Transmission Line for Broadcast Applications

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***Abstract*—The major design criteria for standard broadcast transmission lines and their correlation to published specifications are detailed. Technical performance and applications for DTV are outlined.**

***Index Terms*—Transmission Line, Coaxial Cable, Waveguide**

I. Introduction

Transmission lines are one of the main components in the RF transmission plant. They play a critical role in both the quality and reliability of the broadcast signal. Therefore, the proper choice of a transmission line type to be used can have a significant impact on the success of the station.

The choice of transmission line is typically based on the following criteria:

1) Frequency of Operation
2) Power Handling
3) Attenuation (or efficiency)
4) Characteristic Impedance
5) Tower Loading (size and weight)

For broadcasting, the impedance and size characteristics have been standardized to a fixed set of options: 50 or 75Ω characteristic impedances: 3-1/8, WR1500, GLW1750 circular waveguide, etc. for sizes. Some changes have been made to improve tower loading such as improved outer conductors for rigid coaxial lines to reduce weight and a 7-3/16in rigid coaxial size to bridge the power gap between 6-1/8in and 8-3/16in lines. However, the primary characteristics involved with DTV transmission performance are operating frequency, power handling and attenuation. Associated with these is the consideration of group delay within a waveguide transmission line system. These characteristics will be reviewed for coaxial lines and waveguide.

II. Coaxial Lines

A coaxial transmission line consists of two concentric conductors, the inner conductor being supported within the outer conductor through the use of a dielectric material. The dielectric material may be continuous throughout the line or, as in the case of rigid coaxial lines, located at distinct points along the line in the shapes of pegs or discs. Because of the geometry, all coaxial lines follow common guidelines in determining their electrical and thermal characteristics.

2.1 Frequency of Operation

For coaxial lines, the frequency of operation for a specific outer conductor size and characteristic impedance is limited by the highest usable frequency before undesirable modes of propagation occur, called the cut-off frequency. However, each mode of propagation has a unique cut-off frequency and care should be taken not to confuse the higher-order modes in coaxial line discussed here with the dominant mode cut-off frequencies for waveguides (which will be discussed later).

The coaxial cut-off frequency is important when power handling versus frequency is being reviewed. A larger size of coaxial line will handle greater power levels, however, its frequencies of operation will be at lower frequency ranges. Since higher frequencies have higher attenuations (see next section), it is desirable to run more power to overcome the losses. This results in a situation where a choice must be made between (1) lower ERPs (operating at lower power levels), (2) using waveguide (typically higher windloads) or (3) risking degraded performance due to higher order modes being present. The higher mode coaxial cut-off frequency in MHz, f_c, is approximated using the following equation:

$$f_c = \frac{7520}{(D+d)\sqrt{\varepsilon'}} \qquad (1)$$

where
ε' = dielectric constant or relative permittivity of dielectric to air
D = inside electrical diameter of the outer conductor, in
d = outside electrical diameter of the inner conductor, in

Differences in the maximum operating frequency of specific line sizes are sometimes evident when reviewing various manufacturer specifications. This is typically a result of a different safety factor used when deciding on the specification. A 5-10% reduction in the calculated cutoff frequency is a normal safety factor and will account for manufacturing tolerances and the effects of connections and elbows. For complicated installations (where extensive use of elbows or transitions occurs), additional margin may be necessary to prevent the generation of higher order modes.

