WHITE PAPER

Where Does 75-Ohms Come from Anyway??

ABSTRACT

The Question You Have Asked Many Times is Answered in Historical Context Here…with a Look at The Future of Coaxial Cable…

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Where Does 75-Ohms Come From Anyway??

Conrad L. Young

Abstract- General formulas for and the parameters employed to design and describe coaxial transmission lines are presented. The propagation characteristics of coaxial transmission lines are presented with description of coaxial line characteristics plotted as functions of the ratio of radii of outer and inner conductors. Attenuation and its importance to the launch, carriage, and delivery of video and high-speed data (HSD) via wired broadband networks is highlighted. Historical and future perspectives provided.

Index Terms- CATV, MATV, 75-Ohms, coaxial transmission lines, coaxial cable, transverse electromagnetic (TEM) wave, principal mode of propagation, wavelength, frequency, angular frequency, velocity of light, dielectric constant, loss tangent, skin effect, permeability, resistance, inductance, conductance, phase velocity, attenuation, characteristic impedance, Zo, power capacity per unit length, breakdown voltage, periodicity, NTSC, Channel One (1), spectral efficiency, QAM, M-ary QAM, COFDM, Dual or Siamese coaxial cable, flexible coaxial cable, hardline coaxial cable, 3-GHz.

I. INTRODUCTION

Not long after the first community access television (CATV) systems were installed and generating revenue in Pennsylvania USA in 1948-49 it became obvious to operator and subscriber alike that 300-Ohm Twin Lead cable left a lot to be desired (Young, CATV Hybrid Amplifier Modules: Past, Present, Future, 2009). Susceptible to significant signal leakage when placed near conductive objects or surfaces or due to loss of signal integrity due to environmental decay, Twin Lead cable connecting early CATV users and customers to a community TV antenna could occasionally provide unintentionally “free” TV delivery service to a subscriber’s neighbor. Twin Lead cable, referred to as “Ladder”, “Windowed Ladder”, or “Ladder-Line” cable when configured with between lead cut-out areas (to reduce weight) as shown in Figure 1, was employed in early CATV installations for some of these reasons:

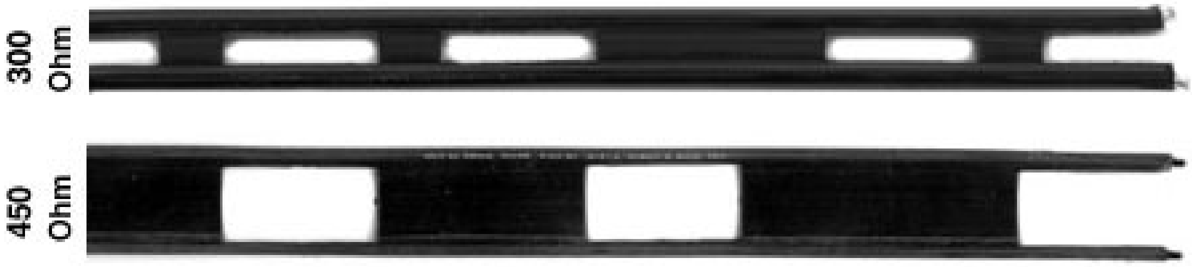


Figure 1. 300-Ohm and 450-Ohm Twin Lead “Ladder” Cable

1. Low transmitted signal loss over distance at the frequencies employed by TV broadcasters in 1948-49 (44 to 216 MHz). See Table 1 and Figure 2.

Type of Cable	α in dB/100 m (DRY)	α in dB/100 m (WET)	F (MHz)	SOURCE
300-Ohm Twin Lead	2.92	7.05	50	(DX Engineering, 2018)
	4.9		108	(Nelson, 1965)
	9.8		162	(Nelson, 1965)
	13.1		216	(Nelson, 1965)
52-Ohm RG58 Coaxial	8.55	8.55	50	(Belden Incorporated, 2019)
	12.5	12.5	108	(Belden Incorporated, 2019)
	15.4	15.4	162	(Belden Incorporated, 2019)
	18.4	18.4	216	(Belden Incorporated, 2019)
75-Ohm RG59 Coaxial	6.73	6.73	55	(Commscope, 2019)
	8.14	8.14	85	(Commscope, 2019)
	11.81	11.81	187	(Commscope, 2019)
	12.47	12.47	211	(Commscope, 2019)

Table 1. Twin Lead versus Flexible Coaxial Cable Signal Loss @ VHF

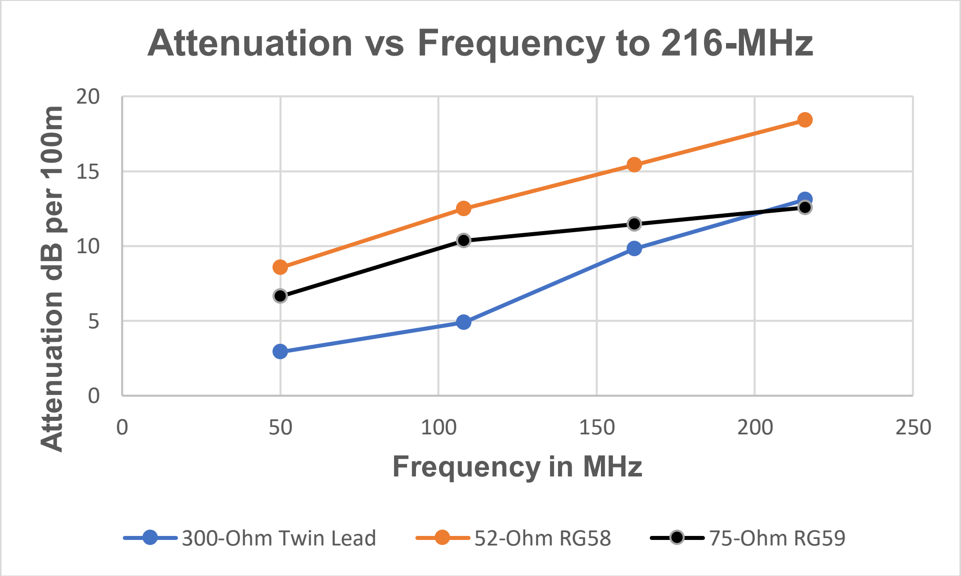


Figure 2. Attenuation vs Frequency_300-Ohm Twin Lead vs Flexible Coax

a. See Table 2 for a list of OTA TV broadcasters operating in the Philadelphia Pennsylvania USA area in 1948-49.

1948-49 Call Sign	Today's Call Sign	NTSC Channel	F (MHz)	1948-49 Network	Today's Network
W3XP		1	42 to 50	Philco Radio & TV Corp	
W3XEP		1	42 to 56	RCA Manufacturing Co	
W3XPF		1	42 to 56	Farnsworth TV Inc of PA	
WPTZ	KYW	3	60 to 66	Philco Radio & TV Corp	CBS
WFIL-TV	WPVI	6	82 to 88	ABC	ABC
WCAU-TV	WCAU	10	192 to 198	CBS	NBC

Table 2. OTA TV Stations Transmitting in Philadelphia PA USA Area in 1948-49 (Early Television Museum, 2019)

  b. Ever wonder why there is no "Channel One (1)" in National Television System Committee (NTSC) channel lineups or incorporated in today's NTSC display, TV, set-top-box (STB) and gateway tuners? In North American broadcast TV frequencies, channel one (1) is a former broadcast (over-the-air, OTA), TV channel. (RCA, 1941) During part of the experimental era of OTA TV operation in North America, 1938-1948, channel 1 was moved around the lower very high frequency (VHF) spectrum repeatedly, with the entire band displaced upward to 50 to 56 MHz in the period 1940-1946 due to an early 40-MHz allocation for the then new Frequency Modulation (FM) radio band. (New York Times, 1940). Channel 1 operated in the frequency range 44 to 50 MHz in the periods 1938-1940 and 1946-1948. (Early Television Museum, 2019)

2. To efficiently feed a non-resonant multi-band antenna - primarily because ladder-line is a differential transmission line that does not suffer from high losses at high voltage standing wave ratio (VSWR), so may be used to feed an antenna that presents the feed-line with any VSWR from 1:1 to ~12:1. So, with ladder-line you can discount resonance and VSWR, until you get to the radio, where you use a tuner to make the match to 50Ω. (Melton, 2019). Note: One of the reasons that relatively short runs of nominal 50-Ohm RG58 coaxial cable is used to connect VHF band antennas, such as antennas used in amateur radio installations, instead of potentially lower attenuation nominal 75-Ohm coaxial cables is that amateur radio receivers and transmitters typically operate using 50-Ohm input/output (I/O).
3. Availability in quantity and at relatively low cost as US military surplus in the period just after the end of World War II (WW 2), notably at the Philadelphia Naval Shipyard.

