Techniques for Time Domain Measurements

Using FieldFox handheld analyzers

Application Note

This application note will introduce time domain and distance-to-fault (DTF) measurement techniques for identifying the location and relative amplitudes of discontinuities while operating in the field. This application note will describe the relationship between frequency domain measurements and time domain transforms and their relationships to time resolution and range. Also shown will be VNA configurations for characterizing band-limited devices such as couplers, filters, antennas and waveguide components, and broadband devices such as cables and connectors. This note will also discuss time domain "gating", a powerful feature that effectively isolates discontinuities in the time domain just as a filter would isolate signal energy in the frequency domain. Measurement examples will be provided using the Agilent FieldFox vector network analyzer.

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Introduction

Testing and qualifying components and systems that function as part of a communications or radar system often requires that the electrical performance of these devices achieve a certain level of specified performance across the operating frequency range. Specifications include Voltage Standing Wave Ratio (VSWR), return loss and insertion loss to name a few. These specifications provide a clear distinction when the device under test (DUT) has passed or failed its performance requirements as a function of frequency. Figure 1a shows the measured VSWR of a system where the VSWR has exceeded the specification at several places across the measured frequency range of 8.5 to 12 GHz. The Agilent FieldFox vector network analyzer (VNA) used in this example was configured with limit lines to help the operator quickly identify whether the DUT has passed or failed the test.

While a frequency measurement provides useful information into the proper functioning of a system, having only swept frequency may not provide enough information to determine the root cause of the problem. When a system fails to meet specification, troubleshooting is often difficult as components would then need to be swapped in and out of the system until performance once again meets the specified requirements. Fortunately, there is another measurement technique that provides details into the location and magnitude of any such problems. This technique relies on measurements in the time domain and a vector network analyzer, such as the Agilent FieldFox, has the capability of displaying the time domain characteristics of one and two port components and systems. Figure 1b shows the time domain transformation of the VSWR measurement with the location of individual discontinuities being displayed as a function of time. In this example, it can be assumed that the largest peak in the time domain is associated with the component causing the out-of-spec condition

for this system. Knowing the propagation velocity of the signal in the transmission system, the physical location of the fault can be determined and the system can be quickly repaired.

This application note will introduce time domain and DTF measurement techniques for identifying the location and relative amplitudes of discontinuities while operating in the field.
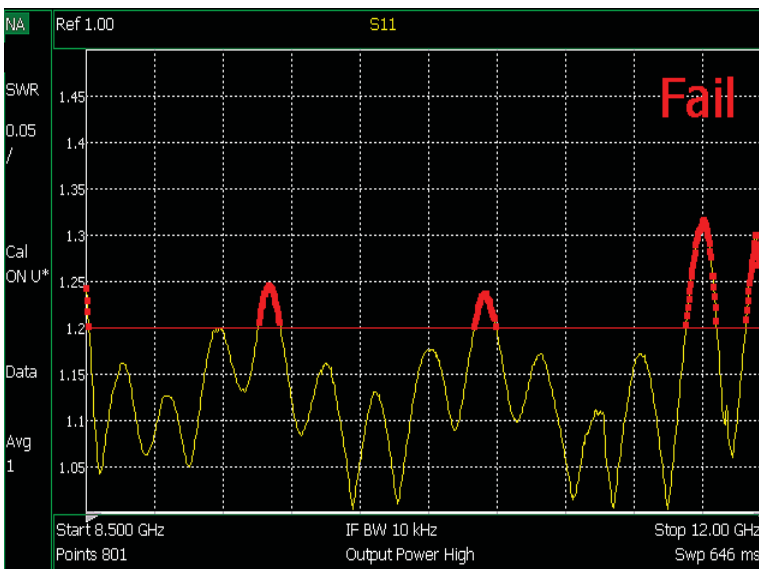
(a) Frequency response
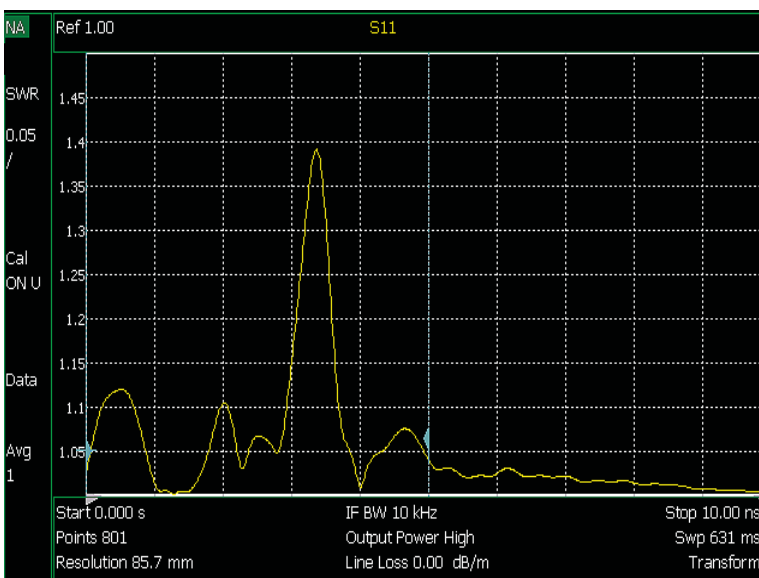
(b) Time response

