ANTENNAS FOR HIGH-FREQUENCY BROADCASTING

High-frequency (HF) broadcasting (also known as shortwave broadcasting) uses discrete bands from 2 to 30 MHz (Table 1). These bands are based on international agreements which also permit broadcasting at other frequencies on a non-interference basis. HF signals propagate by refraction from the E- and F-layers of the ionosphere, regions of ionized gases located approximately 100 to 400 km above the surface of the earth. HF ionospheric propagation is very effective for broadcasting over distances of many thousands of kilometers. The limit of good quality HF service is generally taken to be 6,000 to 7,000 km, this being the limit in two-hop mode where there are two ionospheric reflections. HF has been used extensively for broadcasting across national borders by governmental and private organizations.

GENERAL CHARACTERISTICS

HF broadcasts must use optimum transmit frequencies in order to obtain useful signal strength at the receiver. Frequen-

Table 1. HF Broadcast Bands

Band—MHz	Frequencies—MHz	
2	2.300–2.495	Tropical regions only
3	3.200–3.400	Tropical regions only
4	3.900–4.000	
5	4.750–5.600	Tropical regions only
6	5.950–6.200	
7	7.100–7.350	
9	9.400–9.900	
11	11.600–12.050	
13	13.570–13.800	
15	15.100–15.800	
17	17.480–17.900	
19	18.900–19.020	
21	21.450–21.850	
26	25.670–26.100	

cies of optimum transmission (FOTs) are determined by the electrical characteristics of the ionosphere, which vary with the time of day, month of the year, and level of solar activity. The large variability of the FOT means that an HF broadcasting system must operate over a wide range of frequencies. To minimize the number of antennas, modern transmitting stations employ broad-bandwidth antennas which can operate in many or all of the allocated bands.

HF broadcasting typically uses transmitter carrier powers of 50 to 500 kW, with a few systems using 1000 kW. Currently, HF transmissions use double sideband (DSB) amplitude modulation to allow signals to be received and demodulated by simple and inexpensive receivers. Future plans call for the implementation of single-sideband (SSB) or digital modulation.

A DSB AM signal with carrier power P and modulation index m, where $0 < m \leq 1$, has an average power of $(1 + m^2/2)\ P$ and peak envelope power of $(1 + m)^2\ P$. For 100% modulation ($m = 1$), average and peak power levels are, thus, 1.5 P and 4 P. An antenna excited by a fully modulated 500 kW transmitter must, therefore, be designed to withstand the currents of a 750 kW source and the voltages and fields of a 2000 kW source.

HF broadcasting antennas must have radiation patterns that match the requirements for a particular target service area. The antenna's gain, horizontal beamwidth, and vertical angle of radiation (takeoff angle, or TOA) must be chosen carefully in order to provide a strong signal in the audience area. This requires taking into account the ionospheric propagation characteristics, distance to the audience area, and its geometric shape. Antenna selection is aided by computerized propagation prediction programs such as VOACAP and IONCAP, which calculate TOAs, FOTs, gain, and signal strengths.

Despite the variability of the ionosphere as a refracting medium, some general rules apply to the selection of HF broadcasting antennas. HF broadcasting antennas generally operate in the 6 to 21 MHz frequency bands. Antennas which serve distant audiences have low TOAs, narrow horizontal beams, and high gain of 15 to 30 dBi (dBi is the antenna gain in dB above an isotropic radiator). Antennas that serve nearby audiences have higher TOAs, broader or even omnidirectional beams, and lower gains in the range 9 to 14 dBi. These antennas are often designed to operate down to 2.3 or 3.2 MHz, frequencies which are required for propagation over short distances, particularly at night and when sunspot activity is low.

HF broadcasting antennas are almost without exception horizontally polarized. Although vertically polarized HF antennas have many desirable characteristics, such as low TOA and broad azimuthal patterns, their peak gain is reduced by more than 3 dB if the ground in front of the antenna is not highly conductive. These ground losses may be partially overcome by siting the antenna very close to sea water, which has excellent electrical conductivity, or by installing a ground screen made from a large mesh of copper wires located several hundred meters in front of the antenna. In most situations, such solutions are neither desirable nor possible.

