History of Coaxial Cable 50Ω Characteristic Impedance

Standard coaxial cable impedance for RF power transmission in the U.S. is almost exclusively **50 ohms**. Different impedance values are optimum for different parameters. Maximum power-carrying capability occurs at a diameter ratio of 1.65 corresponding to 30 ohms impedance. Optimum diameter ratio for voltage breakdown is 2.7 corresponding to 60 ohms impedance (incidentally, the standard impedance in many European countries).

Power carrying capacity on breakdown ignores current density, which is high at low impedances such as 30 ohms. Attenuation due to conductor losses alone is almost 50% higher at that impedance than at the minimum attenuation impedance of 77 ohms (diameter ratio 3.6). This ratio, however, is limited to only one half maximum power of a 30 ohm line. In the early days, microwave power was hard to come by and lines could not be taxed to capacity. Therefore low attenuation was the overriding factor leading for the selection of 77 (or 75) ohms as a standard. This resulted in hardware of certain fixed dimensions. When low-loss dielectric materials made the flexible line practical, the line dimensions remained unchanged to permit mating with existing equipment.

The dielectric constant of polyethylene is 2.3. Impedance of a 77-ohm airline is reduced to 51 ohms when filled with polyethylene. Fifty-one ohms is still in use today though the standard for precision is 50 ohms. The attenuation is minimum at 77 ohms; the breakdown voltage is maximum at 60 ohms and the power-carrying capacity is maximum at 30 ohms.

Another thing, which might have lead to 50 ohm coax, is that if you take a reasonable sized center conductor and put a insulator around that and then put a shield around that and choose all the dimensions so that they are convenient and mechanically look good, then the impedance will come out at about 50 ohms. In order to raise the impedance, the center conductor's diameter needs to be tiny with respect to the overall cable's size. And in order to lower the impedance, the thickness of the insulation between the inner conductor and the shield must be made very thin. Since almost any coax that *looks* good for mechanical reasons just happens to come out at close to 50 ohms anyway, there was a natural tendency for standardization at exactly 50 ohms.

Cable impedance

This document tries to clear out some details of transmission lines and cable inductance. This document is only a brief introduction to those topics. If you expect to work much with transmission lines, coaxial or otherwise, then it will be worth your while to get a book on that subject. The ideal book depends on your background in physics or electrical engineering, and in mathematics.

What is the cable impedance and when it is needed?

The basic idea is that a conductor at RF Frequencies no longer behaves like a regular old wire. As the length of the conductor (wire) approaches about 1/10 the wavelength of the signal it is carrying - good 'old' fashioned circuit analysis rules don't apply anymore. This is the point where things like cable impedance and transmission line theory enter the picture. *The key tenet (doctrine) of all transmission line theory is that the source impedance must be equal to the load impedance in order to achieve maximum power transfer and minimum signal reflection at the destination.* In real world case this generally means that the source impedance is the same as cable impedance and the value of the receiver in another end of the cable has also the same impedance.

How cable impedance is defined?

Characteristic impedance of the cable ratio of the electric field strength to the magnetic field strength for waves propagating in the cable (Volts/m / Amps/m = Ohms).
Ohm's Law states that if a voltage (E) is applied to a pair of terminals and a current (I) is measured in this circuit, the following equation can be used to determine the magnitude of the impedance (Z). The following formula will hold truth:

$$Z = E / I$$

This relationship holds true whether talking about direct current (DC) or alternating current (AC). Characteristic Impedance and is usually designated "Zo" or "Z sub O". When the cable is carrying RF power, without standing waves, Zo also equals the ratio of the voltage across the line to the current in flowing in the line conductors. So the characteristic impedance is defined with the formula:

$$Zo = E / I$$

The voltages and currents depend on the inductive reactance and capacitive reactance in the cable. So the characteristic impedance formula can be written in the following format:

$$Zo = sqrt ((R + 2 * Pi * f * L) / (G + j * 2 * Pi * f * C))$$

Where:

- sqrt = square root function
- R = The series resistance of the conductor in ohms per unit length (DC resistance)
- Pi = 3.1416
- f = Frequency
- L = Cable inductance per unit length
- G = The shunt conductance in mhos per unit length
- j = A symbol indicating that the term has a phase angle of +90 degrees (imaginary number)
- C = Cable capacitance per unit length

*For materials commonly used for cable insulation, G is small enough that it can be neglected when compared with (2 * Pi * f * C). At low frequencies, (2 * Pi * f * L) is so small compared with R that it can be neglected. Therefore, at low frequencies, the following equation can be used:*

$$Zo = sqrt (R / (j * 2 * Pi * f * L))$$

If the capacitance does not vary with frequency, the Zo varies inversely with the square root of the frequency and has a phase angle, which is -45 degrees near DC and decreases to 0 degrees as frequency increases. Polyvinyl chloride and rubber decrease somewhat in capacitance as frequency increases, while polyethylene, polypropylene, and Teflon* do not vary significantly.

