

**Abstract:**

This paper explains how to determine a transmission line's characteristic impedance, velocity factor, capacitance, inductance, and bandwidth. These techniques measure coaxial, twisted wire pair (TWP), twinax, triax, twin lead, CAT5, Cat6, Cat 7, power line, and virtually any cable that has at least two conductors paired together.

**Introduction:**

Transmission line designs optimize their properties to deliver an electrical signal over distances with high efficiency and low cost; all transmission line designs result in a consistent set of properties; they all have a(n):

1. Characteristic impedance ( $Z_0$ )
2. Capacitance per unit length (C)
3. Inductance per unit length (L)
4. Velocity factor (VF)
5. Some finite bandwidth (BW)
6. Conductor resistance (R)

More complicated transmission line, such as shielded TWP or twinaxial cable, use more than two conductors per signal and may have multiple  $Z_0$ 's etc. The  $Z_0$  between the signal pair will usually be different than between the signal pairs and the shield. Multiple transmission lines in close proximity of each other have an additional property called

7. Crosstalk

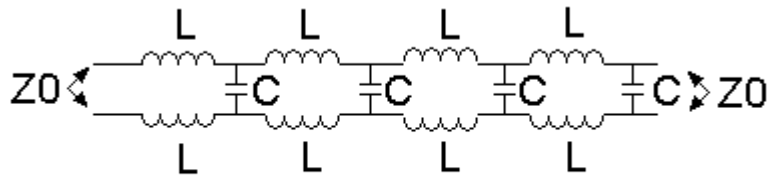
Since there many different types of signals that need to be delivered, many varieties of transmission lines were developed. RF signals sometimes require high power delivery over medium to short distances, other cases look for low loss and low interference over long distances. Computer networks try to deliver wide BW using low cost TWP cable. Power delivery needs to minimize  $I^2R$  losses; these lines use high voltage to drop I and low resistance to drop R. The complete list of signals that use transmission lines would fill several pages, so we only present this high level introduction here.

The AEA Technology network analyzers may be used to measure any of all of these parameters on almost any type of transmission line. Although not all cables make suitable transmission lines, we will refer to transmission lines as cables for the remainder of this paper.

## Theory:

One general property of all transmission lines is they have a uniform cross section, which results in a uniform distribution of inductance, capacitance and resistance along the length of the cable. These quantities may be measured using a network analyzer.

Lets look at an ideal transmission line model:



### Transmission Line Model

The model consists of series inductive elements with parallel capacitive elements. In an actual cable the elements become infinitesimally small; i.e. each tiny portion of cable, no matter how small, has both elements. This means the elements are “uniformly distributed”. When we measure the capacitance (or inductance) of the cable, we measure the total capacitance contained in some unit length, usually one foot or one meter. The capacitance per foot/meter (C) or Inductance per foot/meter (L) are two of the parameters the network analyzer can determine. The values of L and C may be adjusted by varying the geometry of the cable elements, the details of this cable geometry are beyond the scope of this paper.

The effect of the uniformly distributed components creates an impedance to a signal that is applied to the cable. We name this impedance the “characteristic impedance”, or Z0. Some Z0 calculations are shown below:

$$Z_0 = \sqrt{\frac{L}{C}} \quad L = Z_0^2 * C \quad V = I * Z_0$$

Z0 defines the ratio of voltage to current, as seen above in a variation of Ohm’s law. Note that you cannot measure Z0 with a standard ohm meter, as it will measure an open circuit.

Signals in a vacuum travel at the speed of light, approximately  $299.7924 * 10^6$  meters per second. Signals in a cable travel slower than this. We define the velocity factor (VF) as the ratio of signal velocity in a cable to the velocity in a vacuum. Typical velocity factors range from 40% to 90% and are determined by cable geometry and composition. When tuning a cable to a specific wavelength, the VF must be taken into account.

Due to imperfections in the cable, the cable exhibits a finite bandwidth (BW). The finite BW may degrade the signal of interest, so a network analyzer measurement of bandwidth may be used to verify that the cable meets or exceeds expected BW.

The network analyzer also measures crosstalk between different transmission lines in a cable so there must be a minimum of two transmission lines to make a crosstalk measurement. Cables with too much crosstalk cause signal distortions that reduce system performance.

The resistance of the conducting materials used in cables cause resistive losses. System analysis calculates the acceptable amount of resistance (R) in a cable. Remember to add the resistances of both conductors when figuring the loss. Cables are usually specified with some R per unit length, usually 1000 feet or one kilometer.

#### **Applications:**

For all of the network analyzer readings, especially above 30MHz, use the cable null procedure (Open-Short-Load) for best accuracy. If the frequency of the reading is less than 10 MHz, cable nulling is purely optional.

#### **Characteristic Impedance (Z<sub>0</sub>):**

Set your AEA network analyzer to measure total Z on one plot and reflection coefficient (gamma or  $\Gamma$ ) angle for the second<sup>1</sup>. Connect the cable under test to the network analyzer (S11 port); be sure to leave the far end of the cable open. Gather some data at lower frequencies (usually <20 MHz, depending on cable length). You will need to find a frequency where the reflection angle is either + or – 90 degrees. Once you have zoomed in to this area with desired detail, note the total Z reading at the (+/-) 90 degree frequency. This Z reading is equal to the Z<sub>0</sub> of the cable.

