Reducing Time-to-Repair for Complex MILCOM Systems through Innovative Measurement and Characterization of Transmission Lines

2015 Aerospace Defense Symposium

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Abstract:

Newly developed techniques enable maintenance personnel to reduce downtime due to faulty transmission lines, the major cause of failure in MILCOM systems. This paper first presents transmission line theory for a wide range of media and then relates theory to practical methods for in-the-field system analysis and characterization using ruggedized all-in-one equipment.

Agenda

– Modern Milcom Systems
– Transmission Line Basics
– Frequency Limitations of Connectors and Cables
– Measuring Insertion Loss
  - One-Port Techniques
  - Very Long Cables
  - High loss Cables
– Troubleshooting Transmission Line Faults
  - TDR and Impulse Modes
  - Velocity Factor of Coax and Waveguide
– Conclusions

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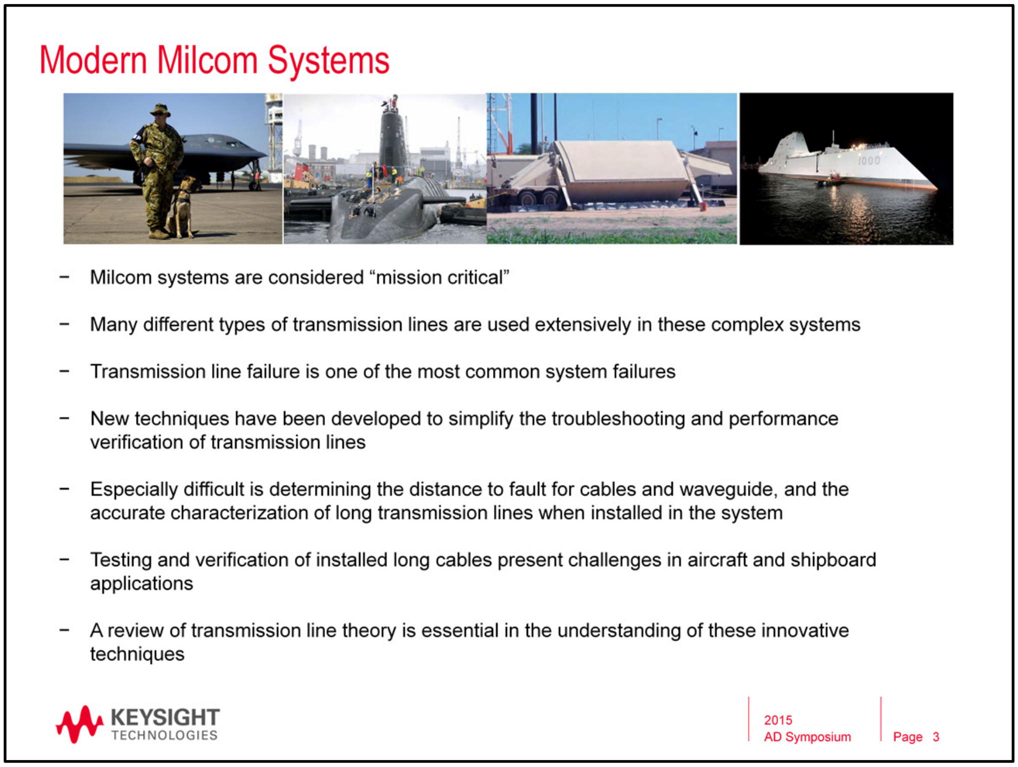


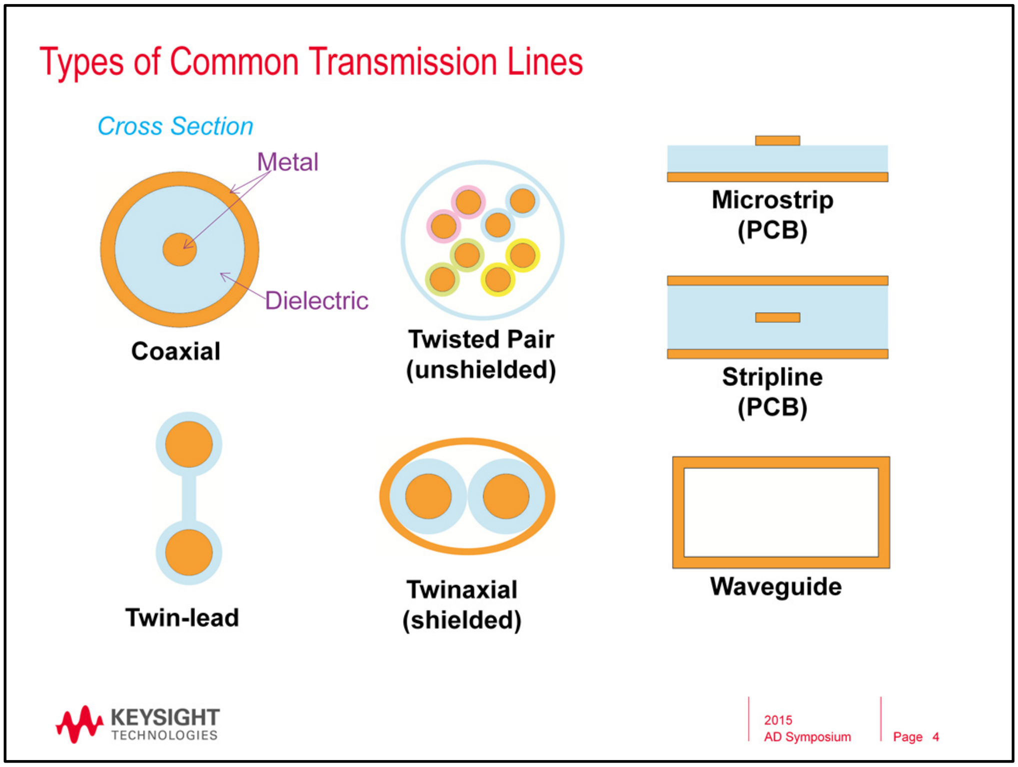
Modern military communication systems are considered mission critical due to the fact that system failure can have life and death consequences. One thing these complex systems have in common is the extensive use of transmission lines of many types. Another shared characteristic is that transmission line failure is one of the most common system failure mode.

This paper will show innovative techniques for the testing and troubleshooting of a number of different types of transmission lines, from twisted pairs to waveguide.

Consider that a modern satellite earth station can have 100 meters of waveguide, with fixed, flexible and rotary components. Accurately pinpointing a fault in the waveguide is critical for the technician working to get the system back on line.

Many military platforms have extremely long coaxial cable runs that travel through bulkheads and around superstructure. Accurately measuring the loss of these cables presents a unique challenge during installation and maintenance of the system, whether it be on a surface ship, submarine or aircraft.

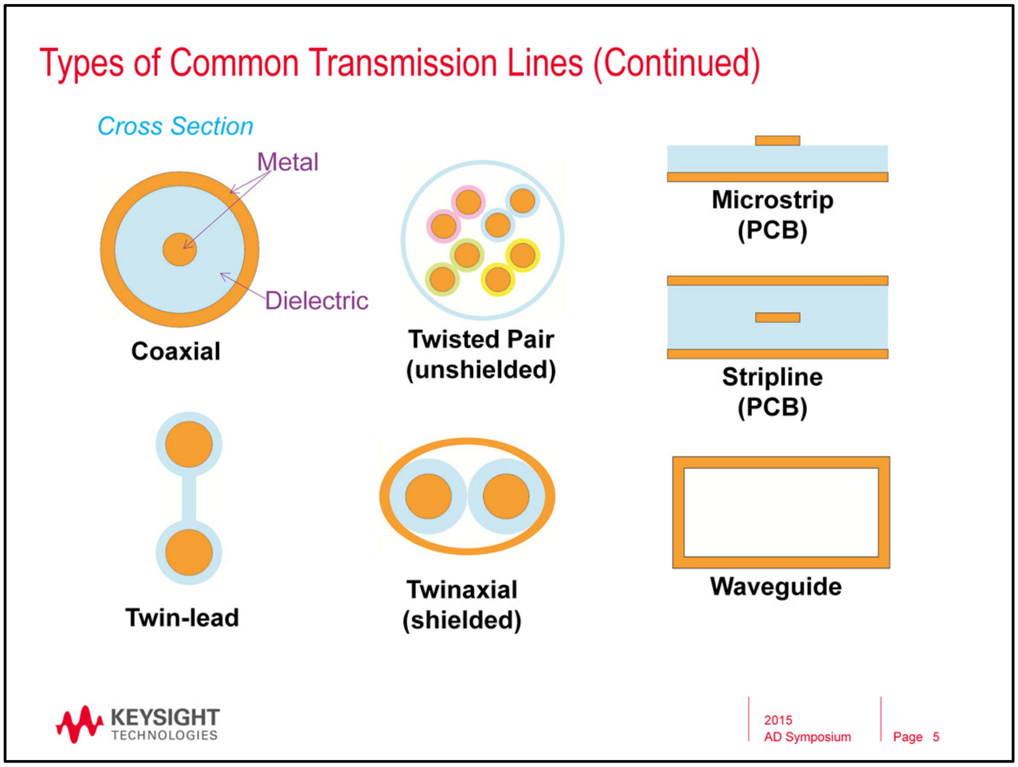
A review of transmission line theory will be presented and then the new techniques will be examined.



A transmission line can have a variety of physical configurations which support propagation of a high frequency signal. It is often desired to have a line with relatively low signal loss while maintaining fixed characteristic impedance along its length. This slide shows the cross section of several of the most popular types of transmission lines with most having two separate conductors. For example, the coaxial line, shown on the upper left, consists of inner and outer conductors separated by a dielectric material. The conductor geometry and dielectric properties determine the characteristic impedance of the line which is either 50-ohm or 75-ohm for the most popular configurations. The signal energy in the coax is confined between the two conductors and flows down the line through the uniform dielectric resulting in a tightly controlled impedance and propagation speed over a large range of operating frequencies.

Twin-lead is another two conductor transmission line that consists of two equal diameter wires separated by a thin dielectric support. The diameter of the wires and their spacing determine the impedance of the line which is often 300 ohms in this older type of transmission line. Twin-lead has a portion of its electromagnetic energy propagating in the dielectric between the two conductor and some of its energy propagating in the surrounding air. Having a signal simultaneously propagating in different dielectrics often limits the frequency range of the line as the impedance and propagation characteristics become a function of frequency. An improved version of the two-wire line, known as twinaxial line, includes a shield placed around the two wires that serves to confine the energy and results in controlled impedance with improved propagation velocity over a much larger range of frequencies. Twinaxial is typically designed for an impedance of 100-ohms.

Twisted-pair is another two-wire transmission line that is extremely popular in data networking applications such as the CAT-5 and CAT-6 cable series. These cables combine 4 pairs of wires bundled within a common outer sheath. This configuration allows 4 independent signals to travel in parallel along the same cable to improve the total data capacity of the cable.



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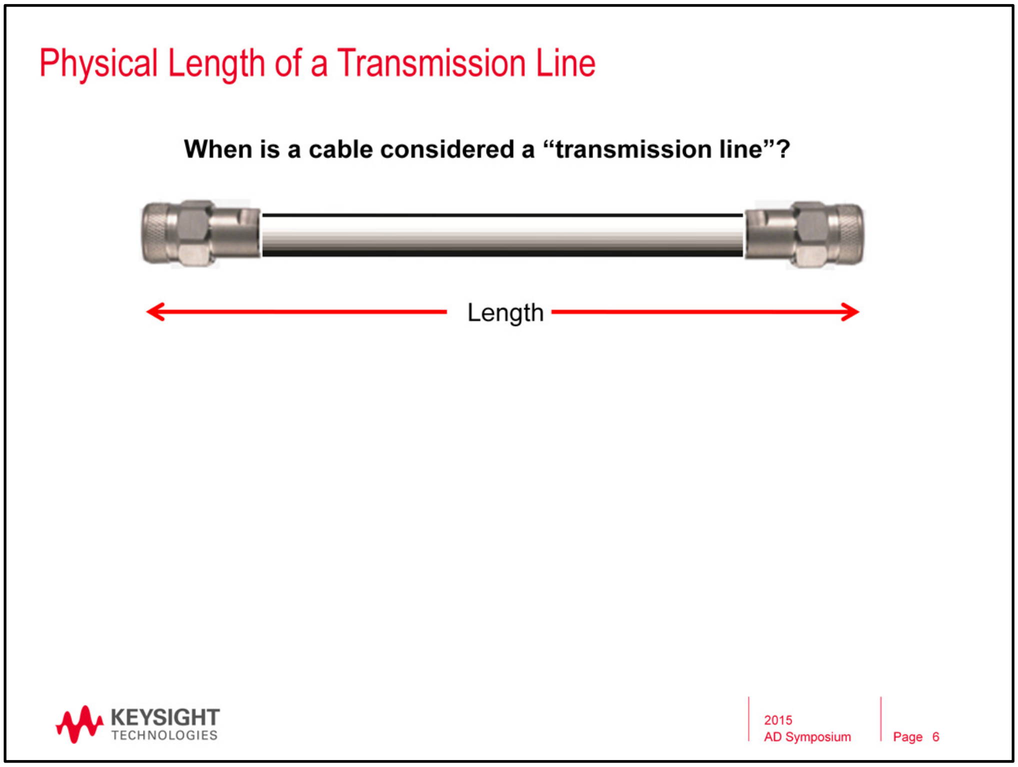
Inexpensive twisted-pair cables are typically unshielded. Higher operating frequency can be achieved when a common shield is placed around the 4 pairs of wire. Twisted-pair lines are also designed for 100-ohm impedance.