The gain of horizontally polarized antennas is much less dependent on ground conductivity. For a horizontal antenna, poor ground conductivity reduces the gain at low and intermediate TOAs by only a few tenths of a dB. It is thus unnecessary to use ground screens for horizontal antennas with low TOAs.

For TOAs above 60°, which are required for short-range broadcasting, vertical antennas are unsatisfactory because their elevation patterns have a null directly overhead. A horizontal antenna, however, can easily be designed to have its peak radiation directly overhead. In this situation, ground losses can reduce gain up to 3 dB, making it worthwhile to install a small ground screen underneath the antenna.

HF broadcasting antennas fall into two main classes: log-periodics and dipole arrays. Log-periodics are wideband, generally not steerable, and best limited to 250 kW carrier power. Dipole arrays are limited in bandwidth but can handle more power and are capable of being steered or slewed electrically by up to ±30°. This allows a broadcaster to serve different target areas with one antenna. An alternative arrangement is for the entire antenna structure to be built to rotate. However, rotatable antennas are rarely used, owing to the cost and complexity of the steering mechanisms and the associated structures.

LOG-PERIODIC ANTENNAS

Log-periodic antennas (LPAs) are a class of frequency-independent antennas first developed in the 1960s. In the HF band, LPAs have been used mainly for communications, but since the 1970s, they have been increasingly used for broadcasting. Unlike a single dipole array, whose operation is limited to a one-octave (2 : 1) frequency range, an LPA can operate over nearly a four-octave (16 : 1) frequency range, covering all of the broadcast bands from 2.3 through 26.1 MHz.

LPAs comprise a series of half-wave dipoles spaced along a transmission line where the lengths of the dipoles and intervening transmission lines follow a geometric progression. The ratio of successive lengths is a constant, commonly called the scaling constant and represented by the symbol τ. By convention, the progression starts with the longest element so that τ is less than 1 and typically in the range of 0.8 to 0.92. LPAs are fed at their high frequency end, where the radiators are smallest. Current flows up the internal antenna feed line until it reaches a group of radiators, called the active region, which are approximately one-half wavelength wide at the excitation frequency. The active region radiates in the direction of the smaller radiators. LPAs typically have balanced input impedances of 100 to 400 Ω and maximum voltage standing wave ratio (VSWR) of 1.8 : 1 or less.

A highly desirable feature of LPAs is the ability to tailor their radiation patterns to satisfy different broadcasting requirements. The designer can control the way the radiation pattern varies with frequency, by making the pattern either independent of or dependent on frequency. This is not true for dipole arrays, whose patterns vary with frequency in a way which cannot be controlled.

The radiation pattern of an LPA is determined by the number and arrangement of its curtains. In some LPAs, the TOA is designed to decrease as frequency increases. This helps the broadcaster reach audiences at varying distances, since long paths generally propagate best using higher frequencies, while at the same time requiring low TOAs. In other cases, the TOA is kept constant, which is very useful for broadcasting to a fixed geographical area. The horizontal beamwidth of an LPA can also be controlled by the designer; although in most situations, a fixed beamwidth is most useful.

The physical size of an LPA depends on its frequency range (principally its low-frequency limit) and radiation pattern characteristics. While the relationships among these characteristics are complex, the following relationships generally apply:

1. The largest radiators of an LPA are approximately one-half wavelength long at the lowest operating frequency. Thus, the lower an antenna's frequency limit, the larger the antenna.
2. The TOA of any horizontally polarized antenna is given by the formula

$$\mathrm{TOA} = \sin^{-1}(\lambda/4h) \tag{1}$$

   where λ is the wavelength at the operating frequency, and h is the height above ground of the radiating element with the highest current. Thus, for a low TOA, an antenna's height will be large compared to its wavelength; conversely, high TOAs require lower heights.
3. The horizontal beamwidth of an antenna varies inversely with its horizontal radiating aperture (the physical width of the active region relative to the wavelength at the operating frequency). Narrow beamwidths require larger apertures and physical size than do broad beamwidths.

LPAs have been designed to operate at transmit powers of 500 kW with 100% amplitude modulation; however, these antennas are large and expensive. Power levels exceeding 250 kW are better handled by dipole arrays. The most cost-effective power range for high-power LPAs is 50 to 250 kW, with 100 kW versions the most common.