Ladder-line was often replaced in CATV installations by flexible coaxial cable starting in 1949-50 because:

(1) of unintended signal loss when near conductive materials as described herein.
(2) of significant increase in attenuation (Jerrold Electronics, 1960) when wet (and "wet" can mean a "misty wet" and not submersion in water). Nominal dry attenuation performance returns when the Ladder-Line dries.
(3) of relative fragility as Ladder-Line decays in unprotected outdoor installations.
(4) master antenna television (MATV) installations in this period demonstrated reliable and consistent delivery of OTA TV signals using flexible coaxial cable, such as nominal 75-Ohm RG59, RG6 and other types readily and cheaply available as military surplus. (Chandler, 2019). Jerrold Electronics MUL-TV MATV System Model

CA-2 through CA-6 Channel Amplifiers in this time period were sold, installed, and operated using coaxial cable interconnects (nominal 72-Ohm). Models CA-2 through CA-6 were specified to operate at one (1) NTSC analog TV channel, channels two (2) through six (6) matching the Model Number (i.e., Model CA-2 operated on NTSC channel two (2) between 54 and 60 MHz and CA-6 (as shown herein) operated on NTSC channel six (6) between 82 and 88 MHz, as examples). See Figures 3-4.

Figure 3. Jerrold CA-6 MATV Channel Amplifier Rear Panel Showing 72-Ohm Coaxial I/O (Chandler, 2019)

Figure 4. Jerrold CA-6 MATV Channel Amplifier Serial Number Plate (Chandler, 2019)

II. GENERAL FORMULAS FOR COAXIAL LINES

Coaxial lines are transmission systems in which electromagnetic waves are transmitted through a dielectric medium bounded by two coaxial cylinders. The skin depth^ at frequencies greater than 10 MHz is small enough so that for most purposes of calculation the conducting boundaries may be considered infinitely thick.

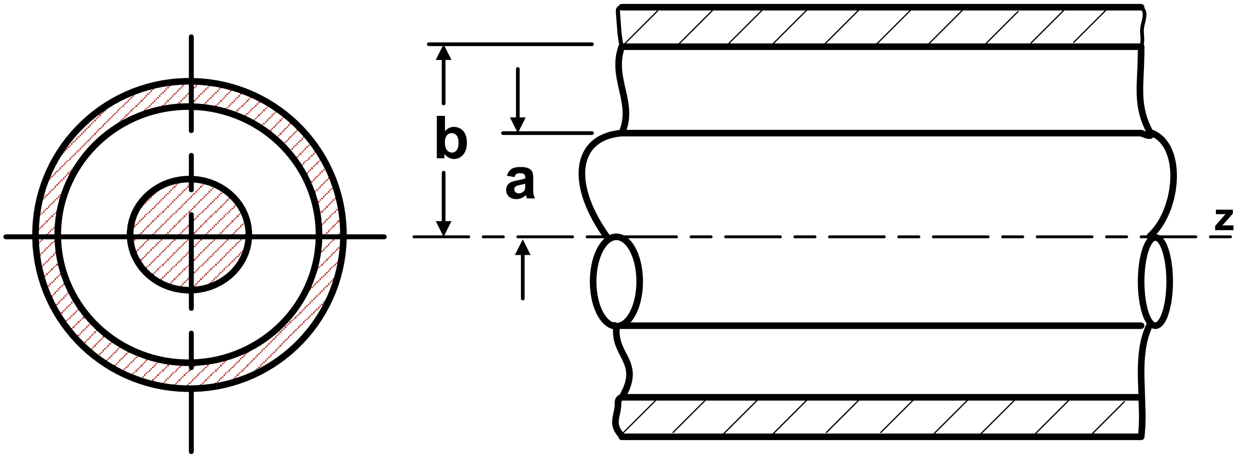


Figure 5. A Section of Coaxial Transmission Line, Illustrating Notation (Moreno, Microwave Transmission Design Data, 1989)

Having two separated conductors, coaxial lines are capable of carrying energy in the principal transverse electromagnetic (TEM) mode of propagation and are generally used with this mode carrying energy. (Ragan, 1948). The characteristics that follow are applicable for the principal mode of transmission, except where noted.

The symbols used are as follows, with “a” and “b” illustrated in Figure 5:

λ	wavelength
f	frequency
ω	angular frequency = $2\pi f$
v	velocity of propagation
c	velocity of light in free space = 3×10^{10} cm/sec
a	outer radius of inner conductor
b	inner radius of outer conductor
ϵ	dielectric constant = unity in free space
ϵ_1	dielectric constant of propagating medium
μ	permeability = unity in free space
μ_1	permeability of medium separating the conductors
R	resistance per unit length
L	inductance per unit length
G	conductance per unit length
C	capacity per unit length
Z_0	characteristic impedance

Coaxial Line Parameters

Inductance (L) per unit length of coaxial line is:

$$L = 0.4605 * \mu_1 (\log_{10} b/a) \times 10^{-8}$$ **henry/cm {Equation 1}**

This formula neglects penetration of fields into conducting boundaries.

Capacitance (C) per unit length between conductors is:

$$C = \left\{ \frac{0.241 * \epsilon_1}{(\log_{10} b/a)} \right\} \times 10^{-12}$$ **farad/cm {Equation 2}**

Conductance (G) per unit length of coaxial line is: $G = \omega C \tan \delta$ **{Equation 3}**

;where ($\tan \delta$) is the loss tangent of the dielectric medium.

NOTES: the conductance per unit length of a coaxial line may be neglected if the line employs an air or very low loss tangent gaseous dielectric. For a solid dielectric line there is an effective conductance resulting from energy loss in the dielectric.

Resistance (R) per unit length is given by:

$$R = \rho/2\pi\delta \quad = \quad \sqrt{f\mu\rho/10^9} * (1/b + 1/a)$$ **{Equation 4}**

;where δ is skin depth in centimeters^, f is the frequency in cycles per second (cps), ρ is resistivity in ohm-centimeters, μ is permeability, and the radii of the coaxial line, b and a, are in centimeters. The resistance of the coaxial line is proportional to the square root of the resistivity of the conductors. This is because of skin effect.

The characteristic impedance (Z_0) of a low-loss coaxial line is:

$$Z_0 = \sqrt{L/C = 138 * \sqrt{\;}\mu_{1/}\,\epsilon_1 * (\log_{10} b/a)} = 60 * \sqrt{\;}\overline{\mu_{1/}\,\epsilon_1 * \ln (b/a)}$$ **in Ohms {Equation 5}**

The characteristic impedance as a function of diametric ratio of outer and inner conductors is shown in Figure 6. The characteristic wave impedance (ratio E/H) in a coaxial line carrying energy in the principal, TEM, mode is $377 * \sqrt{\mu_{1/}\,\epsilon_1}$ Ohms. **{Equation 6}**