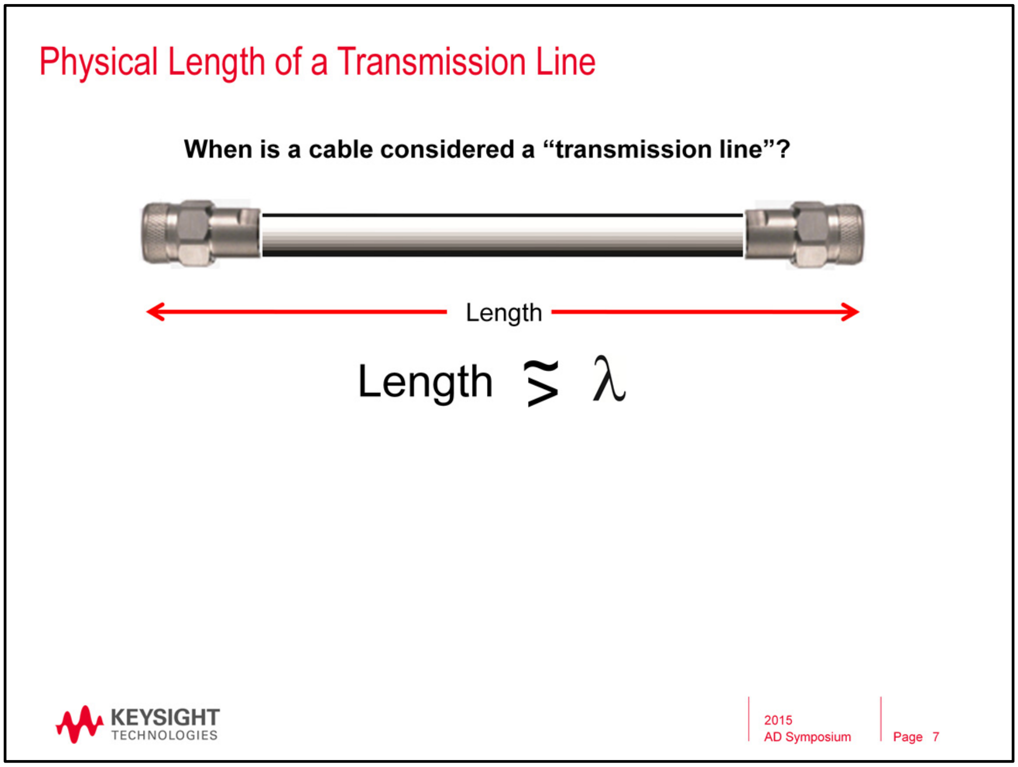
Microstrip and stripline are transmission lines that are primarily used in printed circuit board and integrated circuit applications. They are ideal for connecting transmission lines with surface mount components including integrated circuits in small packages. Here again the geometry of the conductors and dielectric properties of the supporting material determines the impedance and propagation characteristics for the line. While the coaxial and other two-wire cables are appropriate for use over very long distances, microstrip and stripline are used within small devices including most radio and radar components and systems.

The last transmission line type to mention is waveguide. This is the one transmission line structure that does not require two separate conductors. This hollow tube can be constructed using a rectangular cross section, as shown here, or constructed using circular or elliptical cross sections. Electromagnetic field theory is required to understand how the signal travels along this rigid transmission line but key features for using waveguide are the relatively low insertion loss and high power capability.

One key point to mention regarding operating range is that two-conductor transmission lines operate down to DC while waveguide operates only over a narrow range of frequencies. For transmission lines that operate down to DC, is the line still considered a “transmission line” at DC or very low frequency?



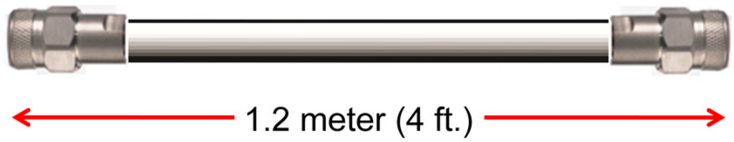
This brings up the question of “when is a cable considered a “transmission line?”



The answer is relatively simple, when its physical length is comparable to the wavelength for the signal of interest. For a cable with an input operating at DC, the voltage and current values are the same at all points along the line. As the operating frequency is increased, the voltage and current values become functions of the position as the cable length becomes proportional to the wavelength. Let's take a look at a cable operating at two different input frequencies.

Physical Length of a Transmission Line

When is a cable considered a “transmission line”?



Example 1:
Frequency (f) = 1 kHz

$$\lambda = \frac{v_{coax}}{f} = \frac{3\text{x}10^8\,\text{m/sec (VF)}}{1\text{kHz}} = 198\text{km}$$

1.2 meter cable is 0.000006λ (=0.002^0)

Not considered a transmission line

Example 2:
Frequency (f) = 1 GHz

$$\lambda = \frac{v_{coax}}{f} = \frac{3\text{x}10^8\,\text{m/sec (VF)}}{1\text{GHz}} = 0.198\text{m}$$

1.2 meter cable is 6.06λ (=2.2k^0)

Yes, this is a transmission line

VF = 0.66 (data sheet)

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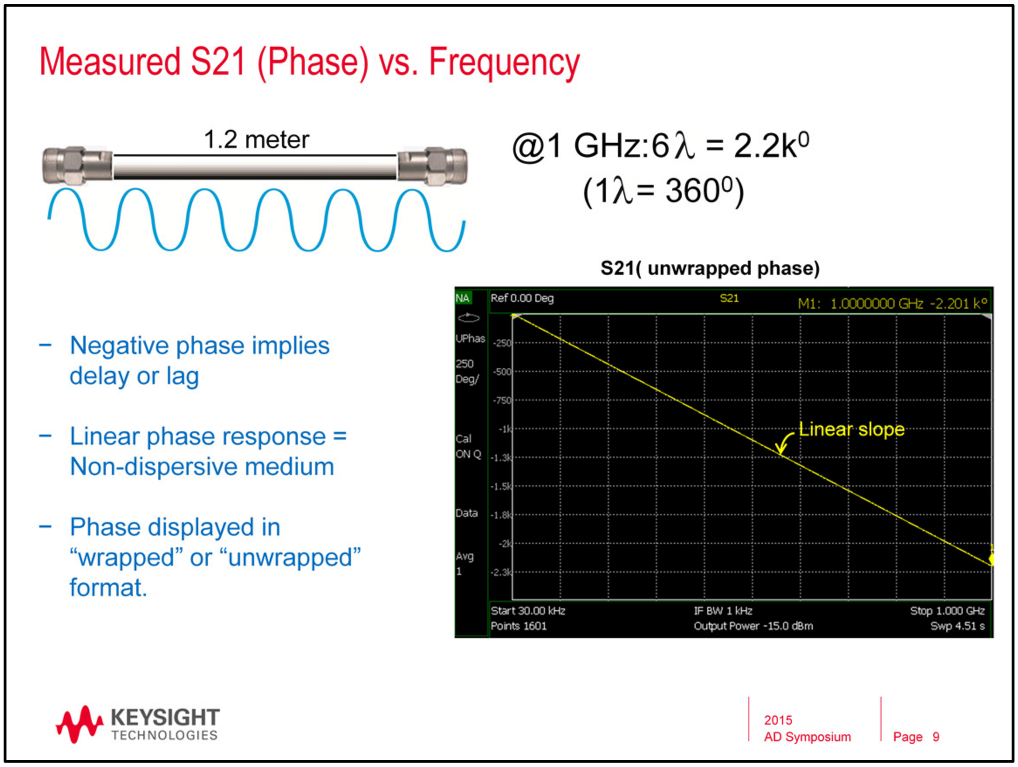
Here is an example of a coaxial cable that is 1.2 meters in length. We wish to determine if this cable would be considered a transmission line when the input signal is 1 kHz and when the input is 1 GHz. When the input signal is 1 kHz, the associated wavelength is 198 km which makes the relative length of this coaxial cable only 0.000006 wavelengths long. Using the relationship that one wavelength is equal to 360 degrees; this cable’s electrical length is only 0.002 degrees at 1kHz. In this case, the voltage and current are essentially independent of location along the cable.

When the frequency is increased to 1 GHz, the signal wavelength is 0.198 meters and the cable is now approximately 6 wavelengths long. Six wavelengths at 1 GHz results in an electrical length of 2,200 degrees. In this case, the cable is considered a transmission line as the cable length is larger than the wavelength of the signal. For the 1 GHz case, the voltage and current, represented as complex signals having a magnitude and phase, are now functions of their location along the coaxial cable.

It is important to note that the calculation of wavelength requires the value for the velocity factor of the cable. In air, a signal will travel at the speed of light, so if a transmission line is filled with air, its velocity factor is 1 or 100% of the speed of light. In a cable filled with a dielectric, the velocity is reduced by the specified velocity factor. For the cable shown in this example, the velocity factory is 0.66 or 66% of the speed of light and the associated wavelength is also reduced by this value (relative to free space).

Knowing that the cable phase is approximately 0 degrees at very low frequency and 2,200 degrees at 1 GHz, what is the behavior of the phase as a function of frequency?

Next we will examine the transmission phase for this cable as a function of frequency.

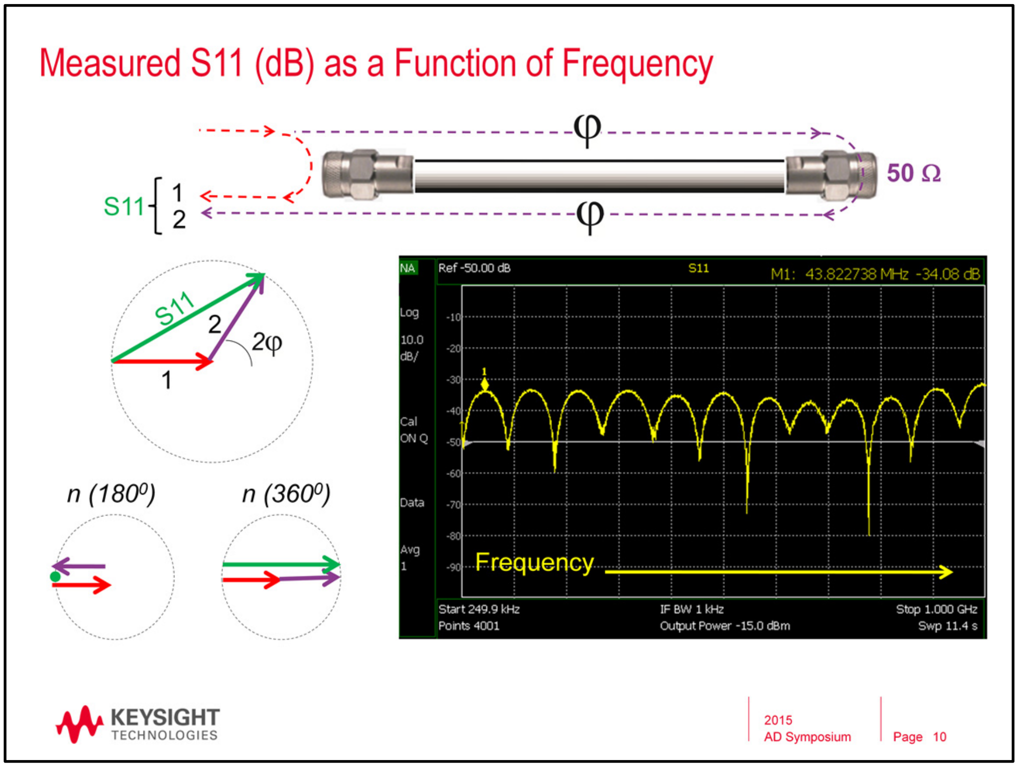


Here is a measurement of the phase response for the 1.2 meter 50-ohm coaxial cable over a range of 30 kHz to 1 GHz. This measurement was performed using the vector network analyzer (VNA) mode on a Keysight Technologies, Inc. FieldFox handheld analyzer. As previously shown, the calculated phase at 1 GHz is 2,200 degrees. As here under the cable illustration, the 1 GHz signal corresponds to approximately 6 full waves of a sinusoidal signal across the length of the cable. If the phase at the input to the cable is referenced as zero degrees, the relative phase at the output is 6 times the 360 degrees or a total phase length of 2,200 degrees.

Using the marker function on FieldFox, the measured phase response at 1 GHz reports -2,201 degrees which matches the calculated value except for the minus sign. As phase is always a relative number to the input, the negative sign corresponds to the fact that the cable represents a delay, or lag, in the signal when measured at the cable output.