An LPA concentrates most of the radio frequency (RF) power into the small number of radiators in the active region. Destructive corona discharge occurs if this concentrated RF energy results in excessive electrical fields perpendicular to the surface of the conductors. The electric field varies inversely with the electrical diameter of the conductor, so fields can be lowered by increasing conductor diameters. Radiators can be made from large-diameter tubes or pipes, but the resulting structures are expensive and mechanically unreliable. A less expensive and more reliable means of increasing electrical diameter is to form two small-diameter (8 to 12 mm) wire cables into a triangular tooth (Fig. 1). Radiators with large electrical diameters are advantageous because they have lower Q and broader bandwidth than thin radiators. In an LPA, lower Q increases the number of radiators in the active region, which decreases the power in each radiator. The larger active region also provides a small increase in antenna gain.

Examples of Log-Periodic Antennas

Short-range LPA. To cover short distances, an HF antenna must direct energy at high angles with peak radiation at vertical incidence; that is, TOA = 90°. According to Eq. (1), the active region at each frequency must be approximately 0.25 wavelengths at the operating frequency. Figure 1 illustrates a two-curtain LPA which provides a vertically-incident pattern giving primary coverage from 0 to 1500 km. Short-range antennas have low-frequency operating limits in either the 2.3 or 3.2 MHz bands. The upper frequency limit is usually set at 18 MHz to cover areas in the 1000 to 1500 km range.

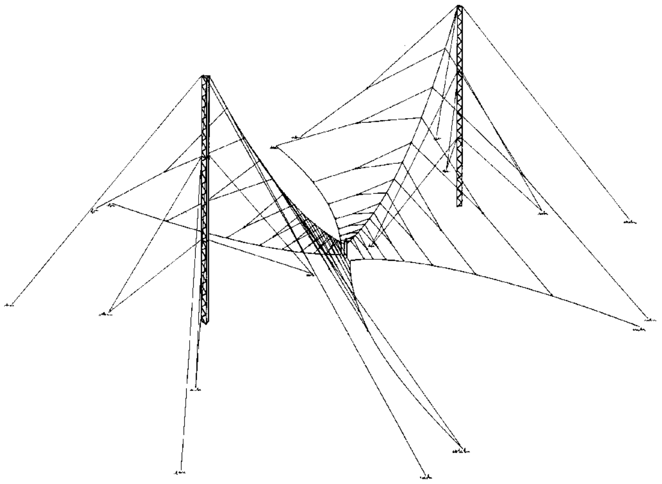

Figure 1. Short-range log-periodic antenna for distances of 0 to 1500 km. The antenna fires downward into the ground, which reflects the signal upwards.

The short-range LPA has a maximum gain of 9 dBi at vertical incidence and produces a nearly circular horizontal pattern. The elevation pattern has its −3 dB points at approximately 50° above the horizon. The antenna obtains its high-angle coverage by firing energy downward into the ground, which in turn reflects it upwards. A ground screen minimizes losses in the imperfectly conducting earth. The short-range LPA is the only horizontally polarized antenna for which a ground screen provides meaningful gain enhancement.

Medium-range LPA. A two-curtain LPA suitable for broadcasting over distances of 700 to 2000 km is illustrated in Fig. 2. While similar to the short-range LPA, this antenna fires obliquely into the ground producing a lower TOA and narrower elevation pattern than the short-range LPA. Antennas of this type have TOAs in the range of 20° to 45°, with gains of 14 to 10 dBi, respectively, and horizontal patterns having −3 dB-beamwidths of 68° to 90°.

Long-range LPA. A four-curtain LPA (Fig. 3) suitable for broadcasting at distances of 1500 km and beyond provides vertical and horizontal patterns that are narrower than the two-curtain LPA. This antenna provides gain of up to 18 dBi and low TOA in the range of 12° to 20°. The −3 dB horizontal beamwidth is 38°.

DIPOLE ARRAYS

Dipole arrays are rectangular or square arrays of half-wave dipoles mounted in front of a reflecting screen (Fig. 4). Dipole arrays have high power handling capacity and provide a wide variety of different radiation patterns to serve different broadcasting requirements. Beams of dipole arrays can be steered in both the vertical and horizontal planes without moving the entire antenna. Dipole arrays have typical gains of 15 to 18 dBi.