Figure 1a. Measured VSWR as a function of frequency (1a), and the time domain response showing several discontinuities as a function of time (1b).

Time domain measurement basics

Time domain analysis is very useful to observe the effects of mismatches along a transmission line system. When an RF or microwave signal propagates along a transmission line, a portion of the signal will be reflected back from any discontinuities encountered along the path. Using time domain analysis, the location of each discontinuity is displayed as a function of time along the x-axis and the amplitude of the reflected signal, or S11, is plotted along the y-axis. Knowing the propagation velocity along the transmission line allows the time measurement to be scaled to physical distance. It is also possible to examine the time domain response of a transmitted signal, or S21, but this measurement requires connection at two ports of a system. As field measurements often limit access to only one port of a system, this application note will primarily focus on the time domain response of reflection, or S11, measurements.
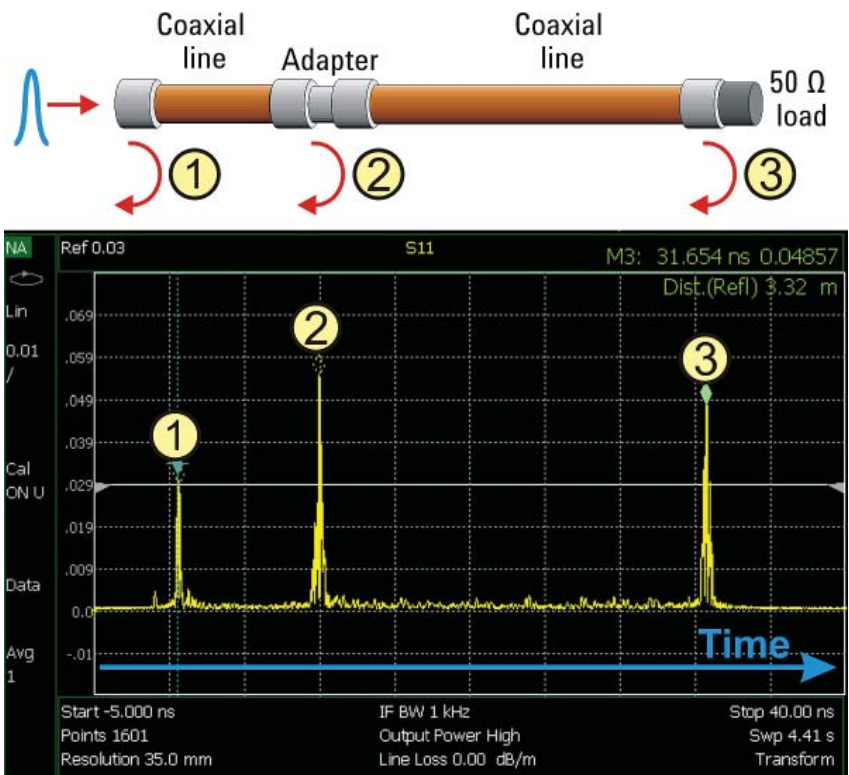
Figure 2 shows a simple example of a time domain response for two short sections of coaxial line connected together with an adapter and terminated in a 50-ohm coaxial load. If the input to the line is excited with a short impulse waveform, then it is possible to observe the reflected impulse response from each discontinuity as a function of time. In this case, there are reflected signals from the input connector (1), the adapter (2) and the termination (3). Excessively large peaks would be representative of problems in one or more of these components. It is also possible to excite the line with a step waveform and details of this technique are shown in the Agilent Time Domain Application Note 1287-12 [1].