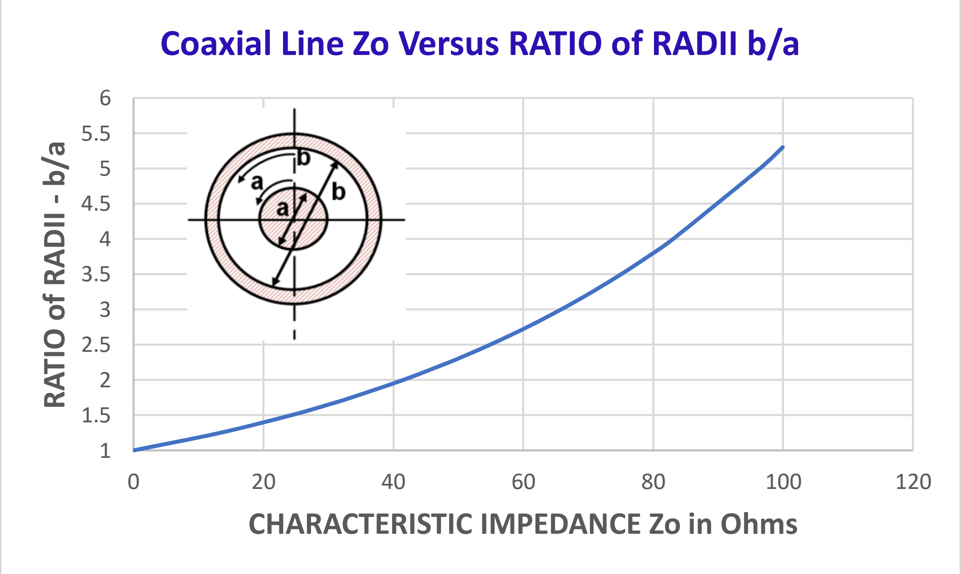


Figure 6. Characteristic Impedance, Zo, of Air-Filled Coaxial Line as a Function of the Ratio of Radii of Outer and Inner Conductors (Moreno, Microwave Transmission Design Data, 1948)

III. COAXIAL LINE PROPAGATION CHARACTERISTICS

Phase Velocity

The propagation constant γ of a coaxial transmission line is derived from the transmission line formulas:

$$\gamma = \sqrt{(R + j\omega L) * (G + j\omega C)} = \alpha + j\beta$$ **{Equation 7}**

where α is the attenuation constant and β is the phase constant. The phase constant β is related to the wavelength of interest λ_1 by the formula:

$$\lambda_1 = \frac{2\pi}{\beta}$$ **{Equation 8}**

The velocity of propagation v in the transmission line is given by:

$$v = \frac{\omega}{\beta}$$ **{Equation 9}**

where losses are small, this velocity becomes:

$$v = \frac{c}{\sqrt{\mu_1 \epsilon_1}}$$ **{Equation 10}**

which is the same as the velocity of an unbounded plane wave in the dielectric medium characterized by $\mu 1$ and $\epsilon 1$. In an air-filled coaxial line, the velocity of the wave is nearly equal to the velocity of light in a vacuum. The wavelength in the coaxial line, $\lambda 1$, is related to the wavelength in free space, λ, by:

$$\lambda_1 = \lambda / \sqrt{\mu_1 \epsilon_1}$$ **{Equation 11}**

Attenuation

For nearly all coaxial lines used at microwave frequencies, the attenuation per wavelength is small enough so that the following approximate formula may be used:

$$\alpha = \frac{R}{2Zo} + \frac{G}{2Yo}$$ nepers/unit length **{Equation 12}**

It is usually simpler to divide the sources of attenuation into conductor and dielectric losses.

1. Attenuation Resulting from Conductor Losses:

The attenuation resulting from conductor losses in a coaxial line is given by:

$$\alpha_c = 13.6 * \frac{\delta\mu}{\lambda} \frac{1}{b} (1 + b/a) \frac{\sqrt{\epsilon_1}}{\left(\ln \frac{b}{a}\right)} \quad \text{dB/unit length} \qquad \{\textbf{Equation 13}\}$$

where δ is the skin depth, λ is the wavelength, b and a are the outer and inner radii of the coaxial line, all in similar units. Also, μ is the permeability of the conductors, and ϵ_1 is the dielectric constant of the medium separating the conductors. For a copper conductor this formula reduces to:

$$\alpha_c = 2.98 \text{ X } 10^{-9} * \sqrt{f} \quad \frac{1}{b} (1 + b/a) \frac{\sqrt{\epsilon_1}}{\left(\ln \frac{b}{a}\right)} \quad \text{dB/cm} \qquad \{\textbf{Equation 14}\}$$

Attenuation increases as the square root of frequency, assuming ϵ_1 is frequency independent, and varies as the square root of the resistivity of the conductors. An optimum ratio b/a = 3.6 exists for a fixed dimension of the outer radius b, and minimum attenuation occurs at this value. This corresponds to a characteristic impedance, Zo, of 77 Ohm for a coaxial line with air dielectric. The minimum attenuation region is broad, and impedance values can vary six (6) percent or more around 77 Ohm without a marked change in attenuation. Variation of air dielectric coaxial line attenuation with diametric ratio, assuming a fixed diameter outer conductor, is shown in Figure 7. A portion of the data used to create Figure 7 is shown in Table 3. Note that Equation 14 is used to derive the data, the radii "b" is held constant, and the ratio of radii "b/a" is kept at 1.2 or higher, otherwise Equation 14 does not work. I arbitrarily used F = 100 MHz. Equation 14 works at any frequency within the general capability of coaxial lines in present manufacture (5 MHz to 18-GHz). When F changes attenuation magnitude changes but the variation with diametric ratio does not (Zo = 77 Ohm maintains its place in immortality).

b in cm	**a in cm**	**ln b/a**	**1/b**	**1 + b/a**	**F in MHz**	**Square Root of F in MHz**	**α in dB/cm**	**b/a**	**Zo in Ohms**
3.6	3	0.182321557	0.28	2.2	100000000	10000	9.98846E-05	**1.2**	**11**
3.6	2.75	0.269332934	0.28	2.3	100000000	10000	7.09685E-05	**1.3**	**16**
3.6	2.5	0.364643114	0.28	2.4	100000000	10000	5.53905E-05	**1.4**	**22**
3.6	2.25	0.470003629	0.28	2.6	100000000	10000	4.57916E-05	**1.6**	**28**
3.6	2	0.587786665	0.28	2.8	100000000	10000	3.94323E-05	**1.8**	**35**
3.6	1.75	0.721318058	0.28	3.1	100000000	10000	3.50835E-05	**2.1**	**43**
3.6	1.5	0.875468737	0.28	3.4	100000000	10000	3.21479E-05	**2.4**	**52**
3.6	1.25	1.057790294	0.28	3.9	100000000	10000	3.03631E-05	**2.9**	**63**
3.6	1	1.280933845	0.28	4.6	100000000	10000	2.97266E-05	**3.6**	**77**
3.6	0.75	1.568615918	0.28	5.8	100000000	10000	3.06073E-05	**4.8**	**94**
3.6	0.5	1.974081026	0.28	8.2	100000000	10000	3.43845E-05	**7.2**	**118**
3.6	0.25	2.667228207	0.28	15.4	100000000	10000	4.77941E-05	**14.4**	**160**
3.6	0.24	2.708050201	0.28	16.0	100000000	10000	4.89077E-05	**15.0**	**162**