2.2 Attenuation

The attenuation of a coaxial line is normally expressed in terms of loss per unit length, dB/100 ft (dB/100 meters). The attenuation is due to conductor and dielectric losses. As a simple equation this can be expressed as:

$$\alpha = A\sqrt{f} + Bf \quad (2)$$

where
α = attenuation constant, dB/100 ft
A = conductor losses
B = dielectric losses
f = frequency, MHz

For rigid coaxial lines, dielectric losses have been considered negligible and with the use of copper conductors, Equation 2 is usually shown as:

$$\alpha = \left(\frac{0.433}{Z_o}\right)\left(\frac{1}{D} + \frac{1}{d}\right)\sqrt{f} \quad (3)$$

where
Z_o = characteristic impedance
D = inside electrical diameter of outer conductor, in
d = outside electrical diameter of inner conductor, in

It should be noted that designs using additional dielectric material for better structural support between the inner and outer conductors (i.e. additional pegs or cylindrical discs), should include additional losses of between 1 % and 4% in the calculations. Also, the above equation assumes a conductivity rating of the copper conductors of 99% or greater. In practice, the surface conditions rarely approach that of newly produced copper tubes due to oxidation and handling of the materials.

To account for this effect on the conductor, a conductivity rating of 95% should be used, resulting in an additional 1-2% increase in attenuation. When comparing manufacturer data, these issues should be reviewed for consistency between specifications. Also note that the conductivity varies with temperature. A 20°C ambient is standard for conductivity ratings. If the temperature of the conductor is different from the standard rating, the conductivity must be adjusted. One area that is not normally taken into account for television broadcast is the actual temperature of the inner conductor during operation. The increased temperature due to power loss in the line results in higher attenuation values. The adjustment factor typically used for attenuation, M_α, is given by:

$$M_\alpha = \sqrt{1 + \sigma_o\left(T_t - T_o\right)} \quad (4)$$

where:
T_t = inner conductor temperature °C
T_o = inner conductor temperature at standard rating, °C
σ_o = temperature coefficient of resistance at standard rating

For a standard temperature rating of 20°C, σ_o = 0.00393/°C. Then:

$$M_\alpha = \sqrt{1 + 0.00393\left(T_t - 20\right)} \quad (5)$$

Therefore, if the rated average power of the line allows an inner conductor temperature of 100°C, during operation at maximum rated power the attenuation will increase by a factor of 1.146. By performing this calculation the system power requirements for TV stations may be determined. The intention is to review design parameters that are not typically used in system analysis but could be used to analyze transmission configurations for DTV. Once the attenuation constant has been determined, the efficiency of the system can be calculated. The total attenuation (α_{total} in dB) is found by multiplying the attenuation constant by the total length. This is then converted to efficiency:

$$Eff = 10^{-\left(\frac{\alpha_{total}}{10}\right)}\left(100\%\right) \quad (6)$$

2.3 Power Handling

The power handling capabilities of coaxial lines are based primarily on two factors: the maximum peak power (or maximum voltage gradient that can safely be present) and the maximum average power, which is determined by the allowable temperature rise of the inner conductor.

2.4 Peak Power

The maximum electric field strength between two coaxial conductors can be calculated from:

$$E_{\max} = \left(\frac{0.278}{d}\right)\sqrt{\frac{P}{\ln\left(\frac{D}{d}\right)}} \quad (7)$$

where

E_{max} = maximum electrical field strength, volts/in
P = power level of signal, watts

Because voltage breakdown levels are extremely sensitive to effects such as internal surface conditions and environmental factors, the theoretical value should not be used in practice. It has become standard procedure to use 35% of the theoretical value in determining the production test voltage and ultimately the rated peak power value. The DC test voltage is derived from the following equation that includes the derating factor:

$$E_p = \left(3.17 \times 10^4\right)\left(d\delta\right)\left(\log\left(\frac{d}{D}\right)\right)\left(1 + \frac{0.273}{\sqrt{d\delta}}\right) \quad (8)$$

where
E_p = production test voltage

δ = air density factor = 3.92 B/T
B = absolute pressure, cm of mercury
T = temperature, K
(δ = 1 for B = 76 cm and T = 23°C = 296 K)