The measurement from any one-port or two-port device can be represented in the time domain and/or the frequency domain. If a measurement is made in one domain, then the other domain can be calculated using a well-known mathematical technique called the Fourier Transform (FT). This transform provides a universal problem

Figure 2. Configuration and measurement of a time domain response showing three discontinuities along a coaxial transmission line

solving method that allows one to examine a particular measurement from an entirely different viewpoint [2]. If a measurement is recorded using a time domain method, then a FT calculation will result in a frequency domain representation of the data. Alternatively, if frequency domain data is initially captured, then an Inverse FT (IFT) will result in a time domain representation of the data. The fact that the same data can be simultaneously displayed in time and frequency creates a powerful analysis and problem solving tool. Fortunately, modern test instrumentation, such as a VNA, includes this mathematical transformation as part of the firmware allowing the user to display either time domain data or frequency domain data, or both. For example, figures 1a and 1b show the frequency measurement and time domain transform recorded using the Agilent FieldFox VNA.

Instruments with time domain capability

There are two basic instruments capable of displaying the time domain response of individual discontinuities along a transmission system; the time domain reflectometer (TDR) and the vector network analyzer (VNA). A time domain reflectometer uses a traditional method of launching an impulse or a step waveform into the test device and directly measuring the response as a function of time [3]. Using a step generator and broadband oscilloscope, such as the Agilent 86100D DCA with 54754A TDR Module, a fast edge is launched into the transmission line. The incident and reflected voltage waves are monitored by the broadband oscilloscope and the position of each discontinuity can be displayed as a function of time.

A vector network analyzer, such as the Agilent FieldFox N9918A VNA is primarily a frequency domain instrument with capability of measuring the reflected and transmission characteristics of one and two-port devices.

Using error-corrected data measured in the frequency domain, the response of a network to an impulse or step function can be calculated using the IFT and displayed as a function of time. As the VNA uses narrowband measurement receivers, the dynamic range will be typically higher than oscilloscope-based TDR systems. Also a VNA includes time domain capability for measuring band-limited devices, called bandpass mode, which will be discussed later in this application note. Lastly, there is a configuration of a FieldFox VNA, known as a cable and antenna (CAT) analyzer, which performs the same frequency-to-time domain transformation but scales the time measurements to an equivalent physical distance to aid the operator in quickly locating faults in RF and microwave transmission lines in the field.

Measurement example using a horn antenna

Figure 3 shows a test configuration that will be used to examine the frequency domain and time domain responses of an over-the-air measurement using an X-band waveguide horn antenna and a separate metal plate placed near the antenna. The high-gain horn antenna is connected to a short length of WR-90 waveguide transmission line and the transmission line is attached to a waveguide-to-coaxial adapter for connection to the VNA. The VNA is calibrated for S11 at the plane where the adapter is connected to the instrument port. The measurements will include the effects of all the components shown in figure 3 and also include effects from other items in the surrounding environment. The metal plate is a 0.3 meter square aluminum plate mounted to a tripod and positioned in front of the antenna. The distance between the metal plate and the antenna is varied in order to examine changes in the frequency and time responses.

Figure 4 shows the measured frequency response of the system under three test conditions; two with the metal plate near the antenna and one without. The yellow curve shows the measurement without the metal plate. There is a small ripple in the measured S11 response due to interaction between the various transmission lines and reflections from items in the surrounding environment. The blue trace shows the frequency response with the metal plate positioned at 1.7 meters from the horn antenna. In this case, there is a larger amount of ripple in S11 when compared to the case with no plate. The orange curve shows the results when the plate is moved closer at a 1.2 meter separation. Here the ripple is even more pronounced as the reflected signal from the plate has larger received amplitude.