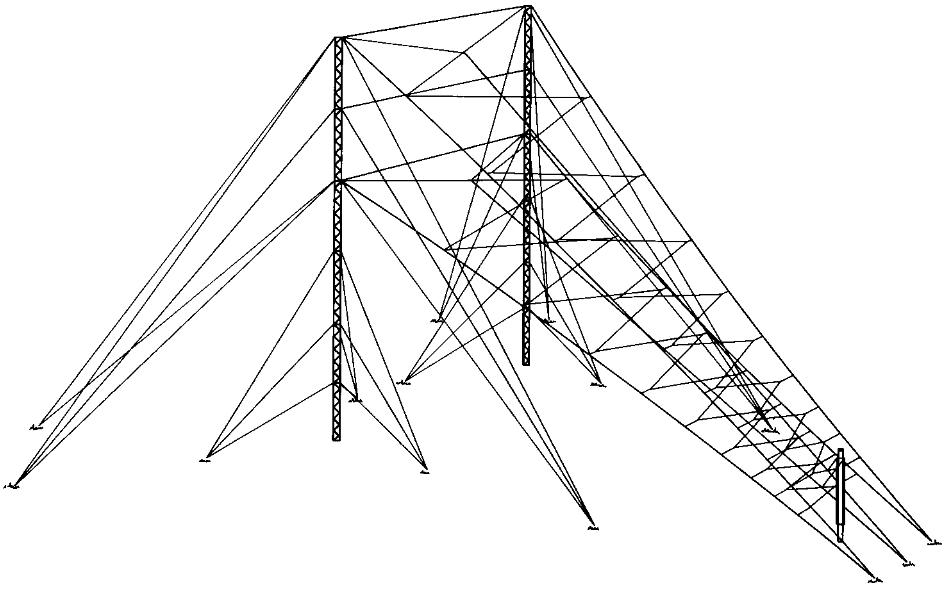

Figure 2. Medium-range log-periodic antenna for distances of 700 to 2000 km. The antenna fires obliquely into the ground producing a low take off angle.

Dipole arrays containing four or more dipoles have low VSWR over a one-octave frequency range. Arrays with fewer than four dipoles generally have narrower impedance bandwidths. Unlike an LPA, one dipole array cannot cover the entire shortwave frequency range, which is four octaves wide. However, two dipole arrays, one operating in the 6/7/9/11 MHz bands and the other in the 13/15/17/19/21/26 MHz bands, can cover the frequencies used in international broadcasting. The dimensions of a dipole array are determined by its design frequency, f_0, which is approximately equivalent to the arithmetic mean of the lowest and highest operating frequencies. The design wavelength, λ_0 (m) is $300/f_0$ (MHz). Horizontal and vertical centers of the dipoles are spaced at $0.5\lambda_0$ wavelengths.

The dipoles in the array are interconnected by a set of balanced transmission lines. The transmission lines terminate at a single feed point having a balanced impedance of 200 to 330 Ω. The input VSWR of a dipole array is generally 1.5 : 1 or less in its operating bands.

A dipole array is described by the standard nomenclature HRS $m/n/h$; H indicates that the antenna is horizontally polarized, R that it has a reflecting screen, and S (if present) that the antenna beam can be slewed horizontally or vertically. The integers m and n indicate, respectively, the number of vertical columns and the number of dipoles in each column. The height h of the lowest dipole above ground is expressed in wavelengths at the antenna design frequency. The m, n, and h parameters determine the antenna's radiation patterns. Most common values are $m = 2$ or 4, $n = 2, 4,$ or 6, and $h = 0.5$ to 1.0. The radiation patterns for various dipole arrays (Table 2) demonstrate the wide variety of radiation patterns which dipole arrays can provide.

The number of vertical columns, m, determines the horizontal aperture of the antenna. For $m > 1$, the -3 dB horizontal beamwidth (HBW) at frequency f is approximately $100° (f_0/mf)$. At $f = 1.34 f_0$, the upper frequency limit of a one-octave bandwidth, the minimum HBW is 75° divided by m.