When f becomes large enough, the two terms containing f become so large that R and G may be neglected and the resultant equation is:

$$Zo = sqrt ((j * 2 * Pi * f * L) / (j * 2 * Pi * f * C))$$

Which can be simplified to the form:

$$Zo = sqrt (L / C)$$

Cables characteristics at high frequencies

At the high frequencies you can't look at the cable as a usual cable. On higher frequency it works as a waveguide. Characteristic impedance is specific resistance for electro-magnetic waves. So: It's the load the cable poses at high frequencies. The high frequency goes (dependent of cable of course) usually from 100kHz and up.

If you feed a Sinusoidal Electrical AC signal of reasonable frequency into one end of the cable, then the signal travels as an electrical wave down the cable. If the cable length is an extremely large number of wavelengths at the frequency of that AC signal, and you measure the ratio of AC Voltage to AC current in that traveling wave, then that ratio is called the Characteristic Impedance (Zo) of the cable. In practical cables the characteristic impedance is determined by cable geometry and dielectric. The cable length has no effect on its characteristic impedance.

What does the coaxial cable model look like?

The coax is represented schematically by a series of capacitors and inductances, a sort of odd filter arrangement; the particular values unique to the particular coax type. At a given frequency, if correctly chosen, that arrangement passes most of the signal; while at higher frequencies, that arrangement attenuates signal.

How does coaxial cable characteristics define the impedance?

The length has nothing to do with coaxial cable impedance. Characteristic impedance is determined by the size and spacing of the conductors and the type of dielectric used between them. For ordinary coaxial cable used at reasonable frequency, the characteristic impedance depends on the dimensions of the inner and outer conductors, and on the characteristics of the dielectric material between the inner and outer conductors.

The following formula can be used for calculating the characteristic impedance of the coaxial cable: (formula taken from Reference Data for Radio Engineers book published by Howard W. Sams & Co. 1975, page 24-21)

Characteristic Impedance = (138 / e^(1/2)) * log (D/d)

Where:

- e = dielectric constant (= 1 for air)
- log = logarithm of 10
- D = inner diameter of cable shield
- d = diameter of center conductor

In a nutshell the characteristic impedance of a coax cable is the square root of (the per unit length inductance divide by the per unit length capacitance). For coaxial cables the characteristic impedance will be typically between 20 and 150 ohms. The length of the cable makes no difference whatsoever in regard to the characteristic impedance.

If the frequency is much too high for the coaxial cable, then the wave can propagate in undesired modes (i.e., have undesired patterns of electric and magnetic fields), and then the cable does not function properly for various reasons.

How is the impedance of balanced pairs determined?

Characteristic impedance is determined by the size and spacing of the conductors and the type of dielectric used between them. Balanced pair, or twin lines, have a Zo, which depends on the ratio of the wire spacing to wire diameter, and the foregoing remarks still apply. For practical lines, Zo at high frequencies is very nearly, but not exactly, a pure resistance.

The following formula can be used for calculating the characteristic impedance of balanced pair near ground: (formula taken from Reference Data for Radio Engineers book published by Howard W. Sams & Co. 1975, page 24-22)

Characteristic Impedance = (276 / e^(1/2)) * log ((2D/d) * (1 + (D/2h)^2))^(1/2))

Where:

- e = dielectric constant (= 1 for air)
- log = logarithm of 10
- D = distance between wires in pair
- d = wire diameter
- h = distance between balanced pair and ground

Not that this formula is only valid for unshielded balanced pair when D and h are order of magnitude larger than d. If the twisted pair is far away from ground (h is nearly infinite), the effect of the ground is negligible and the impedance of the cable can be approximated with simpler formula (my own derivation from formula above):

Characteristic Impedance = (276 / e^(1/2)) * log ((2D/d)

For Twin Lead Zo will be typically between 75 and 1000 ohms depending on the intended application. The impedance of typical old telephone pair in the telephone poles in the air has characteristic impedance of around 600 ohms. The telephone and telecommunication cables in use have typically a characteristic impedance of 100 or 120 ohms.

What kind of electrical model I can use for long coaxial cable?