In practice, it could be possible that metallic structures placed near an antenna system could have a negative effect on the system performance as reflections from these additional structures could create ripples large enough to cause an out-of-spec condition. As mentioned, examining only the frequency response does not provide sufficient insight into the root cause of the problem(s). The time domain response under these measurement conditions will be examined next.
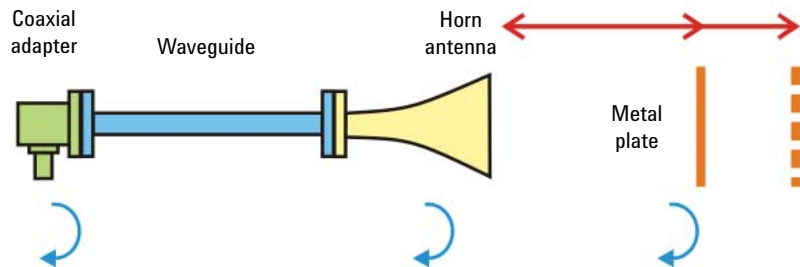

Figure 3. Configuration for measuring the frequency domain and time domain responses of an over-the-air measurement using an X-band horn antenna
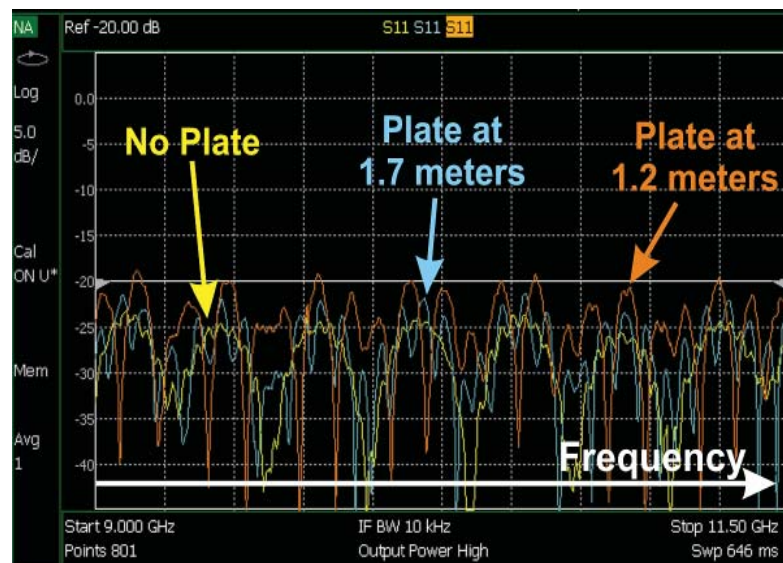

Figure 4. Comparison of the measured frequency response of the X-band antenna system under three test conditions; two with the metal plate near the antenna and one without the metal plate

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Measurement example using a horn antenna

Figure 5 shows the time domain response of the antenna system using an Agilent FieldFox VNA with the time domain option. For the case without the metal plate, shown as the yellow trace, the peaks associated with signal reflections from the surrounding environment are relatively low in comparison to those from the adapter and antenna. This type of measurement would provide a good baseline for a new system installation and could be used as a comparison as more antenna components and structures are added around this system. Figure 5 also shows the time domain response when the metal plate is positioned near the antenna. For the measurement at 1.7 meters, shown as the blue trace, there is a large peak representing the reflection from the metal plate and a smaller peak to the right representing the reflection from the legs of the tripod. When the plate and tripod are moved closer at 1.2 meters, shown as the orange trace, the measured time domain response shows an equivalent time shift in these peaks. From these measurements, you can see that the peaks associated with the adapter and antenna are static as these components were not changed during the testing. There is also a noticeable increase in the peak amplitude associated with the metal plate when the plate is moved closer to the antenna. This increase in peak amplitude is due to the reduction in space loss as the signal now propagates over a shorter distance.
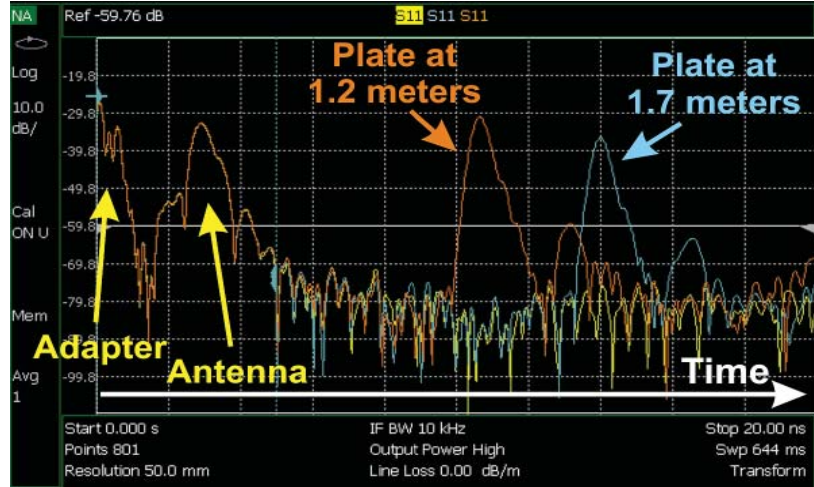