Table 3. Data Used to Create Figure 7 Graph

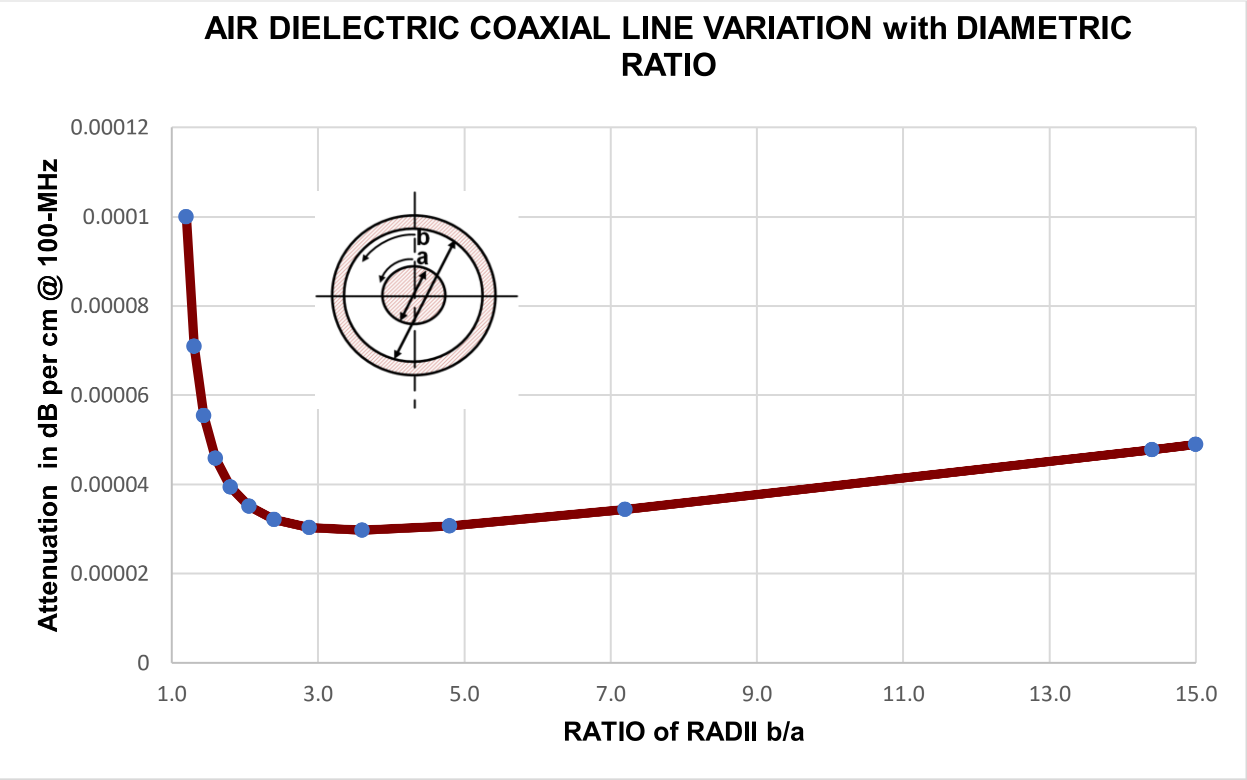


Figure 7. Air Dielectric Coaxial Line Attenuation Variation with Diametric Ratio b/a

Figure 8 shows the impact to attenuation magnitude of employing a solid dielectric with a dielectric constant, ϵ_1, of 2.3 (polyethylene, PE) (Anixter, 2008) versus a coaxial line employing air dielectric ($\epsilon_1 = 1.00059$). Equation 14 was employed with all other parameters constant resulting in a 52% increase in attenuation per cm (for b/a = 3.6, Zo = 77 Ohm). Note the attenuation curve shape remains the same regardless of dielectric constant.

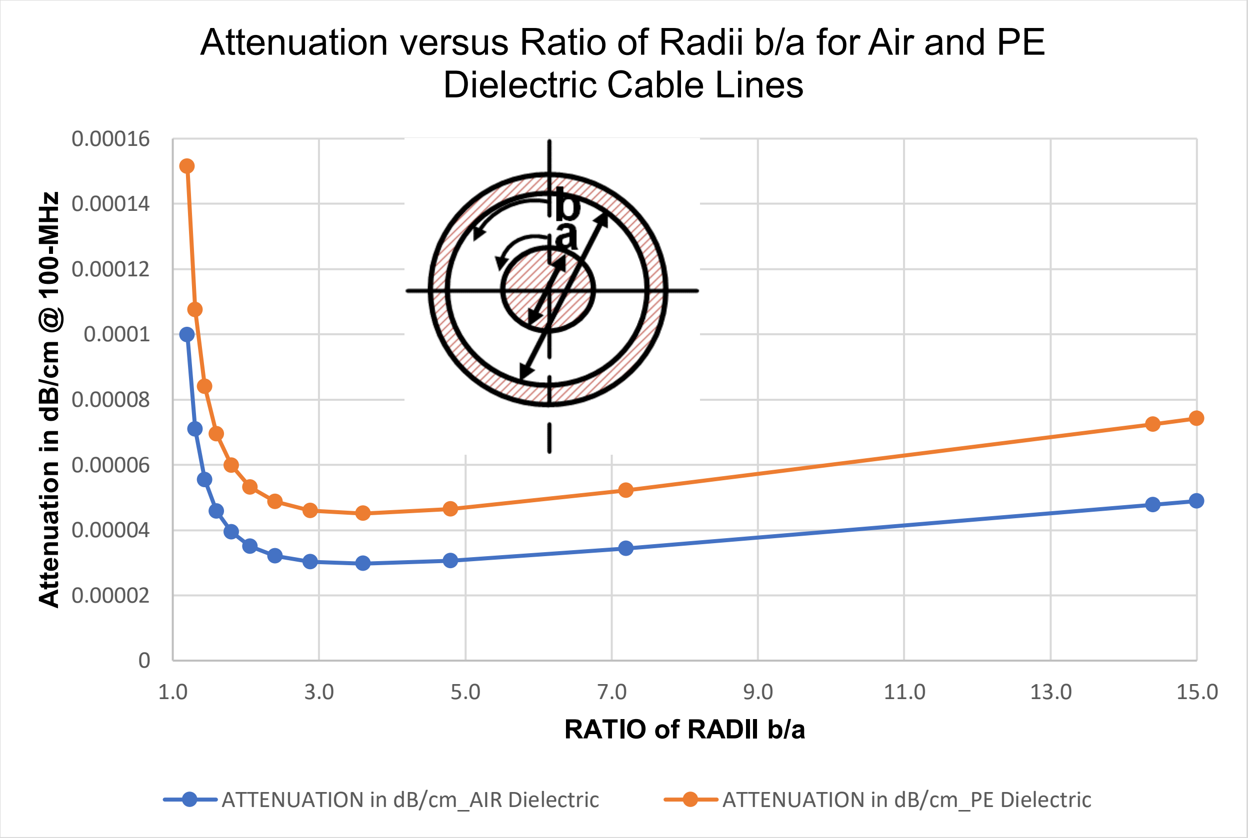


Figure 8. Attenuation vs Ratio of Radii b/a for Air and PE Dielectric Cable Lines

2. Attenuation Resulting from Dielectric Losses:

The attenuation in a coaxial line α_d resulting from dielectric losses is given by:

$\alpha_d = 27.3 * \sqrt{\epsilon_1/\lambda} * \tan\delta$ dB/unit length **{Equation 15}**

If the dielectric constant and loss tangent are independent of frequency the following is true:

1. Conductor losses are proportional to the square root of frequency.
2. Dielectric losses are linearly proportional to frequency.

Hence, at higher frequencies dielectric losses become increasingly important.

Breakdown in a Coaxial Line

Breakdown occurs when the maximum voltage gradient exceeds a limiting value. This limiting value is approximately 30,000 volts/cm for an air-filled coaxial line under ordinary atmospheric conditions. The electric field intensity E at any point in the region between the inner and outer conductors of a coaxial pair is given by:

$E = V/r * \ln(b/a)$ volts/cm **{Equation 16}**

;when the voltage between conductors is V. The gradient is a maximum when the radius r is equal to the radius of the inner conductor a. For a specified outer radius b and maximum field strength E_m, the allowed potential difference between conductors is:

$$V = E_m*b\,((\ln(b/a)/(b/a)))$$ volts **{Equation 17}**

For maximum voltage between conductors, the optimum ratio b/a is 2.718. This corresponds to a characteristic impedance, Zo, of 60 ohms.

Maximum Power Carried by a Coaxial Line

The power that can be transferred by a matched line depends upon the ratio V^2/Zo. Hence the maximum power, P, that can be carried by a coaxial line is:

$$P = ((E_m^2 * b^2)/60)*(\ln(b/a)/(b/a)^2))$$ watts **{Equation 18}**

;where E_m is the maximum allowable voltage gradient. For a specified outer radius b, the maximum power can be carried by a coaxial line when the ratio b/a = 1.65. This yields a characteristic impedance, Zo, of 30 ohms.

IV. HIGH FREQUENCY PHENOMENA

a. Attenuation

At lower frequencies attenuation in a coaxial cable is primarily the result of conductor losses and increases as the square root of frequency. However, dielectric losses increase linearly with frequency with increasing importance at high frequencies. Also, conductor losses are higher than theory predicts because of "braid factor", the ratio of resistivity of the outer braid to the resistivity of a solid outer conductor. See Figure 9.