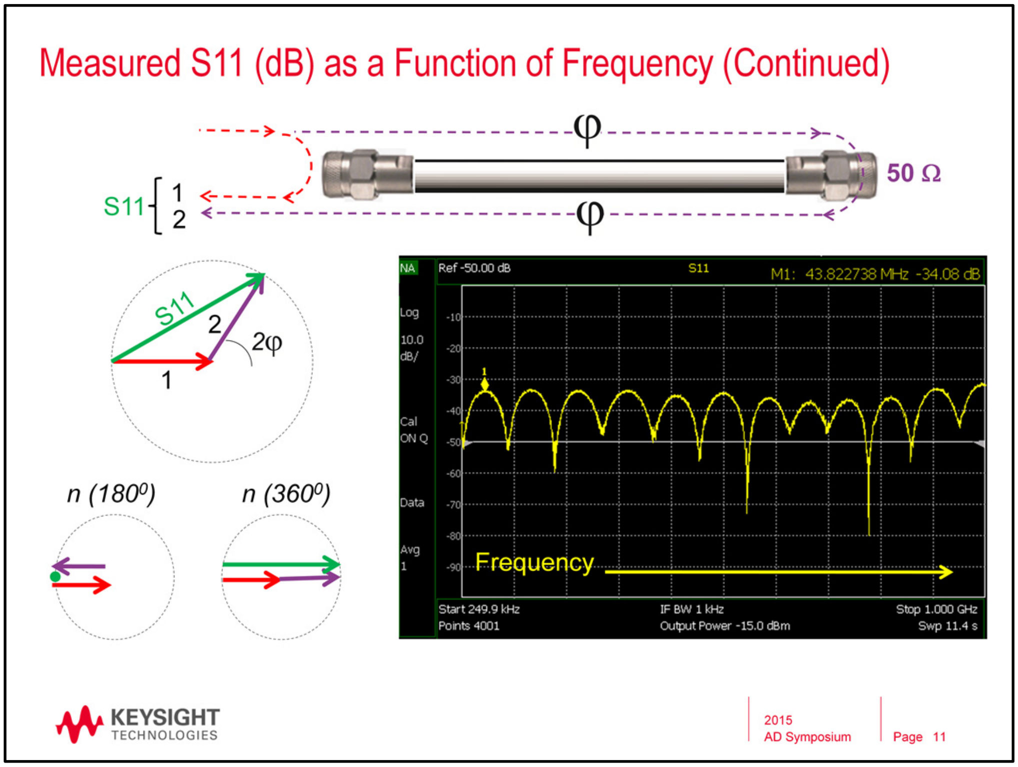
A few more things to point out concerning the measured response: First, the transmission phase for this cable is a linear function over frequency. We will shortly discuss that the time delay of a transmission line is related to the slope of the phase response. A linear phase slope represents a fixed time delay across the measured frequency range. If the phase slope is not linear, the transmission delay will be a function of frequency resulting in distortion of the signal as it passes through the transmission line. Lastly, the phase response can be displayed in an “unwrapped” format, as shown here, or in a “wrapped” format that displays the phase varying between +180 degrees to -180 degrees. The wrapped format effectively reports the measured phase response as a multiple of a 360-degree range.

So why is it necessary to discuss the phase through a transmission line when most of the test specifications are related to the performance of magnitude quantities such as return loss and insertion loss? On the next slide, we will discuss the effects of phase on the measured return loss of a cable.



Here is the measured return loss of the 1.2 meter 50-ohm coaxial cable terminated in a 50-ohm load. The return loss is measured as the "S11" s-parameter using the VNA mode on FieldFox. The frequency range for this measurement covers 30 kHz to 1 GHz.

Assuming that there are no discontinuities along the length of the cable and the termination is close to an ideal 50-ohm load, the measured reflection at the input is a combination of reflections from the connector and connector-to-cable interface from both ends of the cable. As the input connector is close to the VNA test port, it introduces little phase shift to this reflected signal, as shown here as vector "1" with an angle equal to zero. The portion of the signal that passes through the cable will include a phase shift of "phi" degrees due to the cable length. Using the 1.2 meter cable from the previous discussion, this phase shift would be 2,200 degrees at 1 GHz. When the transmitted signal hits the output connector, a portion is reflected back to the VNA source. If the two connectors are of the same type, it can be assumed that the reflection from the output connector will be the same as the reflection from the input connector. After the reflected signal from the output passes back through the cable, the total phase shift will be two "phi". These two reflected signals, each having an equal amplitude but a relative phase difference of two "phi", will add into a single vector shown here as S11 on the left. As the frequency is swept over a wide range, the second reflection will sweep around a circle relative to the input reflection. It should be noted, as before, that the phase "phi" is actually a negative value as transmission through the cable represents a lag which represents a negative phase shift.



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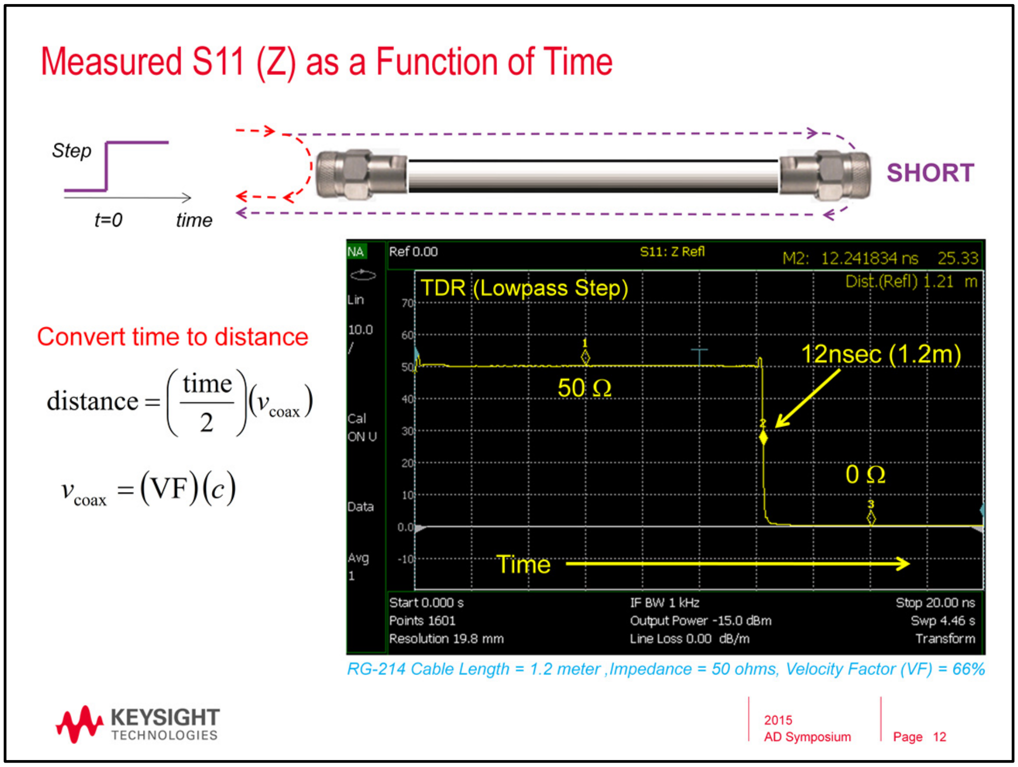
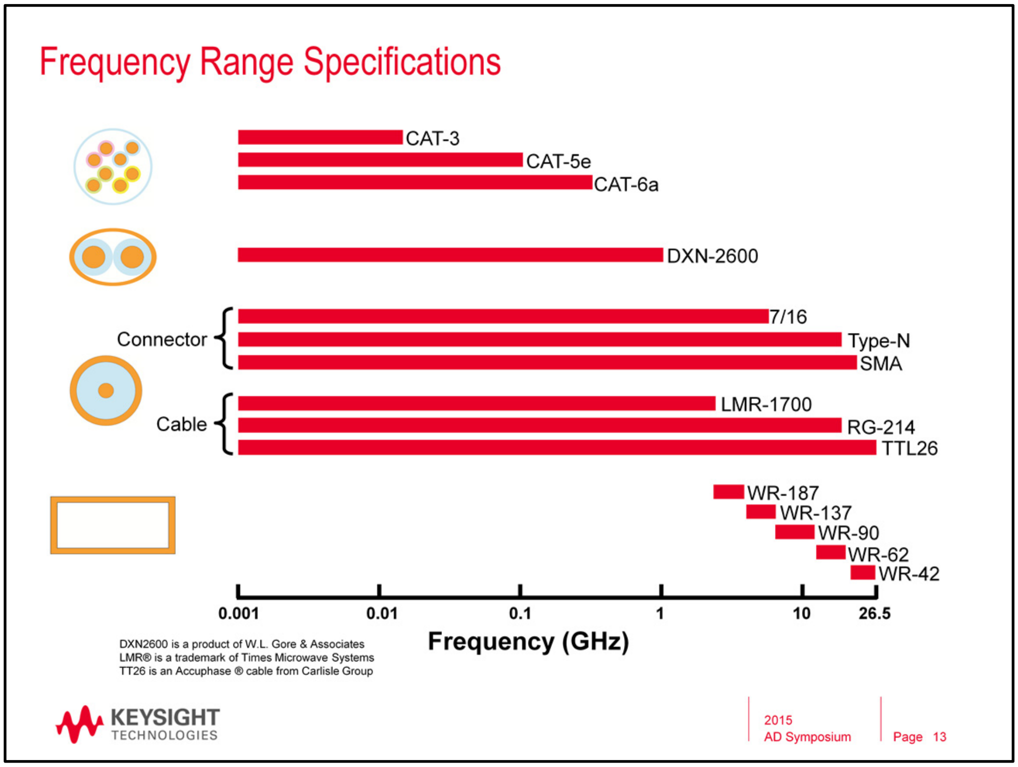
If the relative phase difference between the two reflections is a multiple of 180 degrees, the reflections will subtract and the measured S11 will be a null in the frequency response. If the relative phase difference is a multiple of 360 degrees, the reflections will add to a peak at that particular frequency. The measured S11, shown here on the right, displays this effect of vector addition and subtraction from these two reflections. If the reflection magnitude of the input and output connectors are identical, the peaks in the measured S11 response will be 6 dB higher than the reflection from a single connector. If one of the connectors was faulty, or there was damage to a portion of the cable, the measured frequency response of S11 may not provide any guidance to where the fault occurs. In this case, converting the frequency response into a time domain response can provide additional information regarding the physical location of the fault. On the next slide, we examine an example of the time domain response of this cable.



Here is the measured time domain response of the 1.2 meter cable, for this case, terminated in a short. The measurement was recorded using the VNA mode in FieldFox and configured to display the time-domain response (TDR) using the measured S11. In this example, FieldFox simulates a TDR step response and the analyzer was formatted to display the impedance (Z) as a function of time.

A TDR response is the result of exciting a transmission line with a stepped waveform and measuring the input to the line as the step travels down the line and reflects back from any discontinuities. In the example shown here, the step is referenced to time equal to 0 (t = 0) and the analyzer calculates the impedance of the cable as a function of time. Initially the impedance is approximately 50 ohms which is the impedance of the coaxial cable. At a later time, the step arrives at the short. As a short circuit implies a zero voltage across its terminals, the reflected step must be the negative of the incoming step. When the reflected step arrives back at the input it completely cancels the forward signal. The result in the time domain is an impedance reported as 0 ohm occurring at the time it takes for a signal to propagate twice through the cable. In this measurement, the two-way transit time is reported as 12 nanoseconds measured at the point of the transition in the step. Knowing the velocity factor of the cable and dividing the total transit time in half, the measured time to the short can be converted to the physical length of the cable, which is 1.2 meters in this case.

The TDR response not only provides the type impedance at a discontinuity but also reports the location of the discontinuity relative to the input of the transmission line. This technique is very useful when troubleshooting transmission lines that may have not passed their requirements for return loss and/or insertion loss. We will discuss these troubleshooting techniques in more detail later in this paper, but first it is important to understand the basics of frequency limitations for transmission lines. Next we will review the operating frequencies for several types of two-wire lines, coaxial cables and waveguides.

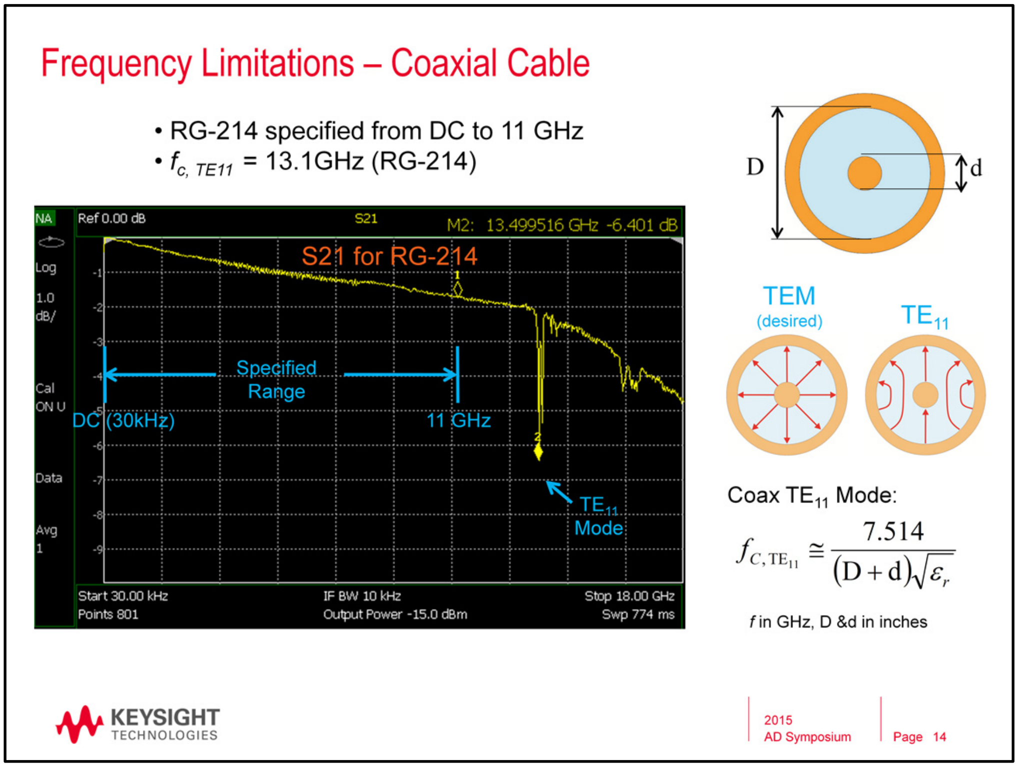


Here is a chart showing the specified frequency range for different types of popular transmission lines. Our first category is twisted-pair datacomm cables which include CAT-3, CAT-5e and CAT-6a. These cables are specified to operate up to 16 MHz, 100 MHz and 250 MHz respectively. CAT-5e cables, with the “e” representing enhanced performance, have improved crosstalk between the 4 pairs of lines. CAT-6a, with the “a” representing augmented, have further improved crosstalk and noise performance, achieved through additional outer shielding.