Figure 5. Time domain response of the antenna system under three test conditions; two with the metal plate near the antenna and one without the metal plate

As shown earlier in figure 4, the environmental reflections introduce a ripple in the frequency domain response. It would be useful to confirm the system performance without the effects from the environment. Under this test requirement, the VNA has a gating function that is configured in the time domain to filter out specific reflections and allow the frequency domain response to be viewed without the effects from these reflections. The next section will introduce the basic concepts of time domain filtering also known as gating.

Gating and frequency response

The basic concept of gating is to introduce a time filter to remove unwanted reflections from the time domain response. This time filter works in the same way as a frequency filter would in the frequency domain. Once the undesired responses are removed from the time domain, the frequency domain response of the remaining devices can be observed. Figure 6 is a simplified example of an ideal time domain response having three peaks. For this example, the time filter or "gate" is configured to remove the two outside peaks. By adjusting the gate's time center and span, an equivalent bandpass filter can be created in the time domain. Once the gate is activated, the upper and lower peaks are removed from the measurements in the time and frequency domains. Along with the bandpass gate, the FieldFox VNA has another type of gate that can notch out a single peak, or grouping of peaks, leaving behind the remaining peaks above and below this filter response. In either case, once the gate is properly configured in the time domain, the user can return the VNA to the frequency domain to examine the frequency response of the system with the effects of the filtered peaks.
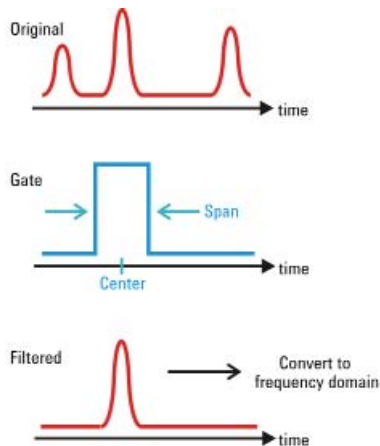
To continue with the antenna example discussed in the previous section, figure 7a shows the time domain response with and without a gating function. In this example, a bandpass gate is configured to remove the effects of the metal plate and the environment. The yellow trace is the original measurement including the peak from the metal plate reflection. The blue trace shows the time domain response with the bandpass gate configured to filter any response to the right of the antenna. With the bandpass gate applied, the time response only includes the effects of the coaxial adapter and the antenna. It is also possible to remove a single peak, or group of adjacent peaks, using a notch gate.

Figure 7b shows a comparison between the original frequency response including the plate and environmental reflections, shown in yellow, and the response when the gate is applied, shown in blue. As shown with

gated response, there is a reduction in the ripple across the measured frequency span as the reflections from the environment have been filtered out from the measurement. Gating is a very powerful tool to examine the reflection and transmission properties of a component or system by selectively removing specific responses from the measurements in any domain.