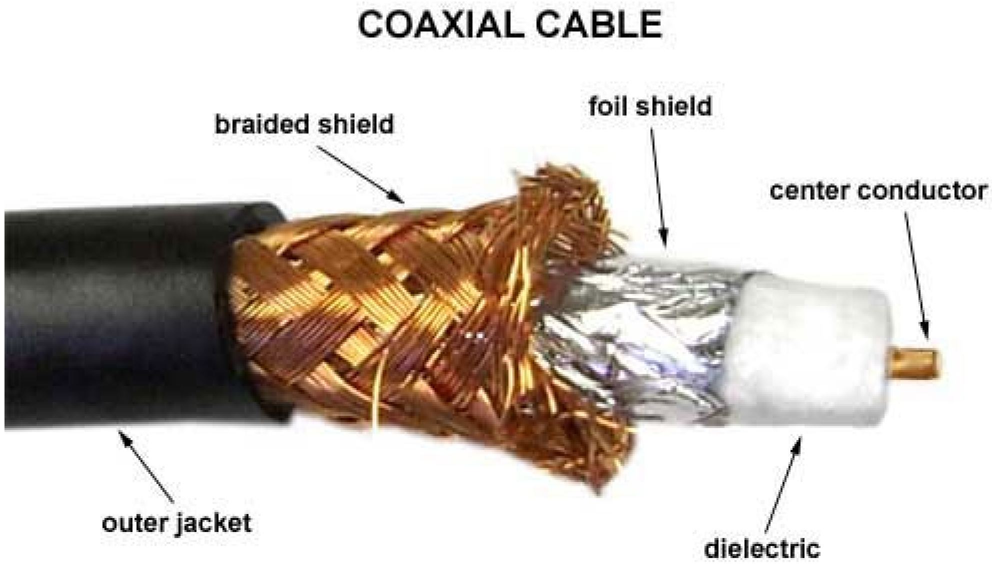
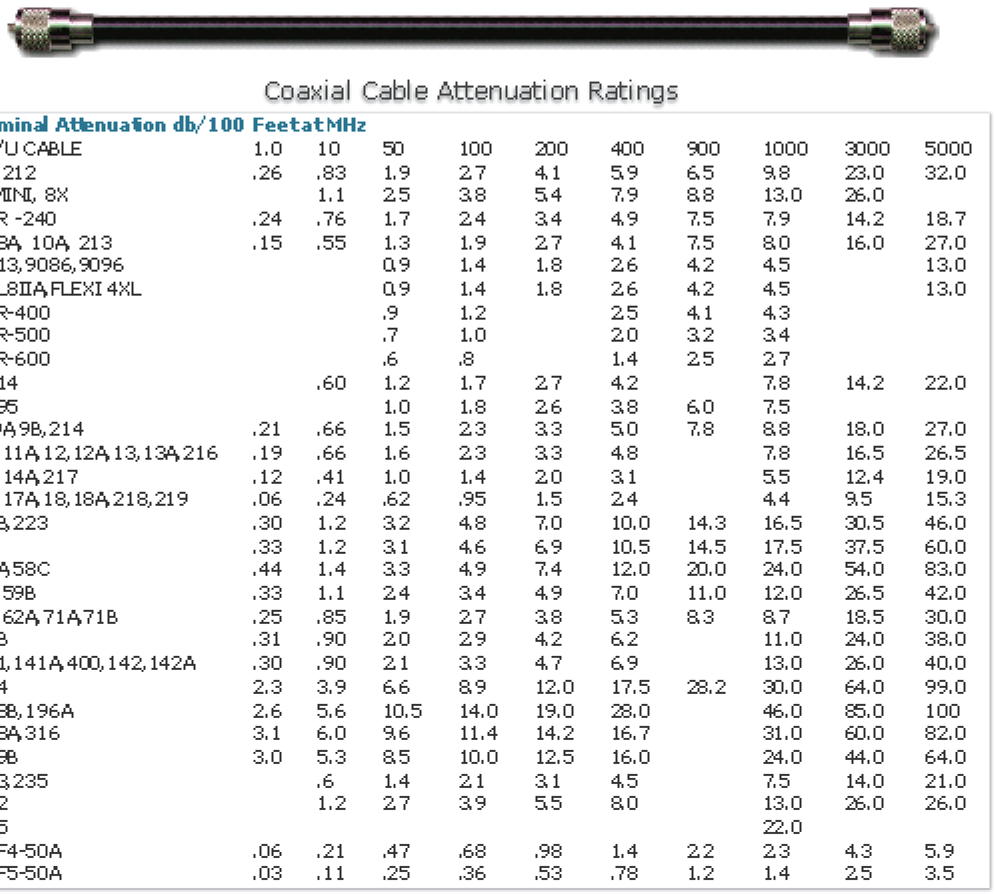


Figure 9. Illustration of Coaxial Cable Structure (Cable Wholesale, 2019)

Attenuation in the cable varies over time for a variety of reasons, including:

1. With prolonged temperature cycling polyethylene (PE) dielectric can be contaminated by the outer cover material raising attenuation at frequencies above 9.5 GHz by as much as 300 per cent. (Moreno, Microwave Transmission Design Data, 1948). This situation is improved by addition of a stabilizer to the dielectric and by use of a noncontaminating vinyl outer jacket.
2. Chemicals in the outer jacket can increase attenuation by corroding the outer braid. Bare copper is most susceptible with silver braid or tinned copper demonstrating greater resistance to corrosion. If the braid is not corroded attenuation may be increased by flexing of the cable, which tends to loosen the braid. When this occurs, former characteristics may often be regained by leaving the cable motionless for 24 hours.
3. When the braid has corroded it is sometimes found that repeated flexing of the cable results in *reduced* attenuation from the effects from the inadvertent polishing of the braid contacts.
4. Temperature cycling and flexing cause increasingly erratic behavior in the cable at higher frequencies, due in part because of the greater importance of the braid contacts.

Table 4 shows attenuation of various coaxial cables in dB per 100 feet (multiply each attenuation value by 3.281 to get dB per 100 meters) up to 5-GHz.



Coaxial Cable Attenuation Ratings

Nominal Attenuation db/100 Feet at MHz

RG/U CABLE	1.0	10	50	100	200	400	900	1000	3000	5000
6A,212	.26	.83	1.9	2.7	4.1	5.9	6.5	9.8	23.0	32.0
8 MINI, 8X		1.1	2.5	3.8	5.4	7.9	8.8	13.0	26.0	
LMR -240	.24	.76	1.7	2.4	3.4	4.9	7.5	7.9	14.2	18.7
8, 8A, 10A, 213	.15	.55	1.3	1.9	2.7	4.1	7.5	8.0	16.0	27.0
9913,9086,9096			0.9	1.4	1.8	2.6	4.2	4.5		13.0
4XL8IIA,FLEXI 4XL			0.9	1.4	1.8	2.6	4.2	4.5		13.0
LMR-400			.9	1.2		2.5	4.1	4.3		
LMR-500			.7	1.0		2.0	3.2	3.4		
LMR-600			.6	.8		1.4	2.5	2.7		
8214		.60	1.2	1.7	2.7	4.2		7.8	14.2	22.0
9095			1.0	1.8	2.6	3.8	6.0	7.5		
9,9A,9B,214	.21	.66	1.5	2.3	3.3	5.0	7.8	8.8	18.0	27.0
11,11A,12,12A,13,13A,216	.19	.66	1.6	2.3	3.3	4.8		7.8	16.5	26.5
14,14A,217	.12	.41	1.0	1.4	2.0	3.1		5.5	12.4	19.0
17,17A,18,18A,218,219	.06	.24	.62	.95	1.5	2.4		4.4	9.5	15.3
55B,223	.30	1.2	3.2	4.8	7.0	10.0	14.3	16.5	30.5	46.0
58	.33	1.2	3.1	4.6	6.9	10.5	14.5	17.5	37.5	60.0
58A,58C	.44	1.4	3.3	4.9	7.4	12.0	20.0	24.0	54.0	83.0
59,59B	.33	1.1	2.4	3.4	4.9	7.0	11.0	12.0	26.5	42.0
62,62A,71A,71B	.25	.85	1.9	2.7	3.8	5.3	8.3	8.7	18.5	30.0
62B	.31	.90	2.0	2.9	4.2	6.2		11.0	24.0	38.0
141,141A,400,142,142A	.30	.90	2.1	3.3	4.7	6.9		13.0	26.0	40.0
174	2.3	3.9	6.6	8.9	12.0	17.5	28.2	30.0	64.0	99.0
178B,196A	2.6	5.6	10.5	14.0	19.0	28.0		46.0	85.0	100
188A,316	3.1	6.0	9.6	11.4	14.2	16.7		31.0	60.0	82.0
179B	3.0	5.3	8.5	10.0	12.5	16.0		24.0	44.0	64.0
393,235		.6	1.4	2.1	3.1	4.5		7.5	14.0	21.0
402		1.2	2.7	3.9	5.5	8.0		13.0	26.0	26.0
405								22.0		
LDF4-50A	.06	.21	.47	.68	.98	1.4	2.2	2.3	4.3	5.9
LDF5-50A	.03	.11	.25	.36	.53	.78	1.2	1.4	2.5	3.5