Next on this chart is twinaxial which is a two-wire cable also with shielding. For example, the DXN-2600 has a high frequency performance of 1 GHz. When discussing coaxial cable assemblies, especially into the microwave regions, is it important to distinguish the individual performance of the connector and the cable. Shown here are the specified frequency ranges for the 7/16, Type-N and SMA connector types. The larger 7/16 connector has an upper range of 7.5 GHz while the smaller diameter SMA will operate up to 18 GHz. When examining the performance of raw coaxial cable, the diameter of the cable also places a limit on the upper frequency range. For example, the large diameter LMR-1700, is specified to
2.5 GHz, while the smaller diameter TTL26 upper range is 26.5 GHz. When manufacturing a cable assembly, the frequency limitation for the complete assembly is that of the component with the lowest individual performance. For example, placing a 7/16 connector on a LMR-1700 cable restricts the frequency range to that of the cable.

It should be noted that both conductor configurations will operate down to DC. The one type of transmission line which includes a low frequency limitation is waveguide. This single conductor “tube” only operates over a narrow range of frequencies. For example, the WR-90 waveguide has a specified operating range from 8.2 GHz to 12.4 GHz.

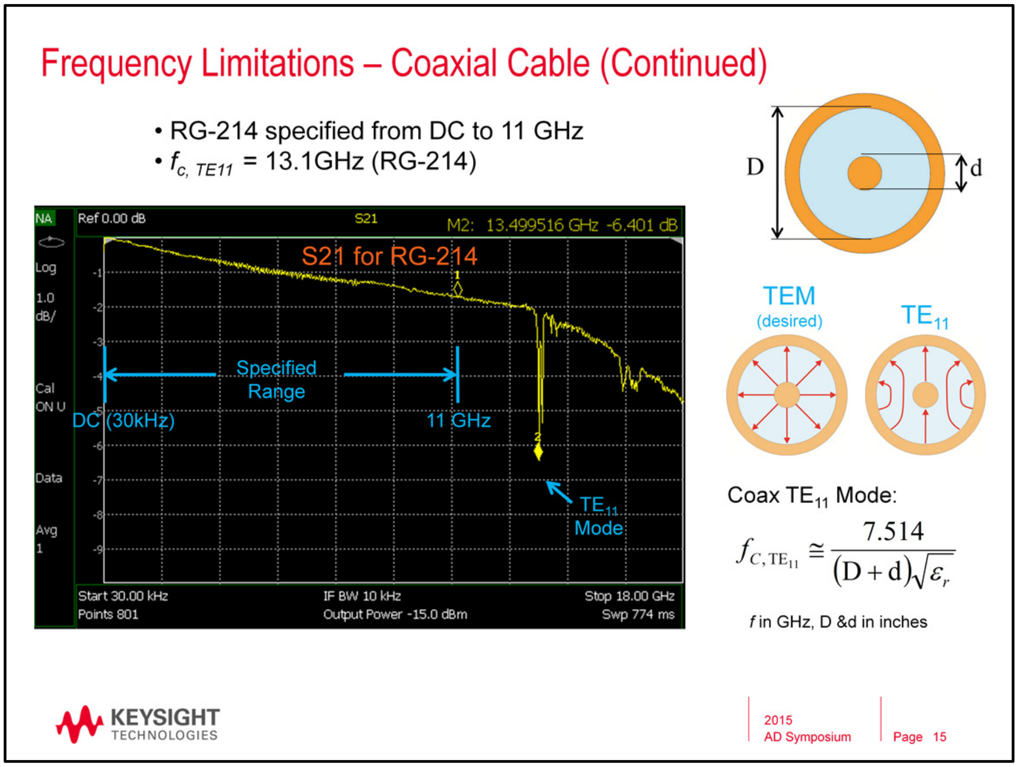
So what causes a transmission line to have an upper frequency limitation? Limitations are associated with the physical geometry of the line that may result in propagation of undesired modes. Over the next two slides, we will discuss the causes for frequency limitations on coaxial cable and waveguide.



In this example, we will discuss the upper frequency limit for RG-214 coaxial cable. The specifications for this cable include an upper limit at 11 GHz. This frequency was selected in order to operate below the frequency in which higher order modes could begin to propagate along the cable.

The effects of higher order modes are shown here on the S21 measurement. In this example, FieldFox was configured to display the cable loss over the frequency range of 30 kHz to 18 GHz. As shown here, the cable loss is well behaved to almost 13 GHz. At 13.5 GHz there is a sudden drop in the insertion loss due to higher order modes propagating on the line. Transmission lines modes are directly a function of the geometry of the cable.

Examining a cross section of the coaxial cable, we find an inner conductor of diameter “small d” and an outer diameter of “large D”. The space between the conductors is typically filled with a low loss dielectric with dielectric constant “epsilon sub r”. The characteristic impedance of the cable is typically designed to either 50-ohm or 75-ohm by adjusting these three values. Without going into too much detail about electromagnetic theory, the coaxial line can be examined as a two-conductor system or as a single-conductor waveguide. At low operating frequencies, the signal propagates with the electric field starting at the inner conductor and extending radially outward to the outer conductor. As shown on the left illustration, this TEM mode is the desired mode of transmission. TEM stands for “transverse electromagnetic” and is the dominant mode in all two-conductor transmission lines. As the operating frequency increases, a second, undesired, mode can be launched on the line. As shown on the rightmost illustration, the outer conductor begins to support a waveguide mode with the electric field lines starting and ending on the outer conductor. The frequency for this undesired mode, named TE_{11}, can be estimated with the equation shown here (F in GHz and D, d are in inches). For RG-214, the calculated frequency is 13.1 GHz. Cable manufacturers and industry committees will set a safety margin as a percentage of this mode frequency, and in the case of RG-214, the upper limit is specified to 11 GHz.



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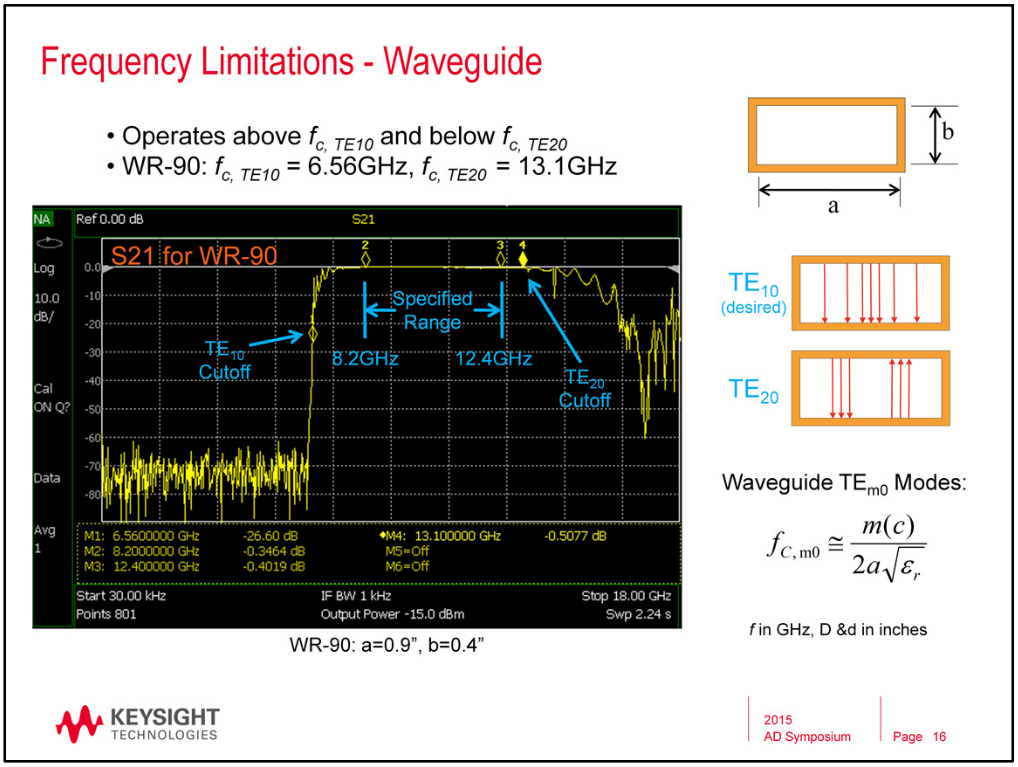
So why does a second mode of propagation result in changes in the insertion loss of the cable?

When the signal energy couples into other modes and reaches the end of the cable, only the dominant TEM mode will couple out of the line while the higher order mode will remain trapped in the cable resulting in a loss of energy. Also, higher order modes will propagate with different velocities as they travel down the transmission line. Having signal energy shared between different propagating modes will create distortion in the signals should the multiple modes re-combine at the output.

It may be worth noting that there are numerous other modes that can propagate on a coaxial line, we only discussed the TE_{11} mode as this is the first undesired mode having the lowest frequency for propagation and thus results in the limitation for the frequency range of the cable.

Next we will discuss the frequency range limitation for waveguide and the associated modes in this transmission medium.



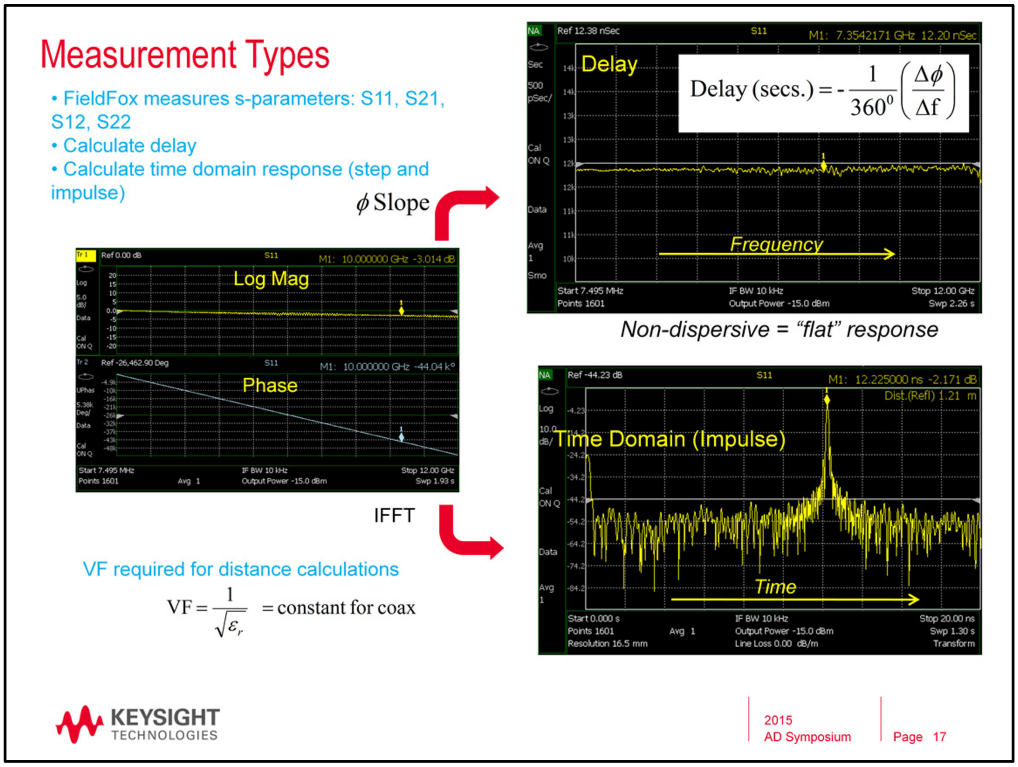
Waveguide is another type of transmission line with a frequency range limitation set by higher order modes. The S21 measurement on the left is the frequency response for a short section of X-band WR-90 waveguide. At the higher frequencies, like coax, higher order modes create a condition where the transmission response is not well behaved. Unlike coax, you will notice that there is a high level of attenuation at the low-end of the frequency range.