#### **Capacitance per foot (or meter) (C):**

You must know the physical length of the cable to determine C. The C calculation will only be as accurate as the length measurement. Set your AEA network analyzer to reactance on one of the plots. Connect the cable to the network analyzer (S11 port); be sure to leave the far end of the cable open. Set the center frequency to 100 KHz. Set the sweep width to get the desired frequency resolution. Try to pick a frequency with a reactance of approximately -200 ohms. Use the formula below to calculate the C:

$$C(\text{pf}) = \frac{10^{-6}}{X * 2 * \pi * f * L}$$

Where:

X = reactance reading with negative sign (i.e. 200)

f = frequency of X reading

L = Length in feet or meters

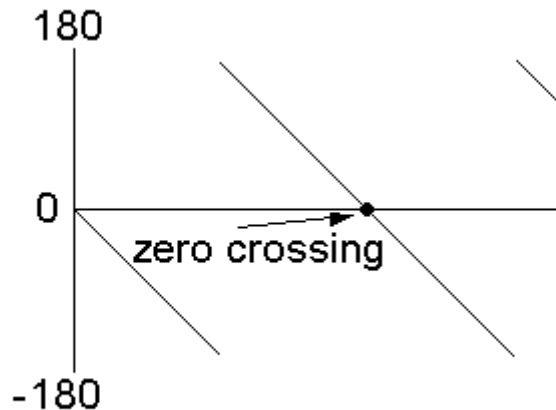
### Inductance per foot (or meter) (L):

Take the readings for C and Z0 outlined above. Use the middle formula below to calculate L.

$$Z_0 = \sqrt{\frac{L}{C}} \quad L = Z_0^2 * C \quad V = I * Z_0$$

### Velocity Factor (VF):

You must know the physical length of the cable to determine VF. The VF calculation will only be as accurate as the length measurement. Set your AEA network analyzer to reflection coefficient angle on one of the plots. Connect the cable to the network analyzer (S11 port), be sure to leave the far end of the cable open. Set the center frequency equal to the first positive to negative zero crossing. Set the sweep width to get the desired frequency resolution. Use the formula below to calculate the VF:



$$VF = \frac{2 * \text{len} * f}{c} = 0.00667128 * \text{len} * f$$

where:

len = physical length in meters

f = frequency in MHz (first zero crossing)

c = 299.79224 X 10<sup>6</sup> meters/sec

Note: multiply result by .3048 if len is in feet.

### Bandwidth (BW)

You can measure the BW of the cable without knowing its length, but if you want to compare to the manufacturer's specifications, you will need to know the physical length of the cable and normalize your reading. Set your AEA network analyzer to reflection coefficient (gamma, or  $\Gamma$ ) magnitude for one of the plots. Connect the cable to the network analyzer (S11 port); be sure to leave the far end of the cable open. Set the center frequency and sweep to cover the frequencies or attenuation level of interest. Use the table below to determine the attenuation. The BW of the cable equals the first frequency that attenuates to the specified level.

$$\text{Attn} = 10 * \log(\Gamma)$$

$\Gamma$ reading	attenuation
0.794	1
0.501	3
0.251	6
Other	Use formula

Shouldn't that formula be  $20 * \log(\Gamma)$ ? No, the reading of the network analyzer gives the BW for a round trip through the cable; most systems only care about the one way BW.

### Alternate method for Bandwidth (BW)

If you have a 2 port network analyzer, you can measure the BW directly in dB's. If you want to compare to the manufacturer's specifications, you will need to know the physical length of the cable and normalize your reading. Set your AEA network analyzer to log gain for one of the plots. Perform a cable null to normalize the gain path (thru) using a short, high quality cable with appropriate connectors. Once the nulling is done, connect the cable under test to the network analyzer; one end to S11 port, the other end to S21 port. Set the center frequency and sweep to cover the frequencies or attenuation level of interest. You may read the attenuation directly off the log gain scale. The BW of the cable equals the first frequency that attenuates to the specified level.

### Resistance (R)

The best way to measure the cable R is with a regular DVM. For cables less than 100 feet long, a 4 lead ohmmeter is highly recommended. Take good precaution to avoid connector resistances unless you want to include them in the measurement.

You can use a network analyzer to measure the R of transmission line conductors; but the length should be enough to add up to 10 or more ohms. When using the network analyzer to measure R, connect the cable to the S11 port, and short the far end of the line together, and set the unit to plot resistance.

## **Crosstalk**

Crosstalk measurements give meaningful data only if the cables under test are connected in a manner similar to the actual application. For example, Cat 6 cables will give a terrible reading if the cables are left unterminated. If the cross talk signal has to “jump” across to another loaded line, it will see more attenuation than if the other line is left open. To measure crosstalk, you must have a 2 port network analyzer; a single port will not measure crosstalk. Set your AEA network analyzer to log gain for one of the plots. Set the center frequency and sweep to cover the frequencies or attenuation level of interest. You may read the attenuation directly off the log gain scale. Perform a cable null to normalize the gain path (thru) using a short, high quality cable with appropriate connectors. Once the nulling is done, connect the cable under test to the network analyzer; one channel to the S11 port, the other channel to the S21 port. The far ends of the cables should have a load terminator (110 ohms for CAT 6).

## **Conclusion:**

The AEA Technology series of network analyzers provide measurements useful in determining the characteristics and parameters of transmission lines. These tests include the measurement of:

1. Characteristic Impedance (Z0)
2. Capacitance per unit length (C)
3. Inductance per unit length (L)
4. Velocity Factor (VF)
5. Bandwidth (BW)
6. Crosstalk

## **Notes:**

1. Some Bravo versions only plot these two simultaneously on the PC Vision software, or while in CW mode. You may alternately take one of the readings, note the frequency, and then measure the other reading at this frequency.