The production test voltage must now be converted to RF RMS voltage, E_{RF},

$$E_{RF} = (0.7)\left(\frac{1}{SF\sqrt{2}}\right)E_p \quad (9)$$

where
E_{RF} = maximum RF RMS operating voltage with no derating for VSWR or modulation, but includes a safety factor, SF.
$1/\sqrt{2}$ = RMS factor
0.7 = DC to RF factor
SF = safety factor for voltage (typically 1.4 for coaxial cables and 2 for rigid coax)

The peak power rating in watts, P_{pk}, can now be calculated:

$$P_{pk} = \frac{E_{rf}^2}{Z_o} = \frac{\left(\frac{(0.7)E_p}{SF\sqrt{2}}\right)}{Z_o} \quad (10)$$

Once the peak power rating has been determined, it is necessary to derate that value for the effects of modulation and VSWR. These deratings are calculated as follows:

AM:

$$P_{\max} < \frac{P_{pk}}{(1+M)^2(VSWR)} \quad (11)$$

FM:

$$P_{\max} < \frac{P_{pk}}{VSWR} \quad (12)$$

Analog TV:

$$P_{\max} < \frac{P_{pk}}{\left(1+AU+2\sqrt{AU}\right)(VSWR)} \quad (13)$$

DTV:

$$P_{\max} < \frac{P_{pk}}{(PA)(VSWR)}$$

where
P_{max} = derated maximum peak power
M = amplitude modulation index (100% = 1)
AU = aural to visual ratio (20% aural: AU = 0.2)
PA = DTV Peak-Average Ratio, typically 7.

For most installations, the peak power ratings will not be a significant factor as they are typically much higher than a single transmitter system can generate. The primary concern will be for multiple channel installations where two or more TV signals are combined into the same transmission line. If the peak voltages from two or more signals of equal power add together in phase, the equivalent peak power rises as the square of the number of carriers. In this situation, voltage levels can become the primary concern in specifying the transmission line type.

2.5 Average Power

The average power rating is determined by the amount of heat created due to line losses. The amount of heat, or temperature rise, is primarily limited by the safe, lifetime performance of the dielectric material used to support the inner conductor. Since the temperature rise on the inner conductor is greater than the outer conductor, the maximum allowable temperature is normally specified based on inner conductor temperature at the rated power level. Typical industry conditions have been to allow the inner conductor to reach a temperature of 100°C with an ambient temperature of 40°C. This means the inner conductor temperature is allowed to rise 60°C above the ambient. The average power rating can then be calculated using the following equation:

$$P_{avg} = \frac{(16380)\sigma D}{\alpha M_\alpha} \quad (14)$$

where
P_{avg} = average power rating for 60°C rise of inner conductor temperature
D = outer conductor outside diameter, in
σ = heat transfer coefficient of outer conductor, watts/in2
M_α = correction factor for attenuation (relative to 20°C)
α = attenuation constant, dB/100 ft at 20°C

Standard heat transfer coefficients are listed below in Table 1 for rigid coaxial line types.

The average power rating is based on the temperature rise on the inner conductor and this in turn affects the lifetime performance of the dielectric material. Therefore, operation at higher temperatures will result in a reduction in the life expectancy and reliability of the line relative to the lower temperature performance.

Field experience has shown that, barring improper installation or damage, the typical failure mode of coaxial lines is damage to the connection points as a result of excessive heating over time. Based on this observation, long-term operation of coaxial lines at elevated temperatures is not recommended.

Line Size	Zo	σ
7/8	50	0.1280
1-5/8	50	0.1200
3-1/8	50	0.1070
4-1/16	50	0.1035
6-1/8	50	0.0970
6-1/8	75	0.0770
7-3/16	75	0.0760
8-3/16	75	0.0740
9-3/16	50	0.0900
9-3/16	75	0.0660

Table 1: Heat Transfer Parameters for Rigid Coax

2.6 Velocity of Propagation

A final performance characteristic to review for coaxial lines is the velocity of propagation or group velocity, V_p. It is expressed as a fraction of the speed of light in a vacuum and is related to, ε', the effective dielectric constant of the insulating medium:

$$V_p = \frac{c}{\sqrt{\varepsilon'}} \qquad (15)$$

where
c = speed of light

As can be seen from this equation, for coaxial lines that are effectively homogeneous throughout their structure, the phase velocity is constant for all frequencies. Therefore, group delay is not an issue when reviewing performance for digital signal transmission.