The number of dipoles in each column (n) and height of the lowest dipole (h) determine the TOA and elevation pattern beamwidth. In typical dipole arrays, $h \leq 1.0$, and $n \leq 6$ (larger values would result in very tall and expensive antennas). The effective height of radiation is the average height above ground of all the excited dipoles. The effective height can be used in Eq. (1) to calculate the TOA.

Modern dipole arrays use reflecting screens to suppress radiation behind the antenna and increase forward gain by

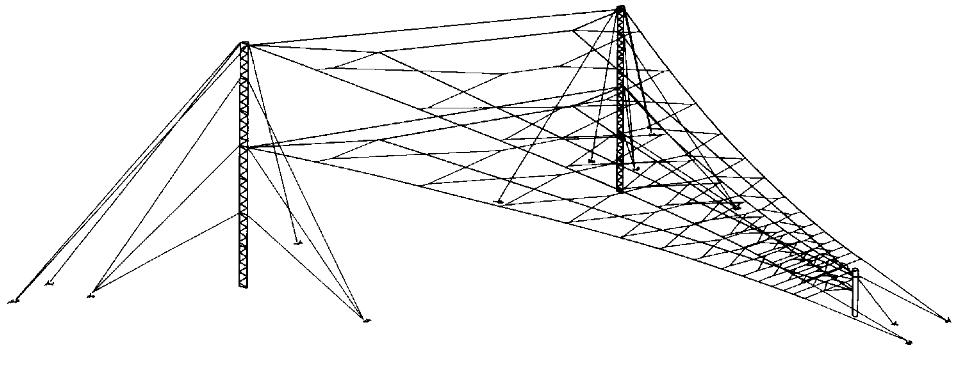

Figure 3. Long-range log-periodic antenna for distances of 1500 km and beyond. The antenna produces a narrow horizontal beam with low take off angle.

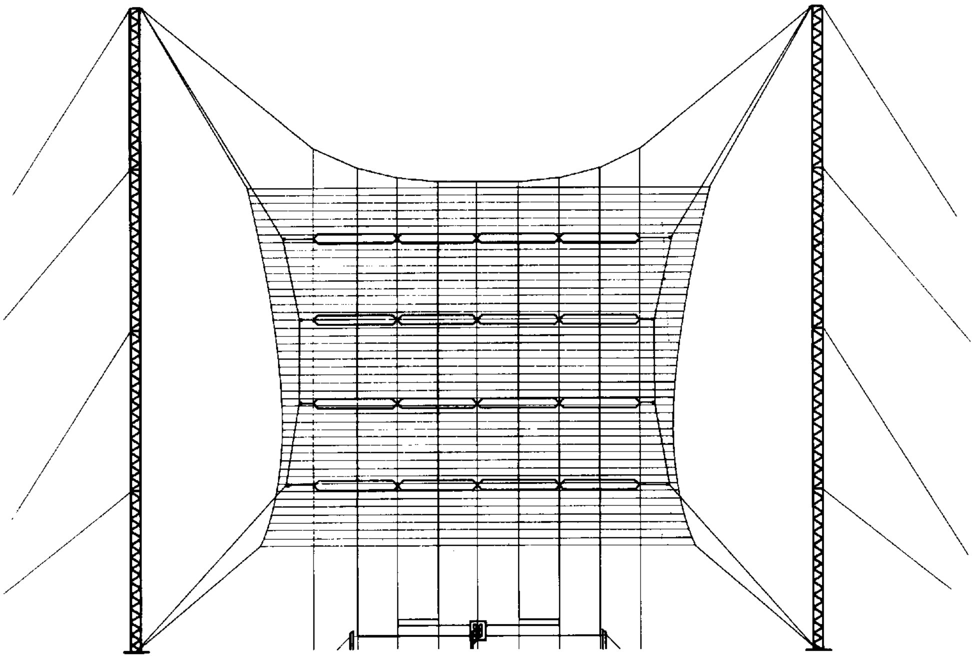

Figure 4. Typical dipole array. Configuration shown is HRS 4/4 containing four columns each with four dipoles. Reflecting screen is mounted behind the dipoles. Slewing switch and transmission lines underneath dipoles steer the beam horizontally.

nearly 3 dB. A typical screen consists of horizontal wires separated vertically by 0.04 to $0.06\lambda_0$. The screen is placed approximately $0.25\lambda_0$ behind and parallel to the plane of the dipoles. It extends approximately 0.125 to $0.25\lambda_0$ beyond the edges of this plane. Screens for 2-, 4-, and 6-high arrays have 25 to 35 wires, 50 to 75 wires, and 75 to 100 wires. These parameters produce a back lobe which is 12 to 15 dB below the gain of the main beam. The back lobe may be reduced further by adding more screen wires. Halving the vertical spacing by doubling the number of wires reduces the back lobe by 6 dB, although there is a tradeoff: screens with more wires impose greater loads on the support towers.