As waveguide is a single-conductor line, the dominant TEM mode found in coax will not propagate in waveguide. In this case, the next propagating mode becomes the desired mode for signal transmission. For waveguide, TE_{10} mode is the dominant mode, and the electric field distribution is shown on the right. This mode does not propagate until the signal wavelength is approximately one half the waveguide’s largest dimension, labeled here as “a”. The equation for the frequency which TE_{m0} modes will propagate is shown here with the dominant mode having m = 1. For X-band WR-90 with its largest dimension standardized to 0.9 inches, the TE_{10} mode is considered to be propagating above 6.56 GHz. This frequency is also known as the cutoff frequency for the waveguide.

The S21 measurement on the left covers the range of 30 kHz to 18 GHz. You can observe the waveguide cutoff as the attenuation is very high at the low end of the frequency range and rapidly improves as the frequency approaches the specified cutoff frequency of 6.56 GHz. Above the cutoff frequency, the insertion loss becomes very low, especially above 7 GHz. The specification for WR-90 starts at 8.2 GHz which places the operating frequency well above the cutoff frequency for this waveguide.

As the frequency is further increased, a second mode of propagation appears, and for WR-90, this is calculated to be 13.1 GHz. This TE_{20} mode begins to affect the S21 of the waveguide which is no longer well behaved. Restricting the frequency range above the cutoff frequency and below the TE_{20} propagation, results in a specified range from 8.2 GHz to 12.4 GHz for WR-90. The same calculations can be performed for a variety of available waveguide transmission lines.

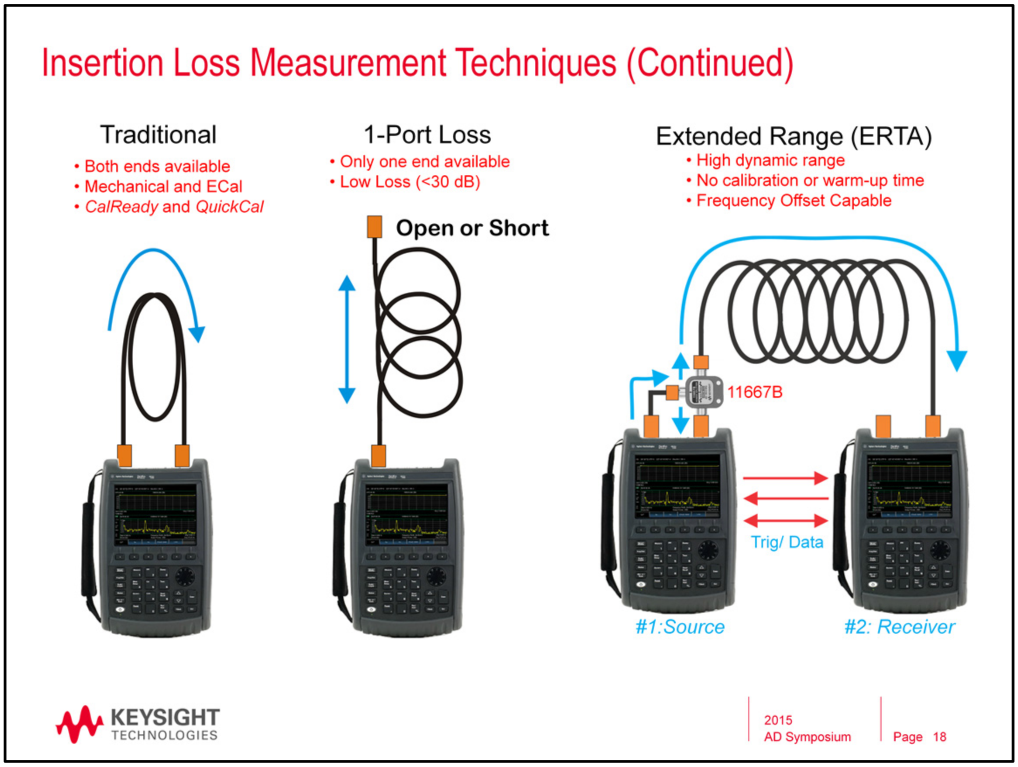
Now that we understand the basics of why transmission lines have an inherent frequency limitation, we can now discuss some of the basic measurements and measurement techniques that can be utilized when characterizing and troubleshooting transmission lines.



Here are several frequency and time domain measurements that were captured using a FieldFox handheld analyzer. The measurement on the left is a frequency sweep of the S11 return loss and S11 phase response for a 1.2 meter coaxial cable with a short placed at the end. The two measurements on the right are derived from the S11 measurements on the right. The upper right shows the delay as a function of frequency. This delay response is calculated from the slope of the phase versus frequency measurement. As we discussed earlier, coaxial transmission lines are non-dispersive and their phase response is linear resulting in a flat delay response. For this cable, the two-way time delay is measured at 12.2 nanoseconds across the 12 GHz span. Having a flat delay response is ideal for transmission lines as the line does not introduce any frequency distortion in the transmitted signal. While delay measurements are not typically required for coaxial cables, they are often required when measuring the performance of filters. Later in this paper, we will discuss delay through waveguide as this response is non-linear as a function of frequency.

The lower right measurement is the time domain response for this cable and short combination. This measurement has time along the x-axis of the plot. FieldFox calculates the time-domain response using an inverse fast Fourier transform (IFFT). For this plot, there is a single peak in the measurement corresponding to the location of the short at the end of the cable. If the velocity factor of the cable is known, a marker can be placed at the peak and the cable length will be displayed. For this example, the marker shows that the cable length is 1.2 meters as expected. This type of measurement is very useful when troubleshooting problems along a transmission line or system.

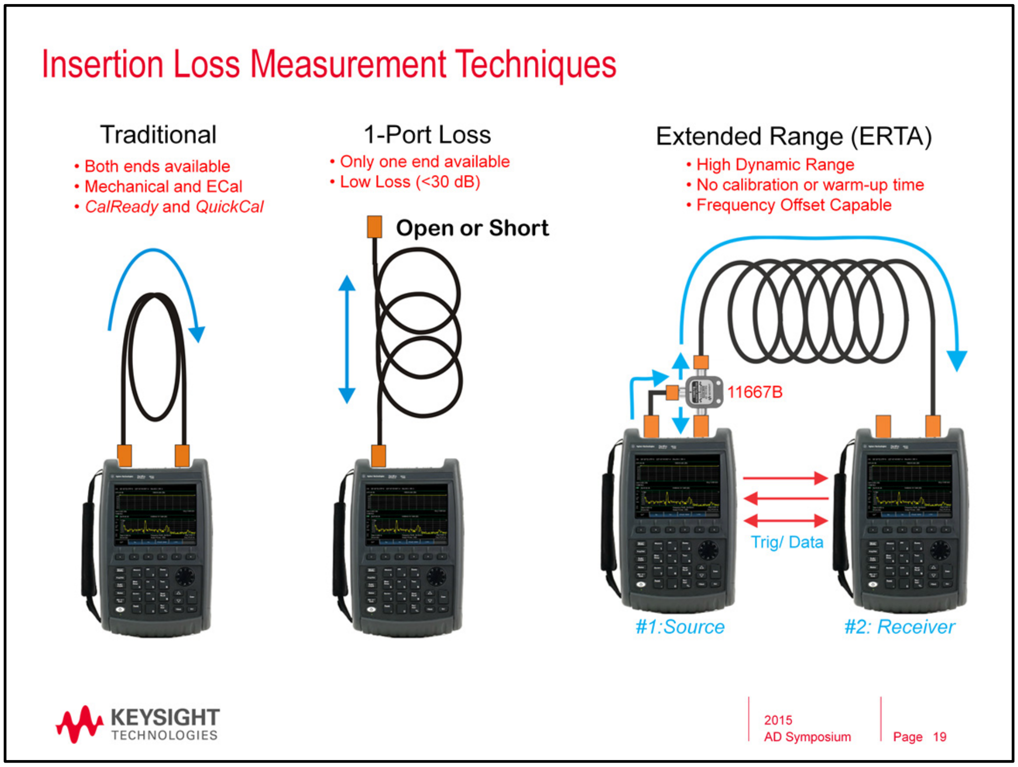
It is important to note that the cable's velocity factor is only required when calculating the physical length of a transmission line in the TDR and time-domain modes. Other measurements including return loss and insertion loss do not require the entry of velocity factor into the analyzer. Over the next few slides we will continue our discussion of insertion loss by examining techniques that can be used to measure low-loss and very long cables.



Here are three techniques available on FieldFox that can be used to measure the insertion loss of a cable or transmission line. Depending on the overall cable loss and whether both ends of the cable will be accessible will determine which technique is best to use.

The traditional 2-port method, shown on the left, is the configuration to use when both ends of the cable can be directly connected to FieldFox. This configuration will result in the highest measurement accuracy as FieldFox can apply a full 2-port calibration to remove all measurement errors associated with adapters and jumper cables required for the test. On FieldFox, a full two-port user calibration can be performed using a mechanical or electronic calibration kit. FieldFox also includes the unique “CalReady” and “QuickCal” calibrations which provide high accuracy measurements without the need for a calibration kit. Additional information about FieldFox calibration can be found in the references at the end of this paper.

The center configuration shows a technique for measuring the insertion loss from only one end of the cable. Often when a long cable is installed into a system, it is difficult to physically connect FieldFox to both ends without introducing an equally long jumper cable into the test setup. Fortunately, the 1-port cable loss technique will eliminate the need to carry an extra-long, high-quality test cable as part of the equipment requirements for on-site testing. This simple 1-port configuration requires a single connection to one end of the cable and leaving the other end either open or terminated in a short. It is preferred at microwave frequencies to use a shorted termination to eliminate fringing fields found in an open-ended cable which could alter the measured results. In this configuration, FieldFox measures the S11 of the cable and calculates the one-way insertion loss from the two-way reflected measurement. This technique is ideal for cables whose insertion loss is less than 30 dB. When the insertion loss is larger than 30 dB, the dynamic range of the test system begins to reduce the accuracy of the measurement.



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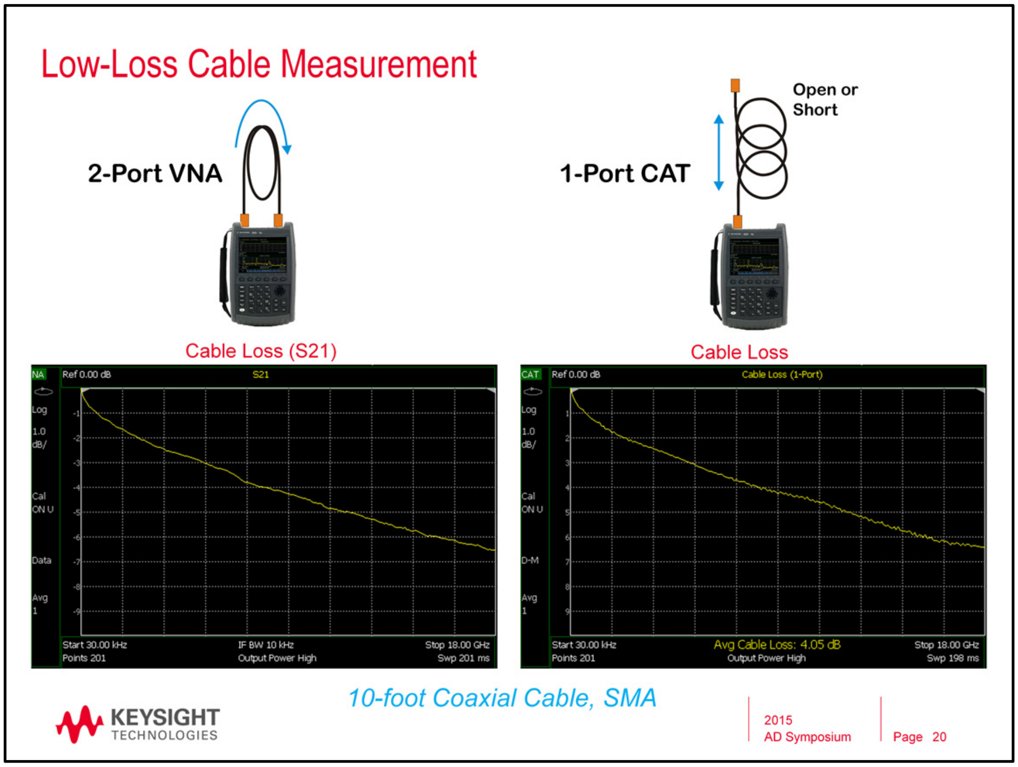
The third configuration, shown on the right, requires the use of two FieldFox analyzers connected at different ends of the cable. This technique is referred to as extended range transmission analysis (ERTA) and is a test mode on FieldFox. With both analyzers configured in ERTA mode, one FieldFox acts as the sweeping source and the other as a sweeping receiver. Both the source and receiver are synchronized using a master/slave configuration and a shared trigger. The high dynamic range receiver found in FieldFox requires no calibration or warm-up time. At the source, a two-resistor power splitter, such as the Keysight 11667B, splits the signal between the local and remote analyzers. The measured insertion loss is displayed on both analyzers as a ratio of the two measurements. The ERTA configuration is ideal for transmission systems with high insertion loss (>30 dB). This configuration is also capable of measuring transmission paths which contain a frequency conversion element such as a frequency downconverter or upconverter.