It should be noted that when a discontinuity along a transmission line reflects energy, that portion of the energy will not reach subsequent discontinuities further down the line. This effect can hide, or "mask," the true response of the later discontinuity. This condition also occurs when the transmission path has insertion loss along the length of the line. The gating function does not compensate for the masking effect and masking will be discussed in the next section of this application note.
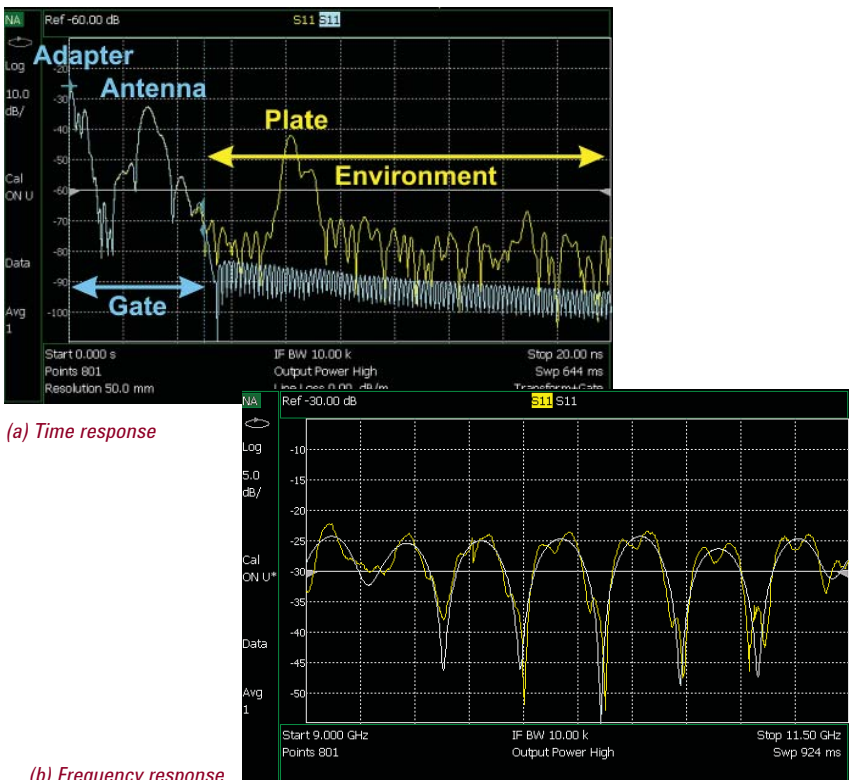

Figure 6. Simplified example of an ideal time domain response having three peaks and the results when a time "gate" is applied to the original response

(a) Time response

(b) Frequency response

Figure 7. (7a) time and (7b) frequency domain responses of the X-band antenna system with and without a gate function applied to the measured data

Masking in coaxial lines

Figure 8 shows the time domain response of a short length of RG58 coaxial cable with the end of the cable terminated in an open circuit. The time response shows a single large peak representing the reflection from the end of the cable. It is expected that an ideal open circuit would have an S11 of 0 dB resulting from all of the energy being reflected back to the source. As shown in figure 8, the measured peak for this test configuration has a lower value at -4.2 dB. The measured peak is lower by twice the average cable loss resulting from the combination of the signal loss in the forward direction and then the loss passing through the cable a second time after being reflected from the open. The insertion loss of the cable is "masking" the true response from the open circuit. Gating around the peak response from the open would not correct the amplitude measurement as gating is a post-process that occurs after the measurement has been acquired. It is important to note that if the transmission system has very high insertion loss, then the amplitude of the reflected signals could be

below the dynamic range of the VNA and would not be observed on a time domain display. This would also occur if the transmission path contained a very large discontinuity that reflected most of the energy and prevented any later reflections from being observed on the time domain display.

If the insertion loss of the cable is known, the Agilent FieldFox VNA and CAT analyzers allow the cable loss to be entered into the instrument. Compensating for the cable loss will improve the amplitude measurements in the time domain. It should be noted that coaxial cable insertion loss is a function of frequency with the loss increasing at higher frequencies. The cable insertion loss factor can be entered as a single value representing the average loss or, when using the CAT mode DTF, can be entered into a table of frequency/loss pairs. The FieldFox CAT mode also includes a set of built-in cable specifications for quick selection based on the cable types installed in the system.