Slewing Dipole Arrays

Phase delays can be inserted via RF switches in the internal feed lines of a dipole array to slew, or steer, the pattern in the horizontal plane. Horizontal slews of up to ±30° relative to boresight are accomplished by switching in delay lines which introduce a progressive phase delay from column to column. Slews greater than 30° should not be used since the result would be high VSWR and excessive side lobe levels. For maximum horizontal coverage with minimum complexity and cost, slewing systems should provide angular steps equal to approximately 50 to 75% of the HBW. Thus, a five-position slewing system providing 10° to 15° steps is suitable for a four-wide array, which has a minimum HBW of 19°.

Vertical slew may be accomplished by switching off one or more pairs of dipoles in each column. Six-high arrays, for example, commonly have three vertical slew positions. The lowest TOA is obtained with all six dipoles excited. Medium- and high-angle slews are obtained by exciting only the bottom four and bottom two dipoles, respectively.

Slewing of a dipole array can cause resonances near the lower frequency limit. Resonances always produce voltages much higher than normal and may also cause excessive VSWR. Resonances are caused by circulating currents which flow between the interconnected dipoles. At a circulating current resonance, some dipoles have negative input resistance and thus act as a power source rather than a power sink. Circulating current resonances are 50 to 250 kHz wide, comparable to the width of a broadcast band. In four- and six-high arrays, multiple resonances can occur, preventing operation in one or more bands. Resonant frequencies are determined by the path length between the dipoles and can be changed by altering this length. The prediction and measurement of circulating current resonances is an important part of both the design and construction of dipole arrays.

Table 2. Radiation Patterns of Typical Dipole Arrays Over 2 : 1 Bandwidth

Array Type	TOA	−3 dB HBW	−3 dB VBW	Gain—dBi
HRS 2/2/0.5	13°–25°	40°–70°	13°–25°	18–15
HRS 4/2/0.5	13°–25°	20°–35°	13°–25°	21–18
HRS 2/4/0.5	7°–14°	40°–70°	7°–14°	21–18
HRS 4/3/0.5	8°–16°	20°–35°	8°–16°	23–18
HRS 4/4/0.5	7°–14°	20°–35°	7°–14°	24–19
HRS 4/4/1.0	5°–10°	20°–35°	5°–10°	24–19
HRS 4/6/0.5	4°–8°	20°–35°	4°–8°	25–20

Note: First value in range is for highest frequency. Second value is for lowest frequency.

TRANSMISSION LINES, SWITCHING SYSTEMS, AND BALUNS

A broadcast station's transmitters are connected to its antennas via a feed system which includes balanced and/or coaxial transmission lines. All but the simplest feed systems also include switching, usually provided by a matrix of switches, which select the antennas that are to be connected to the transmitters. Feed systems generally include balanced-to-unbalanced (balun) transformers to match the balanced impedance of most high-power HF antennas to the unbalanced impedance of modern transmitters.

Rigid Coaxial Line. RF output is typically taken from the transmitter by means of a rigid coaxial transmission line. Coax sizes range from $6\frac{1}{8}$-inch EIA-standard for 100 kW to 9-inch (nominal, not standardized) for 500 kW. Characteristic impedance is usually 50 or 75 Ω. Coax lines outside the transmitter building require constant pressurization with 3 to 10 psi of dry air to prevent condensation of moisture. Lines within the building do not require pressurization.

Switch Matrix. The typical switch matrix comprises a number of rows and columns of motorized single-pole, double-throw switches. Typically, transmitters feed the rows of switches; in turn, the columns of switches feed the antennas. The matrix configuration allows any transmitter/antenna combination while prohibiting the connection of two transmitters to a single antenna, or two antennas to a single transmitter.