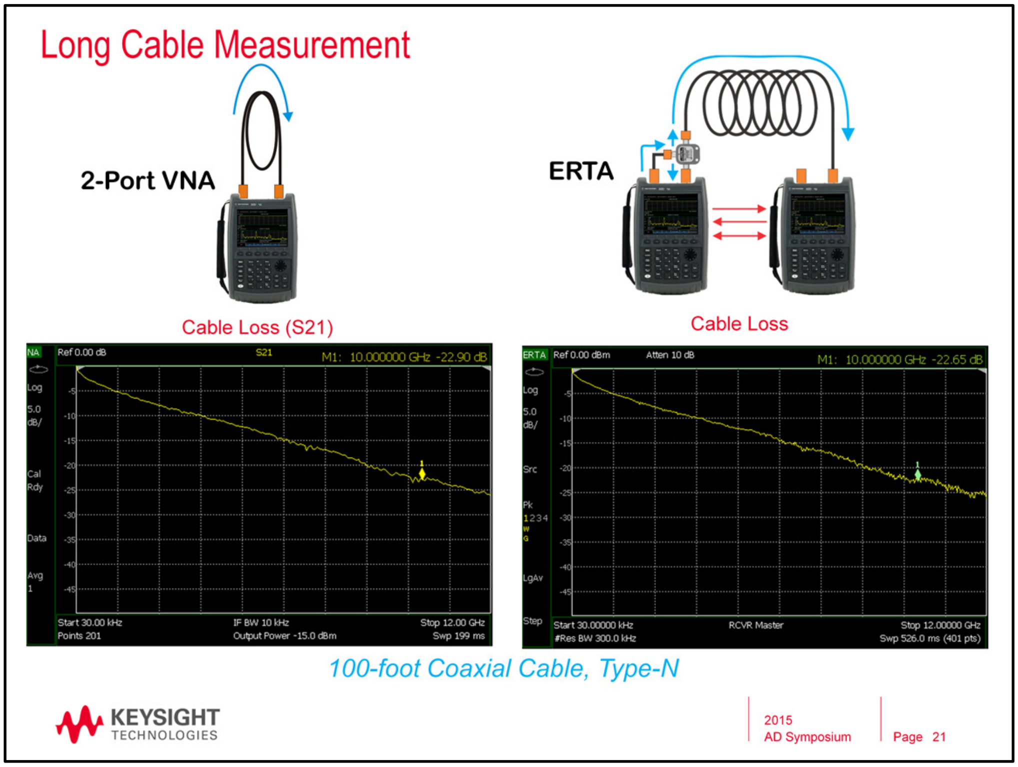
The next two slides will compare examples of insertion loss measurements using these techniques.



This slide compares the insertion loss measurement using the traditional 2-port technique and the novel 1-port technique. The cable under test is a 10-foot length of flexible coax with SMA connectors. The left trace represents the measured S21 using FieldFox in the vector network analyzer (NA) mode. The right trace represents the 1-port cable loss measurement using FieldFox in the Cable and Antenna Test (CAT) mode. The 1-port measurement included an initial measurement of the cable with a 50-ohm termination placed at the end of the cable. In this case, a 50-ohm load is placed at the end of the cable under test. The measurement of the 50-ohm load is saved to the FieldFox memory using the *Trace*, *Data-> Mem*. The load is removed and the cable is terminated in an open (or short), the same as before. The measurement of the open (short) is then subtracted from the memory using the *Data Math*, *Data-Mem*. This additional measurement step may improve the observed ripple in the 1-port cable measurement.

In general, the traditional 2-port insertion loss measurement will be more accurate than a 1-port cable measurement, but having a measurement process that does not require an instrument connection to both ends of the cable is a great benefit when characterizing installed cabled systems. It should be noted that the 1-port cable loss measurement is only useful for coaxial transmission lines. The FieldFox dispersion model is not valid for waveguide transmission lines or when fixed attenuators are inserted along the coaxial cable.

Next we will compare the two-port measurement with the extended range transmission test.

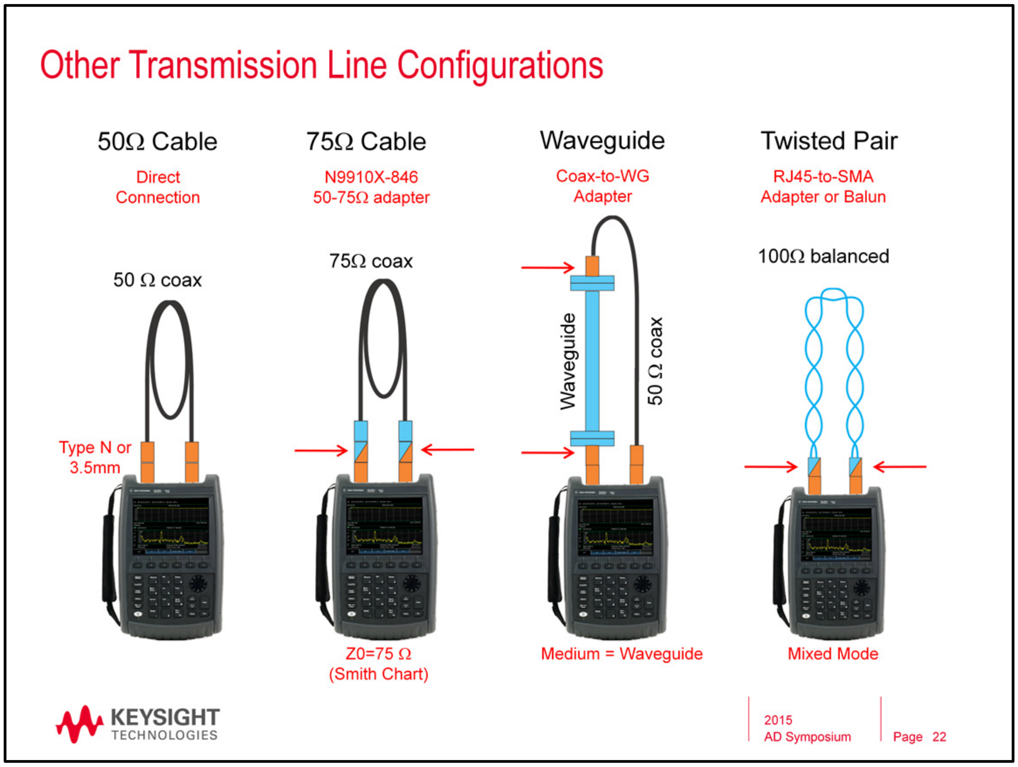


Here is a comparison of the insertion loss of a long lossy cable using the traditional method and the ERTA technique. For this example, a 100-foot length of coaxial cable with approximately 25 dB of insertion loss at 12 GHz is measured using the two techniques. The two measurements are almost identical with the exception of a slightly higher noise level near 12 GHz using the ERTA technique.

For applications when both cable ends are not locally available, the one-port technique and ERTA technique are ideal solutions for installed cables and transmission systems.

As we have concentrated most of our discussion on coaxial cable assemblies, it is important to discuss measurement techniques using other types of transmission lines.

Next we will examine configurations for waveguide and twisted pair cables.



FieldFox, like most Keysight analyzers, are generally configured as 50-ohm instruments with coaxial test ports. As shown on the left, FieldFox is configured with either Type-N connectors, for models up to and including 18 GHz, or 3.5 mm connectors for the 26.5 GHz model. When measuring 50-ohm coaxial cable, the cable can often be directly connected to the analyzer's test ports. If the cable under test has different connector types, such as 7/16, TNC or 7mm, then adapters will be required to interface the instrument's test ports with the cable. Ideally, a calibration kit will be required to match the connector type of the cable under test. If the appropriate calibration kit is not available, FieldFox includes the *QuickCal* option to extend the calibration to the end of the test adapters.

When measuring 75-ohm cable, adapters will be used to convert the 50-ohm test port to the 75-ohm characteristic impedance of the cable under test. In this case the adapters, such as the Keysight N9910X-846, will be connected to FieldFox. If a 75-ohm calibration kit is not available, QuickCal may also be used to improve the accuracy of the measurement by adjusting the FieldFox built-in calibration to include the adapters. If measurements using the Smith Chart format are required, then the FieldFox system impedance should be set to 75 ohms for proper readout of the measured impedance.

The measurement of waveguide also requires the use of adapters. In this case, coaxial-to-waveguide adapters are selected to interface the test ports of FieldFox to the flange type of the waveguide under test. Ideally, a waveguide calibration kit should be used for the highest measurement accuracy. Additionally, when measurements are made in the time domain, it is important to set the type of "medium" to "waveguide" so FieldFox can properly adjust the frequency dispersion characteristics on the analyzer. We will discuss dispersion characteristics for waveguide later in this paper.

Finally, the measurement of twisted pair cable, also known as mixed mode measurement, requires the use of either an RJ-45 to SMA adapter or a balance to unbalanced (BALUN) adapter. For mixed mode measurements, FieldFox requires an option for these types of measurements and Keysight engineers can provide assistance when configuring the analyzer's options and adapters for all the options listed here.

For the last part of this paper, we will discuss techniques to troubleshoot and locate failures along transmission lines and systems. We will begin by introducing the types of failures that may occur on these lines.

Troubleshooting Transmission Lines

CAT and VNA Modes

- Verify transmission line performance (line sweeping)
- Determine the location of damage (DTF)
- Determine the type of failure

Types of Faults

- Loose connector, flange screws
- Failed seal at a cable splice or flange (water ingress)
- Failed solder joint at connector interface
- Cut, crushed and/or weather-induced cracks
- Minimum bend radius exceeded
- Breakdown, arcing and multiplication effects

Images courtesy of John Arthur, Wireless EDGE

DTF = Distance to Fault

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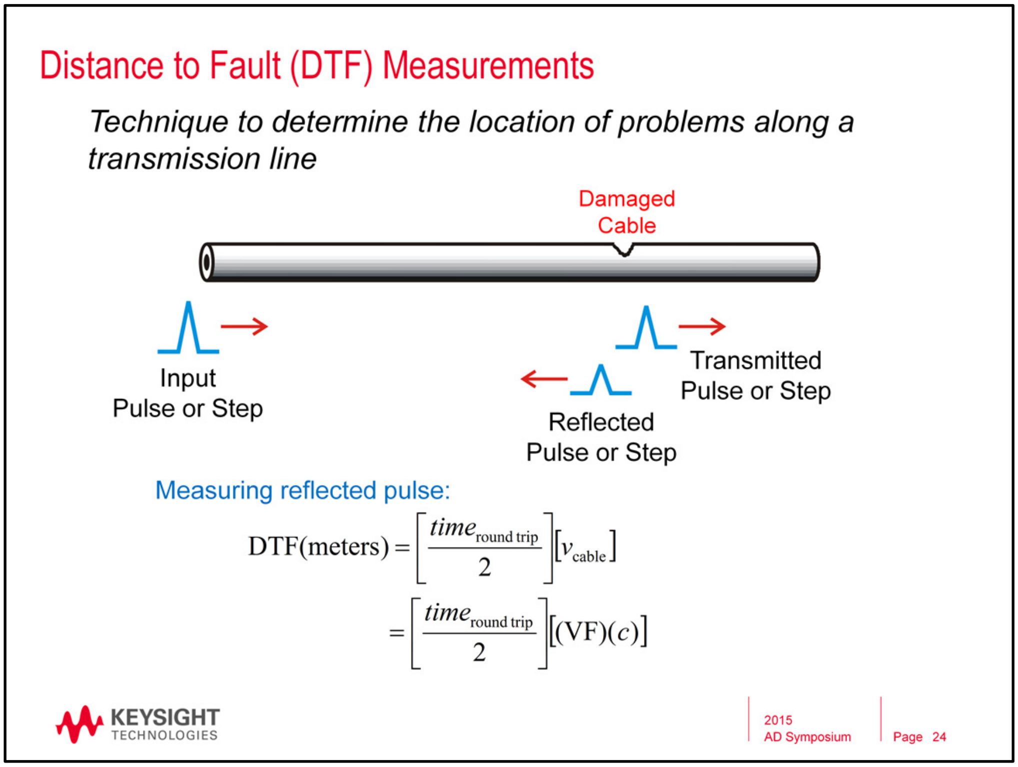
Complex feed systems for radar, cellular, data communications and cable distribution, to name a few, all require the verification of the RF performance as a function of frequency. We've been discussing several of the configurations for testing these systems also known as line sweeping. If a transmission line is found to be faulty and outside the desired specification, then it becomes important to rapidly identify the location and type of failure. Measurement techniques including distance to fault, or DTF, result in the physical location where a problem is found to exist along a transmission line. In some types of measurements it is also possible to identify the type of failure.