Table 4. Coaxial Cable Attenuation to 5-GHz for Various Types (Harold Melton, KV5R, 2019)

Note that most of the coaxial cables listed in Table 4 have a nominal Zo of 50-Ohms, not 75-Ohms. That is because the KV5R web site exists as part of the ham radio community which employs radio equipment using 50-Ohm input/output (I/O).

Tables 5 and 6 and Figures 10 and 11 list popular 75-Ohm Zo coaxial cables with their attenuation given to 3-GHz in dB per 100-feet or in dB per 1320-feet (one quarter mile).

PN:	50 MHz	500 MHz	1000 MHz	2000 MHz	3000 MHz
RG-59	2.4	8.0	12.0	19.3	26.5
H+S 179-01	5.8	19.0	27.5	40.2	50.4
H+S 400-FR-75	0.8	2.8	4.1	6.0	7.7
Times 400-75	0.8	2.7	3.8	5.7	7.1
Commscope 2312V 500	0.6	2.3	4.1	7.0	11.0
Commscope P3 875 CA	0.3	1.1	1.5	2.3	2.9

Table 5. Popular 75-Ohm Coax Cable α in dB per 100-Feet to 3-GHz

PN:	50 MHz	500 MHz	1000 MHz	2000 MHz	3000 MHz
H+S 179-01	77	251	363	531	665
H+S 400-FR-75	11	37	54	79	102
Times 400-75	11	35	52	75	97
Commscope P3 875 CA	4	14	20	30	38
Commscope 2312V 500	8	30	55	97	145

Table 6. Popular 75-Ohm Coax Cable α in dB per 1320-Feet to 3-GHz

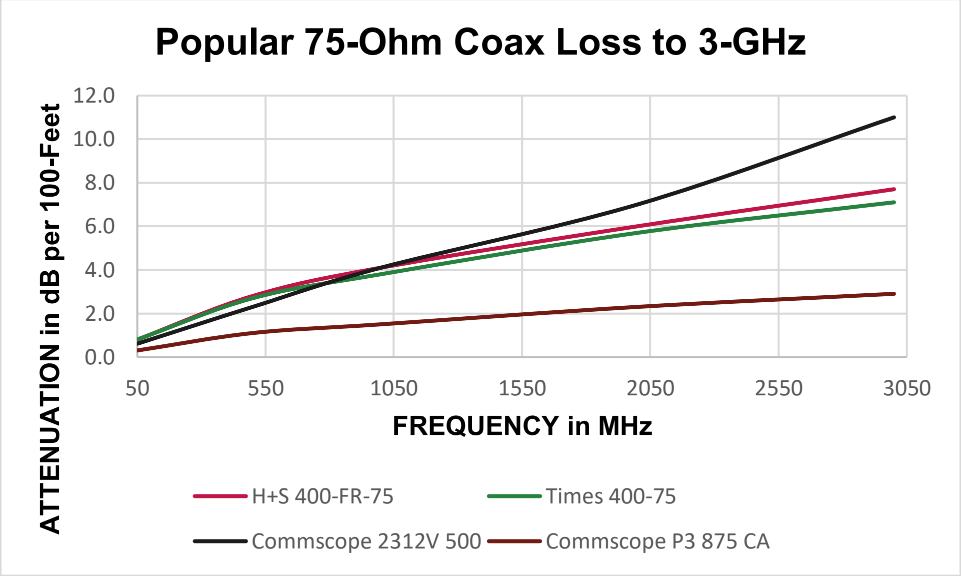


Figure 10. Popular 75-Ohm Coax Losses to 3-GHz in dB per 100-Feet

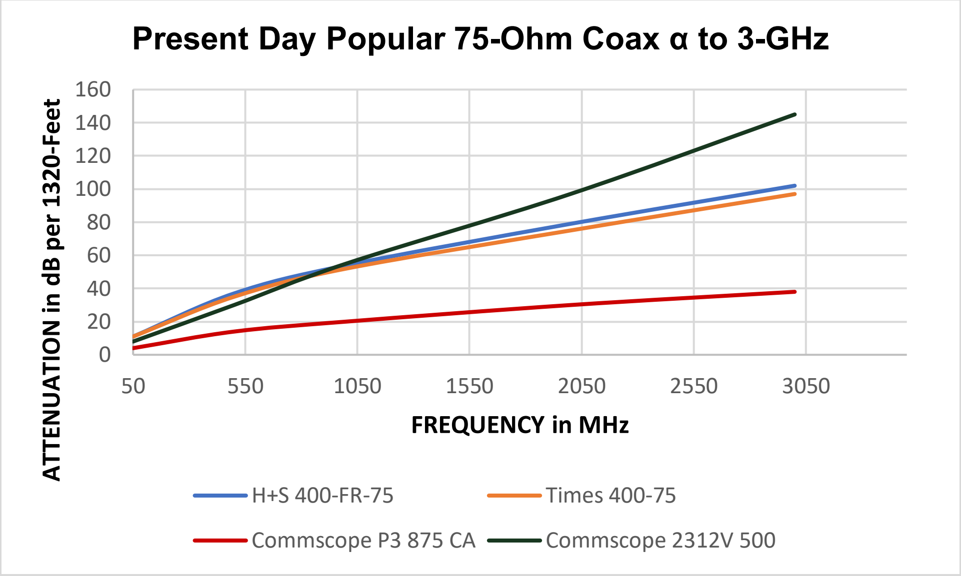


Figure 11. Popular 75-Ohm Coax Losses to 3-GHz in dB per 1320-Feet

What Tables 5 and 6 and Figures 10 and 11 show is that 75-Ohm coaxial cables in present use today in hybrid fiber coaxial (HFC) systems limited to 1218-MHz downstream (DS) bandwidth (BW) will likely need to be replaced with lower loss coaxial cables when frequencies are expanded to 3-GHz and higher. This replacement isn't limited to flexible types installed at or near subscribers (e.g., RF59, RG6, Huber + Suhner 179-01, and similar) but also impacts hardline coaxial cables (e.g., most 0.500-inch and 0.650-inch diameter hardline coaxial cable). Using present HFC architectures there isn't an economical way to deliver -15 to +15 dBmV RF signal level to 3-GHz BW capable displays (assuming that is the required RF signal level) with 3-GHz BW. An HFC plant operating at 3-GHz (likely in time division duplex (TDD) modes as DOCSIS® Full Duplex (D3.1 FDX) is presently specified) has about one and half times (1.46) more BW than a present-day 1218-MHz DS HFC network. Without a new architectural approach, it may be dramatically more expensive in terms of RF power delivery** to create required RF performance levels in a 3-GHz or greater BW HFC network.