If you know the inductance and capacitance of certain length of cable you can use the following electrical model for it:

```
          L      L      L    /   /  L
 ---+uuuu+-+-+uuuu+-+-+uuuu+--/ ... /+uuuu+---
            |      |     | /    /     |
         --+--   --+--  --+--        --+--
       C --+--  C --+-- C--+--       C --+--
            |      |     | /    /     |
     ----------+--------+------+-/ ... /------+---
                         /    /
```

For this model it is a beneficial to know a useful impedance equation, which described the relation of impedance, capacitance and inductance:

$$Z = sqrt (L / C)$$

Can I measure the cable impedance using multimeter?

Cable characteristic impedance is a cable characteristic, which is only valid for high frequency signals. Multimeters use DC current for resistance measurements, so you cannot measure the cable impedance using your multimeter or other simple measurement equipments. It is usually best to check the cable type (usually printed on cable) and it's characteristics impedance from some catalogue instead of trying to measure it.

How can I measure cable impedance?

A relationship exists which makes determination of Zo rather simple with the proper equipment. It can be shown that if, at a given frequency, the impedance of a length of cable is measure with the far end open (Zoc), and the measurement is repeated with the far end shorted (Zsc), the following equation may be used to determine Zo:

$$Zo = sqrt (Zoc * Zsc)$$

Where:

- Zoc = impedance of a length of cable is measure with the far end open
- Zsc = impedance of a length of cable is measure with the far end shorted

NOTE: The Zoc and Zsc measurements both have magnitude and phase, so the Zo will also have magnitude and phase. High frequency measurements of Zo are made by determining the velocity of propagation and capacitance of the cable or by reflectometry.

When cable impedance affects the signal?

In order for a cable's characteristic impedance to make any difference in the way the signal passes through it, the cable must be at least a large fraction of a wavelength long for the particular frequency it is carrying. Most wires will have a speed of travel for AC current of 60 to 70 percent of the speed of light, or about 195 million meters per second. An audio frequency of 20,000 Hz has a wavelength of 9,750 meters, so a cable would have to be four or five *kilometers* long before it even began to have an effect on an audio frequency. That's why the characteristic impedance of audio interconnect cables is not something most of us have anything to worry about.

Normal video signal rarely exceed 10 MHz. That's about 20 meters for a wavelength. Those frequencies are getting close to being high enough for the characteristic impedance to be a factor. High resolution computer video signals and fast digital signals easily exceed 100 MHz so the proper impedance matching is needed even in short cable runs.

How impedance matching works

First, you want to drive the cable with an electrical source that has an output impedance equal to the characteristic impedance of the cable, so that all of the source's output power goes into the cable, rather than being reflected from the cable's input end back into the source. Second, you want the electrical load on the output end of the cable, to have an input impedance equal to the characteristic impedance of the cable, so that all of the power goes into the load rather than being reflected from the load back into the cable.

There are many exceptions to this normal driving method, but those are used for special effects. You can choose an impedance match for maximum power transfer at low bandwidth, or mismatch the impedance for a flatter frequency response. It's the engineer's call, depending on what he wants.

Why impedance matching is needed?

If you have mismatches between the source's output impedance, the cable's characteristic impedance, and load's input impedance, then the reflections can depend critically on the length of the cable. And if you distort the cable, as by crushing or kinking, or if you install connectors improperly, then you can have reflections, with resulting power loss. And sometimes reflected power can damage the power source if its power is sent to the cable (e.g., a radio transmitter). So you need to be careful of impedance mismatches.

An anomaly that is not in all text books is when antenna pushes power back (not a proper termination), it looks at the inside of the shield and the outside, which ever one is lowest gets the power. This means the RF can travel on the outside of the coax. The most difficult concept about coax is the X_L, X_C do not exist (to your transmitter) if cable is terminated.

Most common reasons for listing cable impedance is that because of its reliable electrical characteristics, and that very impedance listing. Coax is often used to carry low-level higher frequency signals that are separated. Separations are very expensive in terms of signal loss -- a perfect impedance match will cost you half the signal, and even a slight mismatch is very costly, particularly at antenna strength signals. Carefully matched carriers, like coax, are necessary to preserve signal at reduced noise.

What effect does the nominal capacitance have on the cable's performance or transmission capabilities?

Capacitance of the cable is nothing to do if the coax is terminated. The transmitter will see absolutely no capacitance nor inductance.

And this transmission line characteristic is used to hide capacitance in high frequency PCB's. Engineers can design the PCB traces so that they have the proper capacitance and inductance values so that the transmitter will see nothing but a proper impedance transmission line.