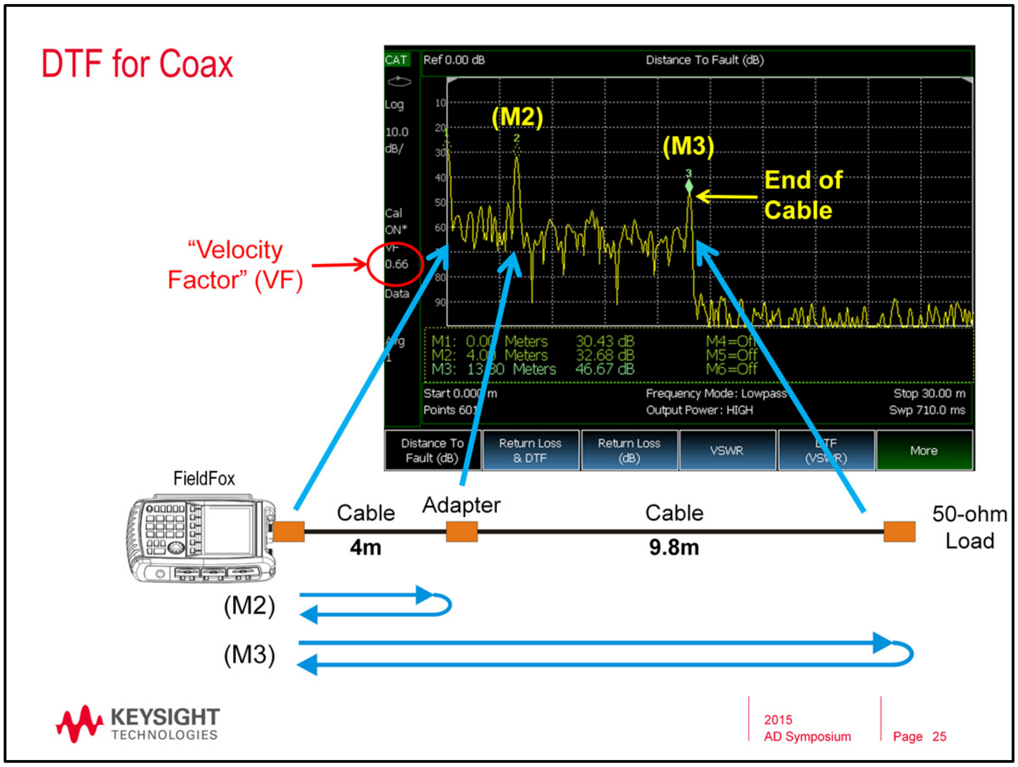
Types of failures include loose or damaged connectors and waveguide flanges, water ingress into the system which is especially prevalent in outdoor installations, broken solder joints, cut cables and damage due to high power arcing.

We'll now examine a typical DTF measurement using a coaxial cable.



A distance-to-fault (DTF) measurement usually requires the introduction of an impulse or stepped waveform at one end of the cable. This impulse or step travels down the transmission line until it encounters a discontinuity in the cable. Depending on the size of the mismatch created by the discontinuity, a portion of the incident waveform is reflected back to the source. In the ideal case, most of the incident signal passes by the discontinuity and continues to the intended load. Unfortunately, if the reflected signal is relatively large then the cable may fail the insertion loss and/or return loss specification. Measuring the time delay for the return signal and dividing this time in half, it is possible to calculate the one-way time and associated distance to the damage. As discussed earlier in this paper, the distance calculation requires an accurate value for the velocity factor for the conversion from time to distance.

FieldFox measures a DTF response by measuring the frequency response of the cable and transforming this measurement into the time domain. We'll now examine a typical DTF response using a coaxial cable.



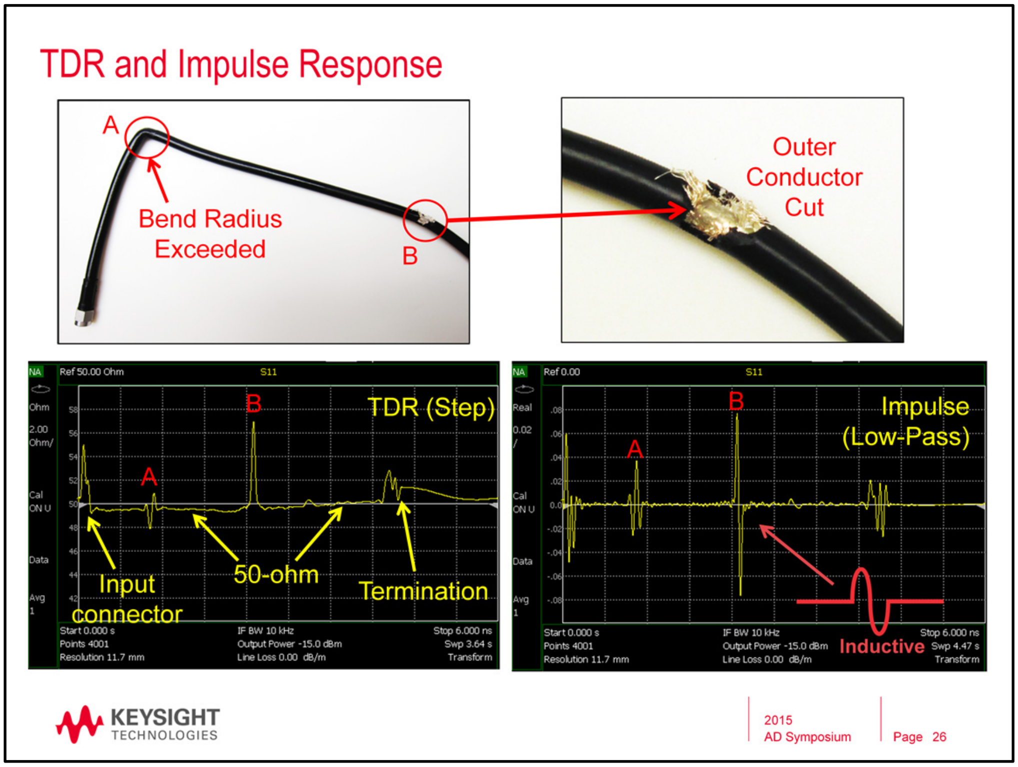
Here is a measurement of the DTF response using two short coaxial cables connected by a coaxial adapter. The shorter cable is connected to port 1 on the analyzer and the second cable is terminated in a 50-ohm load. As mentioned, the response you see here is time domain representation of a measurement recorded in the frequency domain. FieldFox performs this transformation at the push of a button and both the time domain and frequency domain responses can be viewed simultaneously on the same display.

For the measurement shown on this slide, markers are placed at the three peaks in the measured DTF response. The first marker, shown on the far left, reports a distance of 0 meters. This marker represents the interface between the calibrated FieldFox and the first coaxial cable. The second marker, labeled M2, reports a distance of 4 meters. This marker is located at the adapter discontinuity between the two cables. It also indicates that the length of the first cable is 4 meters. The third marker, labeled M3, is located at the 50-ohm load and is reported at 13.8 meters. This measurement can be used to calculate the length of the second cable which is 9.8 meters (13.8 meters – 4 meters). There is a noticeable drop in the measured amplitude to the right of the 50-ohm load signifying the location of the end of the cable.

The diagram at the bottom shows the various signal paths between the FieldFox, the adapter and the 50-ohm load. As these reflection measurements represent two-way signal paths, FieldFox corrects for this assumption and properly reports the marker values as a one-way length. In DTF mode, the scaling along the x-axis also displays the correct one-way distance. In this example, the displayed one-way distance is scaled between 0 meters and 30 meters. These values are easily adjusted on FieldFox.

It should be noted that the cable's velocity factor (VF) must be entered correctly into the FieldFox otherwise the distance measurements will not be correct. It should also be noted when two cable types with different velocity factors are included in the measurement, such as the case when a short jumper cable is connected to a long Heliax cable, the velocity factor of the longer cable should be entered into the FieldFox. Ideally, the short jumper cable should be included as part of the FieldFox user calibration, such as *QuickCal*, and therefore its effects would be removed from the DTF measurement.

This simple example shows the importance of DTF measurements when attempting to locate the physical location of a discontinuity along a transmission system. The peaks in this example represent the magnitude of single reflections from a discontinuity but it is also possible to determine the type of reflection using a TDR and low-pass modes as will be shown on the next slide.



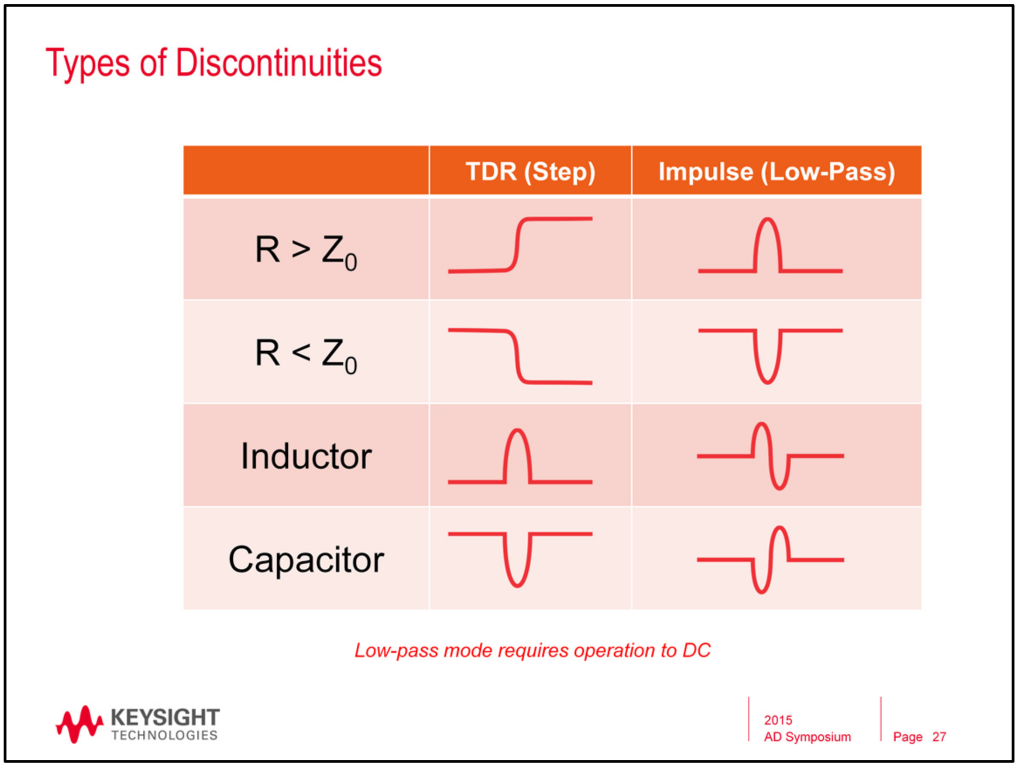
Here is a set of measurements from a cable that contains two different faults. The first fault, labeled "A", is a bend in the cable that has exceeded the manufacturer's specification for minimum bend radius. For this cable, the specified bend radius should be 1-inch or larger.

For this damaged cable, the bend at location "A" is well below this value creating an undesired reflection from this part of the cable. The next fault, located at "B", is a deep cut through the outer conductor of the cable. At this location, the braided shield has been partially removed exposing the inner dielectric of the coax.

Both of these problems can be examined using any one of several time domain techniques available on FieldFox. One technique discussed on the previous slide, is the DTF. DTF will only report the location of these faults. Two additional techniques shown here are the TDR and impulse modes. TDR, also known as the stepped response, and impulse mode can also be used to determine the type of fault on the line. For example, The TDR response on the left shows the cable impedance is generally 50 ohms across most the time domain response until a discontinuity is encountered. The locations of the discontinuities occur at the input connector, the bend at A, the cut at B and the 50-ohm termination at the end. Of all the discontinuities, the cut has the greatest mismatch as shown by the magnitude of the highest signal. On the TDR response, the cut has a single peak in the positive direction. This is indicative of an inductor which is typical for cuts in the outer conductor of cable.

Another very useful time domain response is the impulse response shown here on the right. Impulse response also provides information about the type of discontinuity such as the positive and negative going peaks at location B. This set of peaks, positive then followed with negative, also reports that the fault is inductive. If the fault was capacitive, the peaks would start in the negative direction and then followed with a positive peak.

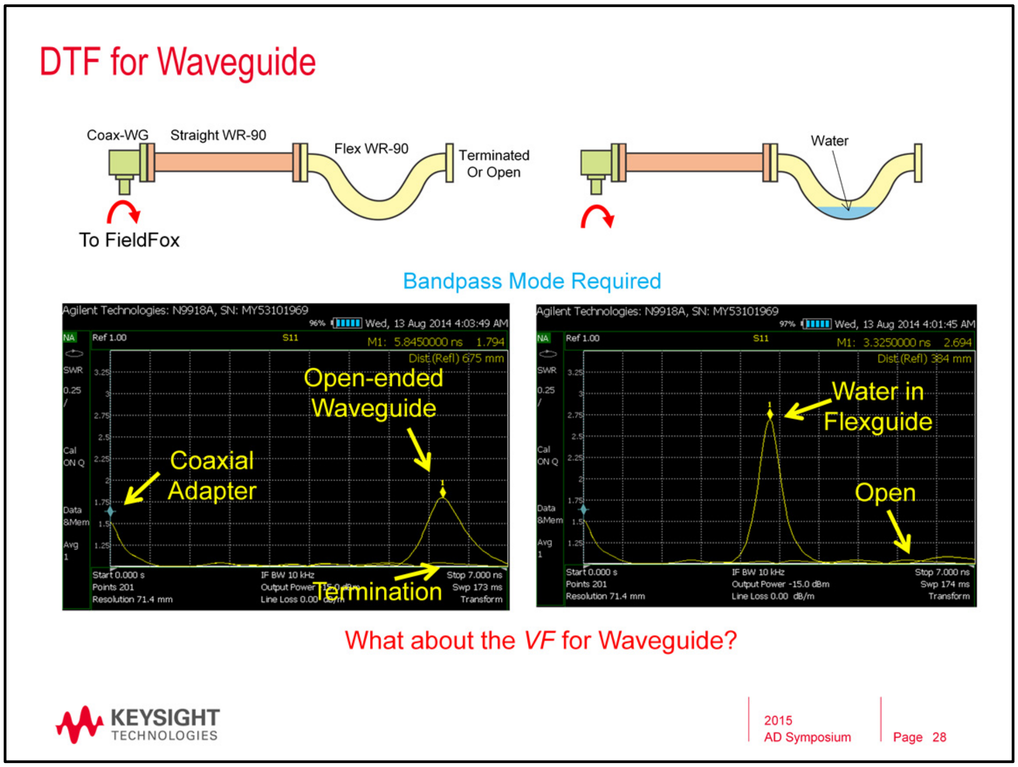
The next slide summarizes the various types of discontinuities that can be identified with FieldFox.