Having recently proposed replacing today's HFC network passive directional taps with a new Active Tap (AT) based HFC architecture, it may be economically feasible to increase HFC BW to 3-GHz sooner rather than later. (Young, The Active Tap: HFC Bandwidth Expansion Enabler, 2019). Figure 12 shows the RF power levels within a proposed new HFC Node + 0 network operating with 3-GHz FDX or DS-only architecture. Figure 12 assumes the following:

1. Commscope P3®`875 CA or equivalent hardline coaxial cable with suitable connectors is employed in the proposed new HFC Node + 0 network. Extrapolated tilt from 54 to 3000-MHz is approximately 25.3-dB positive slope.
2. Active Tap (AT) directional devices replace present-day passive directional taps and possess the RF performance necessary to meet RF attenuation, gain, power levels, linearity, self-monitoring, self-test, and reporting capabilities expected.
3. Subscribers employ RG6 or equivalent flexible cable with no more than 23-dB attenuation per 100-feet at 3-GHz when using suitable connectors with runs ≤200-feet.

4. Distance from Node + 0 RF output port to AT input RF port is no more than 1000 feet.
5. 3-GHz ATs are designed and developed with appropriate gain, attenuation, and RF output levels. NOTE: Present Linear Devices Company (LDC) AT Reference Designs are designed for 1794-MHz BW but possess the ability to operate to 3-GHz with modification. (Young, Active Tap (AT) Reference Designs BPD000x, 2019).

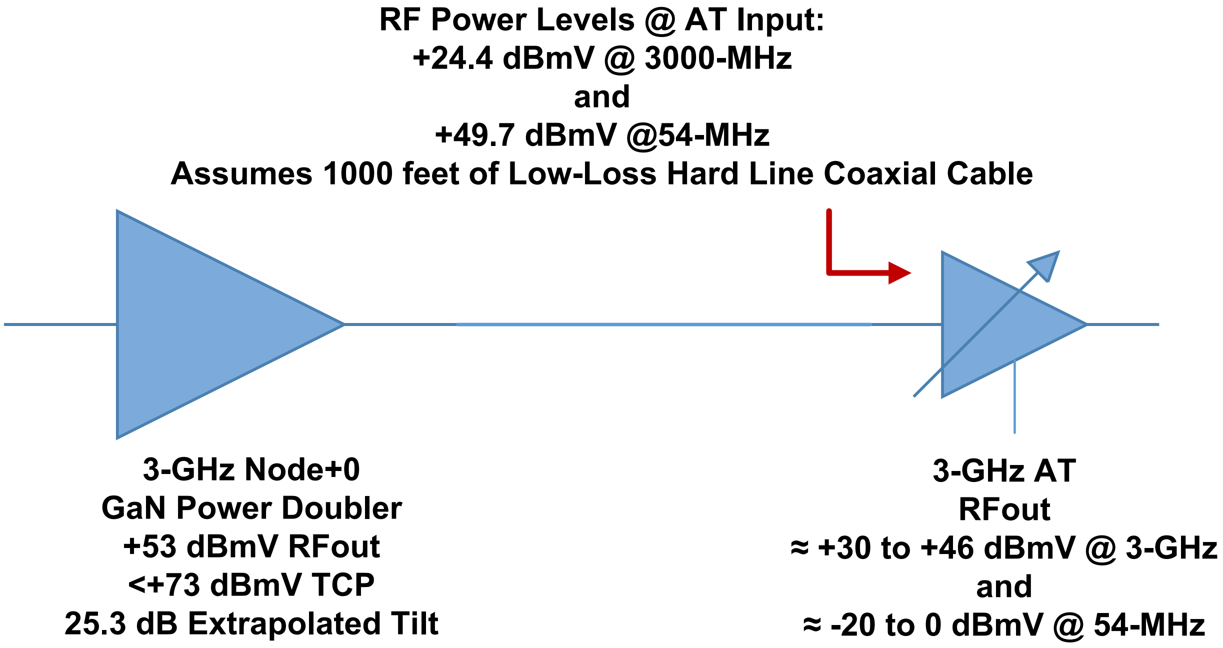


Figure 12. HFC Node + 0 Network RF Power Levels with Active Tap (AT)

Figure 12 shows RF levels at 3-GHz that can be delivered reliably with required linearity and DC performance suitable for development, prototyping, and trial in the short term.

Note that COFDM (Coded Orthogonal Frequency Domain Multiplex) modulation can deliver adequate spectral bit efficiency (measured in bits per second per Hertz) to permit 3-GHz BW HFC networks to deliver in excess of 15 Gbps high speed data (HSD) (3-GHz BW times a minimum of 5 bits per second per Hertz spectral efficiency). See Table 7. (Frenzel, 2012).

MODULATION TYPE	SPECTRAL EFFICIENCY (bits/s/Hz)
FSK	<1 (depends on modulation index)
GMSK	1.35
BPSK	1
QPSK	2
8PSK	3
16QAM	4
64QAM	6
COFDM	>10 (depends on the type of modulation and # of subcarriers)

Table 7. Spectral Efficiency in Bits per Second per Hertz for Various Modulation Types (Frenzel, 2012)

**RF and associated device impacts to increasing HFC network BW from 1218-MHz to 3000-MHz while employing present-day HFC architectures include:

1. Semiconductor material selection
2. Operating voltages
3. Current density
4. Mean time to failure (MTTF)
5. Gain flatness
6. Gain flatness and gain correction
7. Slope correction at levels never implemented to date
8. Linearity
9. Pre-distortion
10. Real-time device monitoring, test, and reporting

b. Periodicity

Periodicity is the name applied to the anomalous behavior of different coaxial cables at different specific frequencies or frequency bands and their harmonics. Periodicity shows as a high standing wave ratio (SWR) and increased attenuation. No coaxial cable checked has been found completely free of this effect. (Moreno, Microwave Transmission Design Data, 1989).

The sources of this effect are periodic variations in the physical construction of the cable that result from the process of manufacture. When the spacing of the variations is some multiple of a half wavelength, the effects add in such a fashion as to seriously impact overall behavior of a length of cable.

The most serious cause of periodicity is variation in the outer diameter of the dielectric. The wavelengths corresponding to the frequencies of measured disturbances have been verified experimentally with mechanically measured variations in the core diameter. Variations of one (1) or two (2) mils (0.001 to 0.002 inch or 0.0254 to 0.0518 mm) are enough to cause pronounced resonances in the region of 3000 MHz (3-GHz).

Other sources include variations in braid uniformity, braid pitch, jacket uniformity, and armor.

In general, smaller diameter coaxial cables are likely to show periodicity effects in the frequency range 1000 to 10000 MHz (1-GHz to 10-GHz), while larger diameter coaxial cables have shown effects at frequencies as low as 175 MHz.

Heating coaxial cables to 85° Celsius (C) for several hours and subsequent cooling increases the number and severity of periodicity effects. This indicates polyethylene (PE) may not be stress-free when extruded.

In general, periodicity effects are serious enough to warrant careful consideration when it is planned to use coaxial cable in critical applications, in applications requiring operation at 3-GHz and higher.

c. Power Handling Capacity

The power-handling capacity of a high-frequency coaxial cable is usually limited by the heating of the cable, and the maximum voltage is limited by the dielectric strength of the dielectric material employed and fittings. The two ratings do not necessarily agree, and if a coaxial cable is operated at its maximum voltage rating, service can be interrupted if the power-handling capacity rating is not to be exceeded.

V. THE FUTURE

For nominal 50-Ohm Zo coaxial cables there exists today cable rated to operate at Ka-Band (26.5 to 40-GHz) with reasonable performance within strict limits (e.g., short distances and employment with suitable connectors). 75-Ohm Zo coaxial cable is limited today to specified operation up to about 6-GHz. This limitation is partially because commonly available 75-Ohm input/output (I/O) connectors are limited in their practical upper frequency of operation. See Table 8.

75-Ohm Connector Type:	Upper Frequency Limit in GHz:	NOTES:
F	3-GHz	Available from Amphenol, Fairview Microwave, and others (with 20-dB min RL).
G	2-GHz	Push-on version of F-Type (usually partially threaded permitting optional screw-on).
5/8-24 Hard Line Pin Connector	3-GHz	Male version aka a “Stinger”; aka as a “precision airline” connector to ANSI/SCTE 125 2018 specification.
SMB	4-GHz	Variation of SMA.
MCX	6-GHz	Features Snap-On/Snap-Off coupling to EU CECC 2220 specification.
N	11-GHz	18-GHz upper F limit in 50-Ohm version. “N” denotes US Navy.