Why is characteristic impedance important in data transmission?

If a cable is terminated in its matching characteristic impedance you can't tell from the sending end that the cable is not infinitely long - all the signal that is fed into the cable is taken by the cable and the load.

If the impedances are not matches, part of the waves in the cable will be reflected back on the cable connections distorting the outbound waves. When these reflected waves hit the wave generator, they are again reflected and mingle with the outbound waves so that it is difficult to tell which waves are original and which are re-reflections.
The same thing happens when pulses are sent down the cable - when they encounter impedance other than the characteristic impedance of the cable, a portion of their energy is reflected back to the sending end. If the pulses encounter an open circuit or a short circuit, all of the energy is reflected (except for losses due to attenuation - another subject). For other terminations, smaller amounts of energy will be reflected.

This reflected energy distorts the pulse, and if the impedance of the pulse generator is not the same as the characteristic impedance of the cable, the energy will be re-reflected back down the cable, appearing as extra pulses.

Can I use coaxial cable without impedance matching?

If the coaxial cable is very short, the cable impedance does not have much effect on the signal. Usually the best way to transmit signal through coaxial cable is to do the impedance matching, although there are some applications where the normal impedance matching on both ends is not done. In some special applications the cable might be only impedance matched at only one end or intentionally mismatched at both ends. Those application are special cases, where the cable impedance is taken into account so that the combination of the cable and the terminations at the ends of the cable produce the desired transmission characteristics to the whole system. In this kind of special application the cable is not considered as a passive transmission line, but a signal-modifying component in the circuit.

What about the velocity of propagation ratio?

Velocity of propagation ratio percentage based on the speed of light in vacuum. The percentage tells what is the speed of the signal in the cable compared to the speed of light in vacuum. In coax cable, under reasonable conditions, the propagation velocity depends on the characteristics of the dielectric material.

Why attenuation figures tend to increase with increasing frequency?

That usually is due mainly to the limited penetration of current into the inner and outer conductors (the skin effect). With increasing frequency, the current penetrates less deeply into the conductors, and thus is confined to a thinner region of metal. Therefore the resistance, hence attenuation, is higher. It also can be caused partly by energy loss in the dielectric material.

How to minimize the attenuation in coax?

For a line with fixed outer conductor diameter, and whose outer and inner conductors have the same resistivity, and assuming you use a dielectric with negligible loss (such as polyethylene or Teflon in the high-frequency range at least), then you get minimum loss in coax if you minimize the expression:

$$(1/d + 1)/\ln(1/d)$$

where d is the ratio of inner conductor diameter to outer conductor ID. A spreadsheet or calculator gets you close pretty quickly: D/d = 3.5911 is close. The formula was claimed to be derived from the formula for coax impedance versus D/d and a formula for loss that you'll find in "Reference Data for Engineers" published by Howard Sams, on pg. 29-13 in the seventh edition.

The interesting thing to notice is that this minimum loss does not directly yield line impedance: the line impedance depends on the dielectric constant of the dielectric. For air-insulated line, the corresponding impedance is about 76.71 ohms, but if the line is insulated with solid polyethylene, then minimum attenuation is at about 50.6 ohms. So, however it came to be, all the RG-58 we use for antenna feeds and test equipment connections is pretty close to minimum attenuation given the above conditions, and that the dielectric is polyethylene.

But if the line uses foam dielectric with a velocity factor of 0.8, then the impedance of minimum attenuation would be about 61 ohms. However, that minimum is a pretty broad one, and you don't start loosing a lot till you get more than perhaps 50% away from the optimal impedance.

Note that foam-dielectric line with the same impedance and outer diameter, as solid-dielectric line will have lower loss. That's because, to get the same impedance, the foam line will have a larger inner conductor, and that larger conductor will have lower RF resistance, and therefore lower loss.

Typical cable impedances

What are typical cable impedances?

The most typical coaxial cable impedances used are 50 and 75-ohm coaxial cables. 50 ohm coaxial cables might be the most commonly used coaxial cables and they are used commonly with radio transmitters, radio receivers, laboratory equipments and in Ethernet network.

Another commonly used cable type is 75 ohm coaxial cable, which is used, in video applications, in CATV networks, in TV antenna wiring and in telecommunication applications. 600 ohms is typical impedance for open-wire balanced lines for telegraphy and telephony. A twisted pairs of 22-gage wire with reasonable insulation on the wires comes out at about 120 ohms for the same mechanical reasons that the other types of transmission lines have their own characteristic impedances.