Here is a summary of the types of discontinuities that can be observed on a time domain response using TDR (step) or impulse modes. For example, when a transmission line is terminated in a load with a resistance that is larger than the characteristic impedance, the TDR response would show a step in the positive direction. If the load resistance is smaller, the step would move in the negative direction. We observed this effect earlier in the presentation when a 50-ohm cable was terminated in a short circuit and the step started at 50-ohm and dropped to 0-ohm at the short. The impulse mode may also be used to identify steps in the characteristic impedance as a single positive peak with the load resistance is larger than Z_0 or a single negative peak when the load is less.

The waveforms for inductors and capacitors are also included here on the table. It should be noted that TDR and impulse modes are only available for transmission line types that have two-conductors and can operate down to DC. When using waveguide, the narrowband response restricts the time domain measurements to a "bandpass" mode of operation. Bandpass mode only provides the location to the fault, the type of discontinuity is not available.

An example for the time domain response using bandpass mode is shown on the next slide.

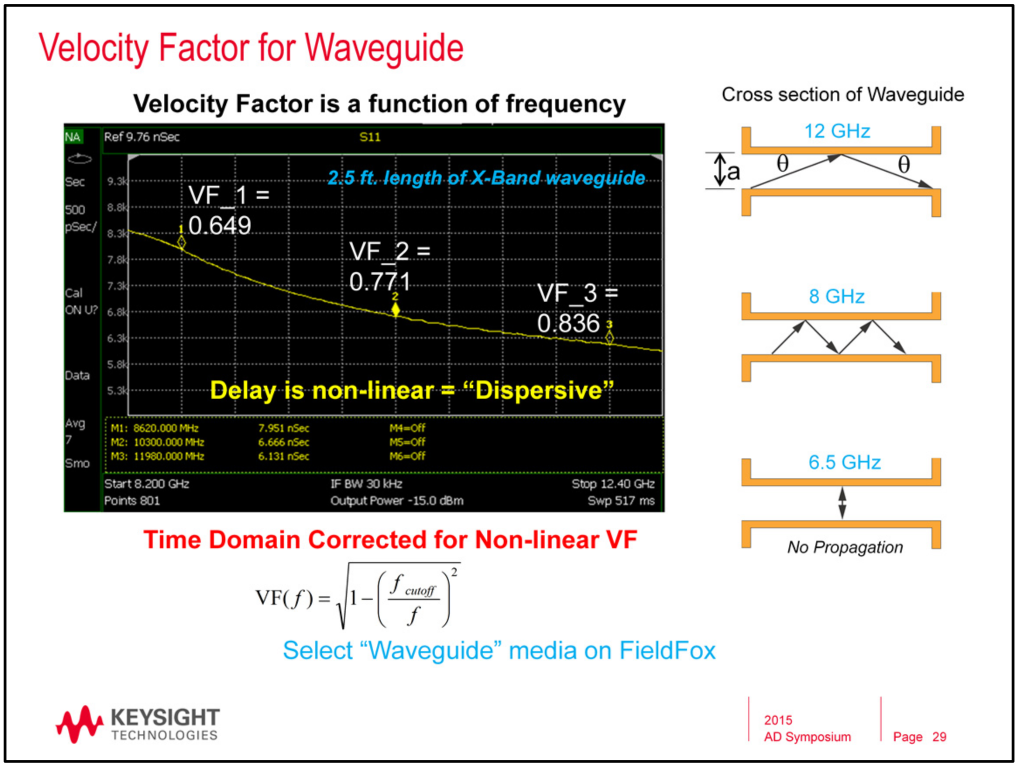


Shown here are examples of DTF measurements using the bandpass mode on FieldFox. The analyzer is initially configured to measure the frequency response of WR-90 X-band waveguide from 8.2 GHz to 12.4 GHz. The transmission system under test starts with a coaxial-to-waveguide adapter connected to FieldFox. Next is connected a 6-inch length of straight rigid waveguide which is then followed by an 18-inch length of flexible waveguide. For these measurements, the flexible waveguide, or “flexguide”, is either terminated in a matched waveguide load or the end flange is left open. FieldFox is configured to measure the S11 and switched to the DTF “bandpass” mode.

The measurement on the left contains two traces, one trace has the flexguide terminated in a matched load and the other trace has the flexguide left open-ended. Both traces on the left show a first peak at the coax-to-waveguide adapter located at time equal to zero. For the measurement with the open-ended flexguide, there is a second large peak at the location of the open. When the flexguide is terminated using a match load, the amplitude of the peak is very low in comparison. Markers placed at the peak of each reflection report the electrical distance and the associated physical location to the discontinuity. For example, the location of the open circuit at the end of the flexguide is measured at 675 mm which is the total length through the adapter, straight waveguide and flexguide. FieldFox automatically calculates the dispersion of the waveguide when the WR-90 type is selected from the “waveguide and cable electrical properties” table.

As a comparison, we’ll now assume that our transmission system was exposed to the environment and water has leaked into the waveguide. For the measurement shown on the right, we partially filled a section of the flexguide with water. When examining the time domain response, we find a large peak in the response that corresponds to the location of the water-filled waveguide. Once again, a marker is used to measure the physical distance to the water which is 384 mm from the input. It is interesting to note that the reflection from the open-ended waveguide is now masked by the water in the waveguide. Water is such a lossy medium for RF that any signal that transmits through the water, reflects from the open and returns through the water a second time is so highly attenuated that it is not observable at the input.

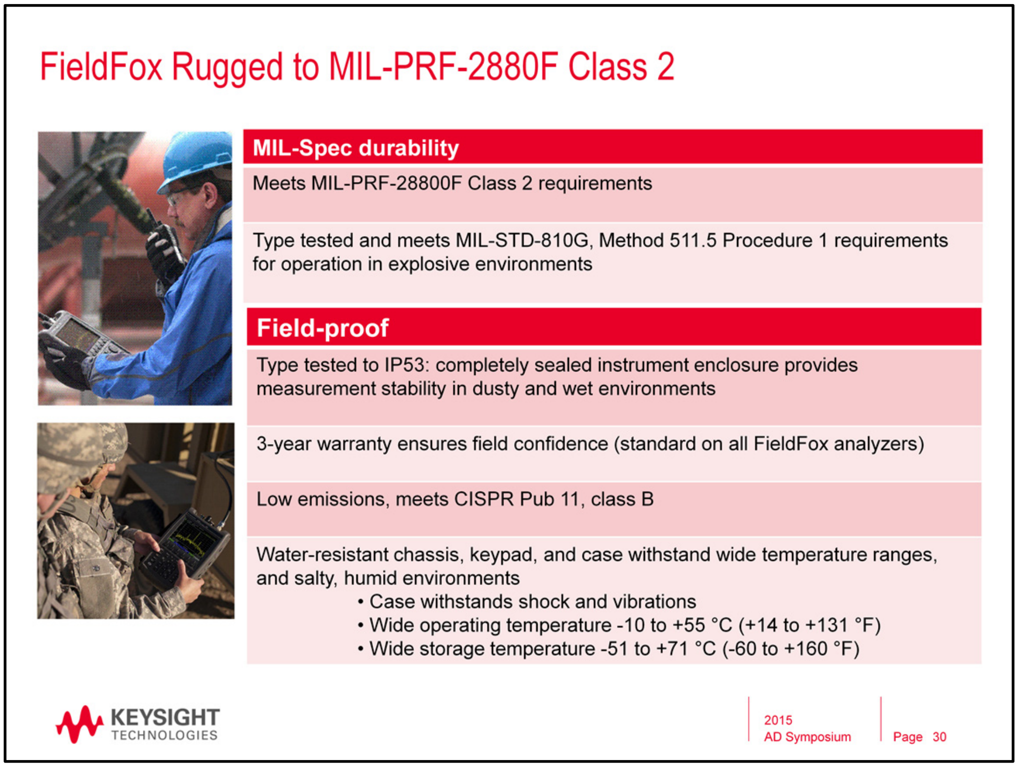
As mentioned earlier, identifying the physical location of a fault requires knowledge of the velocity factor of the transmission line. Waveguide is one of the mediums that does not have a linear delay response and requires an extra step when measuring this line type on FieldFox.



Waveguide is considered a dispersive medium as its delay is a non-linear function of frequency. Shown here is the measured delay of a short section of X-band WR-90 waveguide. The measurements show that lower frequencies have a longer delay than higher frequencies and the overall response is very non-linear. The reason for the different delay times is the result on how different frequencies travel through the waveguide. For example, the illustration on the right shows that signals at 12 GHz travel back and forth across the larger section of the waveguide. The angle of incidence, shown here as theta, is relatively small at the higher frequencies. As the frequency is reduced, the angle on incidence increases towards 90 degrees. The larger angle results in a longer time to travel through the waveguide as it must take a longer path. As the frequency is lowered to the point of cutoff, the angle is now at 90 degrees and the signal no longer travels through the guide but is trapped as it bounces back and forth between the two side walls.

This dispersion in travel time will create distortion in wideband signals. When using FieldFox to locate faults in waveguide systems, it is necessary to configure the analyzer to adjust the velocity factor as a function of frequency. The formula for waveguide velocity factor as a function of frequency is shown in the lower left. This formula is used to adjust the velocity factor to 0.649 at 8.62 GHz, 0.771 at 10.3 GHz and 0.836 at 11.98 GHz to name a few. The user is only required to select "waveguide" as the medium and the analyzer will make the appropriate corrections to the measured data. FieldFox also includes a table for selecting the type of waveguide using the measurement such as WR-90 in this case.

Now having reviewed that various type of measurements that FieldFox can perform on transmission lines, we will now summarize some of FieldFox's key operational specifications when carrying the instrument into the field.



Measurements in the field typically result in the test equipment being exposed to harsh environmental conditions including extreme heat, cold and humidity. Most benchtop instruments would never survive in the field without creating a suitable shelter to house the equipment.

Keysight designed the FieldFox to be the most rugged, reliable and highest performance handheld instrument on the market. The FieldFox meets all requirements for MIL-PRF-28800F Class 2 with no exceptions. FieldFox has also been type designed to meet MIL-STD-810G for use in explosive environments which is very important for flight line test or environments such as on oil rigs. The water-resistant chassis, keypad and case can withstand salty, humid environments and a temperature range of -10 to +55 °C (+14 to +131 °F). The case can also withstand shock and vibration, and a specially designed connector bay protects the RF connectors from damage due to drops or other external impacts.

FieldFox is a completely sealed instrument with no fans or vents. This leads to significant benefits in the field as no dust or moisture is pulled into the unit. Satellite payload development teams are even taking FieldFox into clean rooms since it does not bring any dust or debris with it. The high level of integration also yields a higher instrumentation reliability which led to the industry’s first 3 year standard warranty.

Keysight FieldFox Combination Analyzers

Combination Analyzers can be configured with the following capabilities

- Vector Network Analyzer (VNA)
- Cable and Antenna Test (CAT)
- Spectrum Analyzer
- Vector Voltmeter (VVM)
- Power Meter
- Independent Source

Models include frequencies up to **26.5 GHz**

- 6.6 pounds (3 kg)
- Built-in GPS
- 3.5 hour battery life

Carry precision with you - Keysight-quality measurements

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Keysight FieldFox RF and microwave combination analyzers are equipped to handle routine maintenance, in-depth troubleshooting, and anything in between. FieldFox analyzers deliver Keysight-quality RF and microwave measurements—wherever you need to go. The FieldFox can be configured with a large choice measurement capabilities and models having frequency ranges from 30 kHz to 26.5 GHz.

Conclusions

- Transmission lines have lengths on the order of a wavelength
- Phase affects the magnitude response
- Operating frequency is limited by geometry
- Non-dispersive lines have a linear phase slope
  - Coaxial lines are non-dispersive
  - Waveguide is dispersive
- Transmission line insertion loss can be measured several ways, some with very high dynamic range
- Quickly and accurately troubleshooting cable and waveguide faults requires time domain response
- FieldFox Extended Range Transmission Analysis enables accurate characterization of long cable
- FieldFox is the ideal tool for maintenance of mission critical Milcom systems in the field

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For More Information

Web: www.keysight.com/find/FieldFox

Literature:

- *Techniques for Precise Interference Measurements in the Field,* Application Note, Literature Number 5991-0418EN
- *Techniques for Precise Cable and Antenna Measurements in the Field,* Application Note, Literature Number 5991-0419EN
- *Correlating Microwave Measurements between Handheld and Benchtop Analyzers,* Application Note, Literature Number 5991-0422EN
- *Techniques for Precise Measurement Calibrations in the Field*, Application Note, Literature Number 5991-0421EN
- *Techniques for Precision Validation of Radar System Performance in the Field*, Application Note, Literature Number 5991-4107EN

Thank you for your time
Questions?

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