III. WAVEGUIDE

When using waveguide as the broadcast transmission line, peak power and average power ratings will be much greater than needed for even combined channel operations. Since broadcast waveguide types do not require the use of a center conductor, voltage breakdown and average power levels are controlled primarily by the quality of the installation and any waveguide to coaxial line transitions that may be present. Therefore, these characteristics will not be discussed in this paper.

3.1 Attenuation

Attenuation in a waveguide structure is dependent on its shape, the conductor material and frequency, much like it is in coaxial lines. However, because there are various types of waveguide offered to broadcasters: rectangular, circular, doubly truncated, etc., the discussion is more involved. One characteristic that must be emphasized, however, is that the attenuation is inversely proportional to frequency [1]. This means that for a specific line size, the attenuation constant becomes smaller as frequency of operation is increased.

Both waveguide and coaxial lines exhibit very little change in attenuation values across a 6 or 8 MHz channel. The variation is typically less than 0.05 dB for well-designed systems and can be considered negligible to the overall performance for both analog and digital signal transmission.

3.2 Frequency of Operation

Unlike coaxial lines, waveguide has a non-zero lower cut-off frequency. The lower and upper cut-off frequencies define a band of frequencies in which the performance of the waveguide is acceptable for broadcast use. The upper cut-off frequency is based on the same criteria as coaxial line in preventing the propagation of unwanted modes. The lower frequency cut-off is the frequency at which wave propagation is possible. Therefore, below this frequency there is no usable propagation of the signal. Again, a 5-10% safety margin is desired to account for manufacturing tolerances and components in specifying the actual frequencies of operation.

3.3 Velocity of Propagation

From the previous discussions on attenuation and operating frequencies, it is also true that the propagation of signals in waveguide is somewhat different than that for coaxial lines. Due to the lower cutoff frequency, f_c, the velocity of propagation in waveguide is dependent on the frequency of operation. For waveguide:

$$V_p = c\sqrt{1-\left(\frac{f_c}{f}\right)^2} \qquad (16)$$

As an example of the effect of the foregoing parameters, assume a 1000 ft long run of 15" diameter circular waveguide with a lower cut-off frequency of 461 MHz. At Channel 44 (650-656 MHz), the time difference of arrival from the transmitter to the antenna between the upper and lower as the channel edge is:

V_{p1} = 0.6931 ft/ns
V_{p2} = 0.6995 ft/ns
T_1 = 1442.8 ns
T_2 = 1429.6 ns
$T_1 - T_2$ = 13.2 ns

For the same waveguide used at Channel 30 (566-572 MHz), the time difference will be:

V_{p1} = 0.5703 ft/ns
V_{p2} = 0.581 9 ft/ns
T_1 = 1753.5 ns

$T_2 = 1718.5$ ns
$T_1 - T_2 = 35$ ns

Based on the overall system requirements, these time delays may be negligible. If not, pre-correction can be accomplished since the delay can be readily calculated [2].

IV. SUMMARY

The basic formulas for determining the primary operating characteristics of both coaxial transmission lines and waveguide for broadcast have been presented. For coaxial lines, the broadcast engineer can perform basic calculations to provide a comparison to manufacturer's data. This should provide for a better understanding of safety factors and risks when analyzing new systems for analog and digital transmissions. Waveguide was reviewed primarily to provide more insight into the performance parameters that will most effect its use for DTV. Based on simple calculations, no significant impact on DTV transmission should be present in a well-designed system. Mechanical considerations were not a part of this paper, however, tower loading is a significant issue and should be an integral part of the decision process.

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