Twin lead used in some antenna systems are 300 ohms to match to a folded dipole in free space impedance (However, when that folded dipole is part of a Yagi (beam) antenna, the impedance is usually quite a bit lower, in the 100-200 ohm range typically.).

Cable capacitance and characteristic impedance

Take a chunk of coax, connected to nothing. The center conductor and shield form a capacitor. If you charge that capacitor up to 100V, then short the shield to the center conductor, what is the current flow?

It is not infinite (or determined by parasitic resistance and reactance) like a "normal capacitor" but it is determined by the characteristic impedance of the line. If it is 50 ohm line charged to 100V then the current WILL be 2Amps. (100/50) It will be a square pulse, and temporal width (time duration, pulse width whatever you choose to call it) will be determined by the length of the line (around 1.5 nS/foot depending on line's velocity factor).

This method can be used for example to generate current pulses to semiconductor lasers. To get the pulse lengths longer than easily available with practical coaxial lines you can use lumped impedance near equivalent.

Using coaxial cables in applications

What happens if I use 50 ohm cable for video application which needs 75 ohm cable?

If 50 ohm cable sees a 75 ohm load (the receiver), a substantial part of the signal will be reflected back to the transmitter. Since the transmitter is also 75 ohm, this reflected signal will be substantially reflected back to the receiver. Because of the delay, it will show up as a nasty ghost in the picture. Multiple ghosts like this look like ringing. Also, the reflections cause partial signal cancellations at various frequencies.

How can I convert cable impedance values?

The cable impedance itself can't be converter unless you replace the whole cable with new one, which has the right impedance. If you absolutely need to use the existing cable for your application then there is one way to use the exiting cable: impedance converters. There are transformers, which can make the cable look like different impedance cable when those are installed to both ends of the cable.

In some application it is possible to resistive adapters to convert the cable impedances. Those adapters are simpler than transformers but typically have a noticeable signal loss in them (typically around 6 db for 75 ohm to 50 ohm conversion).

Impedance of circuit board traces

High speed signals can be routed on a circuit board if care is taken to make the impedance of the traces match the source driver impedance and the destination termination impedance. A micro strip line will exhibit characteristic impedance if the thickness, width, and height of the line above the ground plane are controlled.
Characteristic impedance formula:

$$Z = (87 / \mathrm{sqrt}(Er + 1.41)) * \ln((5.98*h)/(0.8*w + t))$$

Where:

- Er = dielectric constant (4.8 for typical fiberglass board)
- h = height of the dielectric (fiberglass board thickness between trace and ground plane)
- t = thickness of the copper material in microstrip
- w = width of the copper material in microstrip

The dielectric constant, Er, for typical 0.062" fiberglass board is 4.8. Using a trace thickness of 0.00134" gives a line width of 109 mils for a 50 ohm microstrip.
When routing circuit board traces, differential pairs should have the same length trace. These trace lines should also be as short as possible.

Impedance matching between different impedances

If two cables with different impedances are connected together or a cable is connected to a source which has different impedance then some kind of impedance matching is needed to avoid the signal reflections in the place where the cables are connected together.

Using transformer for impedance matching

The most classical method for matching different impedances is to use a matching transformer with proper impedance transfer ratio. The impedance transfer ratio of a transformer is determined by using the formula:

$$Za / (Na^2) = Zb / (Nb^2)$$

Where:

- Za = input impedance
- Na = number of turns on input coil
- Zb = output impedance
- Nb = number of turns on output coil

The equation can be converted to format:

$$Zb = Za * (Nb/Na)^2$$

From that equation you can see that Nb/Na is same as the transformer voltage transferring ratio between primary and secondary. This means that when you know that ratio you can use the equation without knowing the exact turns ratio.

Impedance matching network using resistors

The matching network shown below can be used to match two unequal impedances, provided that Z1 is grater than Z2.

```
____
----|____|---+---------
R1    |
| |
Z1        | | R2    Z2
|_|
|
-------------+----------
```

The resistor for this circuit can be calculated using the following equations:

$$R1 = Z1 - Z2*R2 / (Z2+R2)$$

$$R2 = Z2 * sqrt (Z1) / (Z1-Z2)$$

The table below will show some precalculated values for some most common interfacing situations:

Z1 (ohm)	Z2 (ohm)	R1 (ohm)	R2 (ohm)	Attenuation (dB)
75	50	42.3	82.5	5.7
150	50	121	61.9	9.9
300	50	274	51.1	13.4
150	75	110	110	7.6
300	75	243	82.5	11.4

As you can see from the table the cost of simple resistor based impedance matching is quite large signal level attenuation in the conversion process.