Table 8. 75-Ohm Connector Upper Frequency Limits in GHz

It has been about 40 years since a new general type of 75-Ohm I/O connector has been designed, developed, prototyped, tested, and introduced to the marketplace for evaluation, installation, and long-term adoption. On the coaxial cable side, many advancements in 75-Ohm Zo cables have been introduced since WW2. These advances have spanned the areas of design, material science, manufacturing and assembly, reliability and quality improvement, and test and measurement. Until now there hasn’t been a need for coaxial cable original equipment manufacturers (OEMs) to offer a wide variety of low attenuation cables specified to operate to 3-GHz and higher frequencies.

Linear Devices Company (LDC) has embarked on a design and development effort aimed at creating a significantly lower attenuation flexible coaxial cable with associated new connectors primarily for indoor use to beyond 10-GHz. LDC aims include a new flexible cable with mating connectors exhibiting 8-dB per 100-feet maximum attenuation at 3-GHz with no measurable periodicity. One promising design is a variation of what is sometimes termed the “Siamese” or Dual coaxial connector (see Figure 13). Note that a white outer jacket is often used to denote an indoor use coaxial cable.

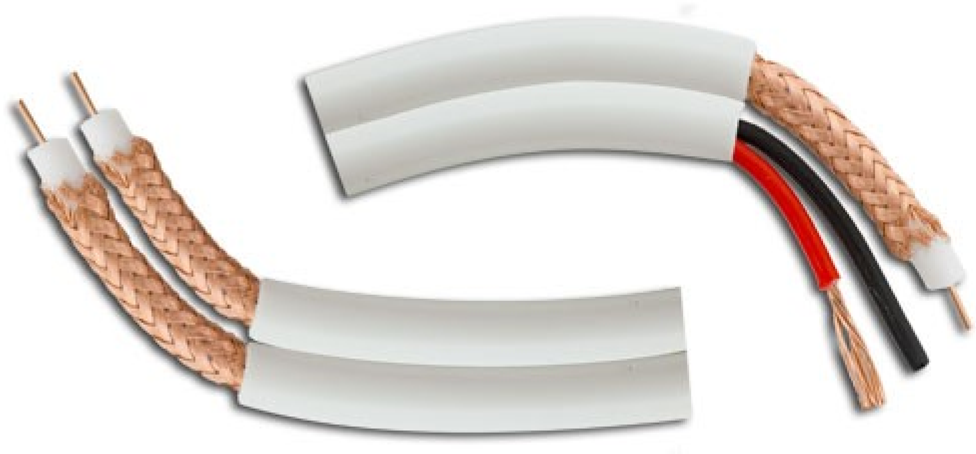


Figure 13. Siamese or Dual Flexible Coaxial Cable

US patents pending.

^Skin Depth is a measure of how closely electric current flows along the surface of a material. At direct current (DC) (i.e., 0 Hertz or a constant voltage), electric current flows uniformly through a conductor. This means the current density is the same everywhere. However, at higher frequencies, the current prefers to flow along the surface, producing surface current.

The skin depth equation is given below:

$$\text{skin depth} = \delta = \sqrt{\frac{\rho}{\pi f \mu}} = \sqrt{\frac{\rho}{\pi f \mu_r \mu_0}}$$

{Equation 19}

In Equation [19], the symbols are:

- *f* is the frequency of the current
- ρ is the resistivity of the material (in Ohms/meter; this is the inverse of conductivity),
- μ is the permeability of the material (a measure of the magnetism)

Note that ($\mu = \mu_0 = 4\pi \cdot 10^{-7}$ [H/m] * $\mu_r = \frac{\mu}{\mu_0}$)

The key point to note from Equation [19] is that skin depth decreases with higher frequency.

This means that electric current flows only on the surface of a conductive material at frequencies >10 MHz . For instance, the skin depth of copper at the frequency 2.4 GHz (= 2.4*10^9) is about 1 micron (1 micrometer = 1/1000 mm). Note that the resistivity for copper is 1.68*10^-8 Ohm-meters (Ω▪m). (Copyright 2019. Antenna-Theory, 2019)

VI. BIBLIOGRAPHY

Anixter. (2008). *Wire and Cable Technical Handbook Section 03, Insulation and Jacket Materials.* Glenview, Illinois USA: Anixter Incorporated.

Belden Incorporated. (2019, 09 20). *Audio Video Systems Part Number: 8240 Distributed Antenna Systems (DAS) 52 Ohm, RG58, 20 AWG, CMX Data Sheet.* Retrieved from Belden: https://www.belden.com/

Cable Wholesale. (2019, September 25). *Coaxial Cable, Connectors, Fittings, and More.* Retrieved from Cable Wholesale: https://www.cablewholesale.com/products/coaxial-cable.php

Chandler, L. (2019, 09 21). *Jerrold Mul-TV Antenna System Channel Amplifier Model CA.* Retrieved from The Old CATV Equipment Museum: http://theoldcatvequipmentmuseum.org/140/141/1411/index.html#JerroldMul-TVAntennaSystemChannelAmplifierModelCA

Commscope. (2019, 09 23). *HomeConnect® 75 Ohm Coaxial Drop Cable, Series 59, black PVC jacket.* Retrieved from Commscope: https://www.commscope.com/catalog/cables/pdf/part/84967/SZ4916503_F59TSV_SM_MT.pdf

Copyright 2019. Antenna-Theory. (2019, 09 21). *Skin Depth.* Retrieved from Antenna Theory dot com: http://www.antenna-theory.com/definitions/skin-depth.php

DX Engineering. (2018, July 25). *DX Engineering 300-Ohm Ladder Line Data Sheet DXE-LL300-Info-Rev 2.* Retrieved from DX Engineering: www.DXEngineering.com

Early Television Museum. (2019, 09 20). *Early Televsion Stations*. Retrieved from Early Television Museum: http://www.earlytelevision.org/prewar_stations.html

Frenzel, L. (2012). Understanding Modern Digital Modulation Techniques. *Electronic Design Magazine*, https://www.electronicdesign.com/communications/understanding-modern-digital-modulation-techniques.

Harold Melton, KV5R. (2019, September 26). *Coax Ratings Charts.* Retrieved from KV5R, Makin' it more fun...: https://kv5r.com/ham-radio/coax-ratings-charts/

Jerrold Electronics. (1960). *Reference Data for Television Systems, JP-1.* Philadelphia, PA USA: Jerrold Electronics.

Melton, H. (2019, 02 19). *Ladder Line.* Retrieved from KV5R: https://kv5r.com/ham-radio/ladder-line/

Moreno, T. (1948). *Microwave Transmission Design Data.* New York City, NY USA: McGraw-Hill.

Moreno, T. (1989). *Microwave Transmission Design Data.* Norwood, MA USA: ARTECH HOUSE, Inc.

Nelson, M. L. (1965). Loss Figures for 300-Ohm Twin Lead. *Electronics World*.

New York Times. (1940, May 21). Threat to Television is Feared in Frequency Modulation Order. *New York Times*, p. 23.

Ragan, G. L. (1948). *Microwave Transmission Circuits.* New York City, NY USA: McGraw-Hill Book Company, Inc.

RCA. (1941, January 1). Television Stations Authorized by the FCC as of January 1, 1941. *RCA Radio Travel-Log, 1941*, p. UNKNOWN.

Young, C. (2009). *CATV Hybrid Amplifier Modules: Past, Present, Future.* Greensboro, NC USA: RFMD Incorporated.

Young, C. (2019, September 2019). *Active Tap (AT) Reference Designs BPD000x.* Retrieved from Linear Devices Company (LDC): www.lineardevicesinc.com

Young, C. (2019). *The Active Tap: HFC Bandwidth Expansion Enabler.* Milpitas, CA USA: Linear Devices Company (LDC).

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