line to the elements and eventually destroying the line. Grounding or "bonding" the transmission line to the tower at frequent intervals is a good means of keeping the potential between the line and tower low and preventing such damage.

8.5 AM Tower Installation

AM towers are a special case. Depending on the feed system, there are several methods of installing a transmission line on an AM tower. In grounded-base (skirted or shunt-fed) towers, the method is essentially the same as with any other tower, except that more frequent bonding of the line to the tower should be done to minimize RF arcs through the line jacket.

There are two basic means of installing transmission lines on insulated-base AM towers. If an isocoupler or isocoil is used, installation above the base insulator is the same as for a grounded-base tower. If a quarter-wave stub is used, the line is installed using insulated hangers. In that case, the line is not bonded to the tower at any location below the shorting stub.

8.6 Rigid Line Installation

Rigid transmission lines are another special case. Rigid lines are fixed to the tower at the top of the run and mounted in spring hangers for the remainder of the vertical run. A nylon-jacketed collar is provided on each spring hanger to prevent horizontal motion. A spring connects the collar to a clamp that is affixed to the line below the collar. The manufacturer provides recommended settings for the springs to insure that the correct amount of tension is applied to the line at each location. The purpose of the springs is to allow differential motion between the line and tower structure because of thermal expansion. A rigid copper transmission line exhibits considerably more thermal expansion than a steel tower. If this is not allowed for, the line will buckle.

9.0 Maintenance

In most cases, once a transmission line and antenna have been installed on a tower, little thought is given them until something goes wrong. That is unfortunate, because they do require a certain amount of maintenance to keep them reliable and operating at peak efficiency.

9.1 Visual Inspections

Regular mechanical maintenance of an FM antenna system should include a complete visual inspection at least annually. This can be done in conjunction with relamping or other tower maintenance to minimize costs. Excitation must be removed from the antenna and other steps taken to insure that the tower is safe for workers to climb and work in the vicinity of the antenna.

The tower worker making the visual inspection should look at each element in the array for proper installation; for burns or pitting on the element ends; for cracks, carbon traces or defects in insulators; and for any evidence of abnormal mechanical stresses. Weep holes in the antenna elements, if any, must be oriented so that they face down.

9.2 Deicer Maintenance

If the antenna is equipped with deicers, they should be turned on during the inspection. The tower worker should then verify that the deicer in each element is working by feeling of the element.

One of the most dangerous icing situations for an FM antenna occurs when all the elements' deicers are working except one. All of the elements except that one remain clear of ice, and a serious mismatch occurs in the interbay line. Because the mismatch is limited to that one element, the transmitter's VSWR foldback circuit may not see sufficient reflected power to cause it to activate. With full power being fed to the antenna, an arc can occur and sustain itself until serious damage has been done to the antenna. From a protection standpoint, it is better to operate with no deicers than with a partially operating system.

A good deicer maintenance tool is a permanently-installed AC ammeter on the deicer circuit. With the deicers operating normally (and after a ten-minute warm-up period), mark on the meter face the nominal current. From time to time, the deicers should be turned on and allowed to warm up. The current can then be checked against the mark. If there is a deviation, a tower worker should be dispatched to investigate.

9.3 Transmission Line Inspection

Transmission lines should likewise be visually inspected annually. The connections at the top and bottom should be inspected for security, and any evidence of movement should be investigated. Ground connections should be checked and tightened and any corrosion should be removed.

In the case of rigid transmission lines, the length of each hanger spring should be checked against the manufacturer's recommendation. If necessary, the springs should be adjusted. Nylon buttons or bushings in the spring hanger collars should be checked. Should these fall out or become damaged, the copper transmission line will chafe against the metal of the hanger. This will eventually wear through the copper of the line, leading to line failure.

Rigid and semi-flexible lines should be checked for "hot spots" near flanges and connectors. In the case of rigid lines, this is every twenty feet. An infrared thermometer can be used for this, or the tower worker can simply feel of the joint and compare it to the adjacent portions of the line. Localized discoloration in rigid lines is a good indicator of abnormal heating. The cause of any significant heating should be investigated, as heating at a joint is a precursor to a line failure. Such heating is often caused by a "split bullet" or chafing in the inner conductor where it makes contact with the "bullet." The heating is evidence of I^2R loss in the joint, which is power not being radiated. In many cases, heating in the joints can quickly produce a thermal runaway situation leading to catastrophic failure of the line.

One tool available today that is of great help in locating hot spots in a transmission line or antenna is infrared photography. Hot spots will show up as a lighter color. The advantages of this method are that it can be done from the ground and it can detect subtler temperature rises. While IR photography has several advantages, it is not a substitute for a good visual inspection.

9.4 FM on AM Inspection

In some situations where an FM antenna is mounted on an AM tower, the transmission line will be mounted using insulated hangers. Each insulator should be inspected for cracks and carbon traces. The shorting stub, usually located somewhere close to 90 electrical degrees (at the AM frequency) above the tower base, should be checked for a good electrical connection at the line and the tower.

Other FM on AM situations employ an isocoupler to cross the base insulator with the FM transmission line. In these cases, it is important that the transmission line be electrically bonded to the tower frequently along its length. Each bond should be checked for good electrical connection. In addition, the entire outer jacket of should be checked for evidence of arc-through to the tower. If such evidence is present, it likely indicates that more frequent bonding is needed. Such arc-through, if permitted to continue, can eventually penetrate the outer conductor of the line and open the line to the elements.

Grounded-base AM towers, such as folded unipoles and shunt-fed antennas, likewise require the FM transmission line to be frequently bonded to the tower steel along its length. The same checks of the bonding and outer jacket should be made on grounded-base AM towers.

9.5 Pressurization Maintenance

Proper pressurization of air-dielectric lines is critical to their performance. Pressurization with dry air or nitrogen has a direct effect on the breakdown voltage (and thus the power handling capability) of the line. If moisture is allowed to enter the line, corrosion will result, producing higher losses, hot-spots and eventual line failure. The pressure integrity of the line and antenna should be checked by closing the air valve feeding the line at the bottom of the run and observing the line pressure over a period of several hours. If the pressure bleeds off, there is a leak and it should be located and repaired.

An adequate nitrogen supply should be maintained at the site to insure that the supply is not exhausted before another delivery can be made. If the pressure integrity of the line is maintained, very little nitrogen should be used. Pressurization equipment should be regularly inspected, at least weekly, and maintained in good working order. Desiccant should be rotated out and dried or replaced whenever it begins to turn from blue to pink. A dehydrator with a saturated desiccant pumping moist air into a line is almost as bad as having no pressurization at all. The use of a self-recharging dehydrator will prevent this from ever happening.

9.6 System VSWR Monitoring

Finally, a check of the system reflected power should be made during every site visit. A significant change, up or down from the nominal value, should be investigated. A more sensitive indicator of load impedance in some power amplifier designs is the screen current. Higher screen current generally indicates a lighter (higher Z) load. If PA tuning is otherwise correct, an increase in screen current may be an indicator of a developing antenna or line problem.

In addition to checking the reflected power, the VSWR foldback and trip circuits in the transmitter or external protection device should be checked from time to time to insure that they are working. Transmitter manufacturers usually provide a procedure for checking and adjusting the internal protective circuits.

If the directional coupler(s) use removable slugs to detect forward and reflected power, they should be checked regularly for proper operation and good connections. A reflected power meter that reads zero all the time may be an indication that the connection, either between the slug and the coupler or between the coupler and the transmitter, is bad. If that is the case, chances are there is no VSWR protection in place, which can lead to a catastrophic failure of the line/antenna and damage to the transmitter.