Switch matrices can be either balanced or unbalanced. Balanced matrices have impedance levels of 300 to 330 Ω. Unbalanced matrices are either 50 or 75 Ω. Balanced matrix switches are generally shielded to minimize RF radiation in the vicinity of the switch. Coaxial switches are inherently shielded by nature of their construction. Coaxial switch matrices are generally preferred in new installations because they are smaller in size and have greater RF isolation between the switches.

Baluns. The input of a balun matches the impedance of the coaxial portion of the system, usually 50 or 75 Ω; the output matches the balanced impedance of the antenna, usually 300 Ω. Some transmitters are equipped with baluns which use a network of motorized adjustable components that are set to different values for each transmitter operating frequency. Another type of balun is a completely passive device which is designed to operate over a wide range of frequencies without tuning. A broadband balun consists of a coaxial section which converts the RF power to a balanced mode, and a tapered balanced transmission line which transforms the impedance to 300 Ω. A typical broadband balun is 33 m long and operates from 6 to 26 MHz.

Balanced Transmission Line. Balanced, or “open-wire,” transmission line is commonly used to feed high-power RF to antennas. This line usually consists of two pairs of copper, aluminum, aluminum-clad steel, or copper-clad steel wire cables held at a fixed distance by means of high-voltage insulators. The line is held under tension 3 to 6 m above ground by poles spaced at 15 to 25 m intervals. Open-wire transmission line costs less than rigid coax and is much easier to repair.

Feed System Configurations

HF broadcasting stations generally use one of three types of feed systems: all balanced, all unbalanced, or combined balanced and unbalanced.

The balanced system is used when the transmitter includes its own balun and therefore provides a balanced output. The RF switches and transmission lines are balanced and have an impedance level which matches that of the antennas.

In the unbalanced system, all feeders from the transmitter to the RF switches and from the switches to the antenna are coaxial lines. Each antenna has a broadband balun whose frequency range matches that of the antenna.

In the combined unbalanced/balanced system, coaxial feeders are used between the transmitter, a coaxial switch matrix, and broadband baluns. The switch matrix is located in the transmitter building. The baluns are placed outside of the transmitter building at locations that are close enough to minimize expensive runs of coax but far enough away to prevent excessive electromagnetic fields at or near the building. The long feeder runs from the baluns to the antennas are balanced open-wire transmission lines.

The balanced system is used primarily at stations that contain a small number of transmitters and antennas. It is the least expensive of the three systems. In stations containing numerous transmitters, a balanced switch matrix will occupy a large amount of space and is therefore not desirable. The unbalanced system is the most expensive but is preferred when there are environmental concerns which necessitate maximum shielding of the transmission line system. The combined unbalanced/balanced system is the one most commonly used at modern stations because it provides a good tradeoff between cost, size, and performance.

Reading List

G. Braun, *Planning and Engineering of Shortwave Links,* London: Heyden & Son, 1982.

R. E. Collin and G. A. Zucker, *Antenna Theory,* vols. 1 and 2, New York: McGraw-Hill, 1969.

K. Davies, *Ionospheric Radio,* London: Peregrinus, 1990.

J. M. Goodman, *HF Communication, Science and Technology,* New York: Van Nostrand, 1992.

G. Jacobs and T. J. Cohen, *The Shortwave Propagation Handbook,* Port Washington, NY: Cowan, 1979.

R. C. Johnson and H. Jasik (eds.), *Antenna Engineering Handbook,* New York: McGraw-Hill, 1993.

J. A. Kuecken, *Antennas and Transmission Lines,* Indianapolis: Howard Sams, 1969.

Y. T. Lo and S. W. Lee, *Antenna Engineering Handbook,* New York: Van Nostrand, 1988.

A. G. Sennitt (ed.), *World Radio TV Handbook,* Amsterdam: Billboard Books, 1998.

W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design,* New York: Wiley, 1981.

W. Wharton, S. Metcalfe, and G. Platts, *Broadcast Transmission Engineering Practice,* London: Butterworth-Heineman, 1992.

J. Wood, *History of International Broadcasting,* London: Peregrinus, 1992.

Ronald Wilensky
Gordon G. Sinclair
Richard R. Greene
Technology for Communications
International