It should be noted that the measured amplitude on any time domain display is actually an average value taken across the entire measured frequency range. Therefore, if the transmission system includes couplers, filters and other items with varying insertion loss, then applying a single factor to compensate for the insertion loss as a function of frequency may not provide accurate amplitude results. This effect will be shown in the next section of this note.
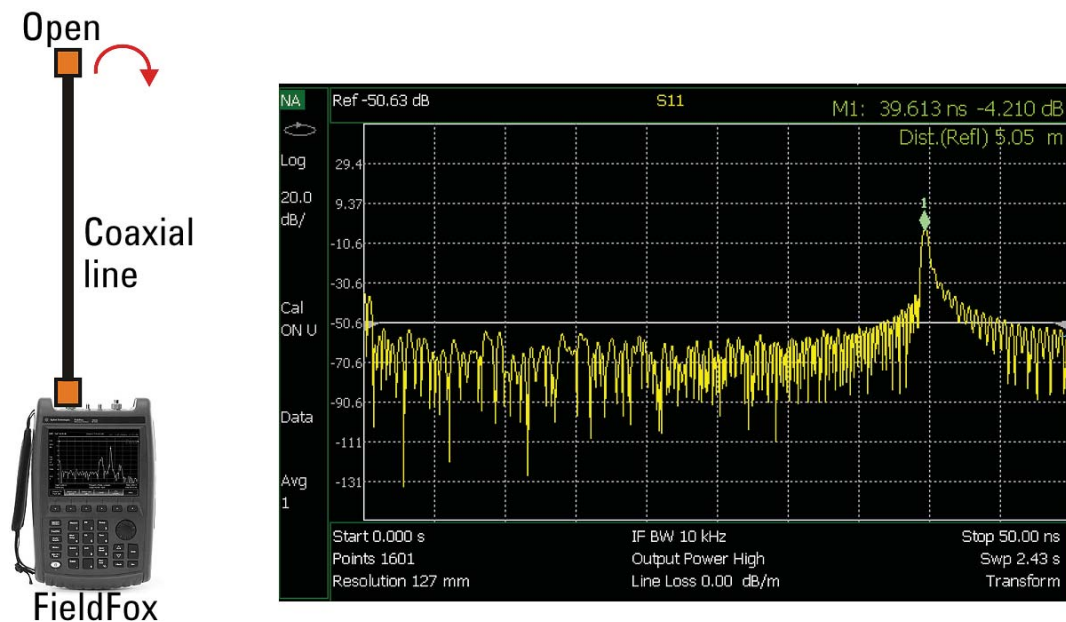

Figure 8. Test configuration and time domain response of a short length of RG58 coaxial cable terminated in an open

Measurement example with bandpass filter

Figure 9 is the test configuration for a system that includes two coaxial cables interconnected with an inline bandpass filter. The longer cable is terminated in either a 50-ohm load or an open ended cable. Being able to swap terminations at the end of the transmission system is very useful when troubleshooting a system and attempting to identify the end of a transmission system. An open or short is typically used to provide a large reflection for identifying the end of the cable in the time domain response.

This simple example will show the effects of masking as the reflected signal passes through the inline bandpass filter. The measured frequency domain response of S11 is shown in figure 10a. For this measurement, the cable is terminated in a 50-ohm load to simulate the effects of a system with the proper termination. The time domain mode is activated and the measured time response is shown in figure 10b. In this case, the cable is terminated with an open in order to see a large reflection in the time response at the end of the cable. As shown in figure 10b, the time domain display shows a series of peaks associated with the various components along the transmission path. The first peak on the left is the reflection from the input cable. The next grouping of peaks is associated with the bandpass filter. A filter is a set of resonators that interact in the time domain to create a unique response. Unless a reference filter is used for comparison, it may be difficult to determine if the filter response appears correct when examining a time domain measurement. Agilent provides several excellent application notes on filter tuning using time domain techniques [4, 5]. The last set of peaks on the right are associated with the open circuit. It is typically expected that an open circuit would result in a single peak as the impulse function is completely reflected from a single point on the transmission line. As shown on this measurement, the time response from the open has a rather complex shape. The

reflection from the open is modified by the transmission response of the bandpass filter as the signal passes through the filter in the forward direction and then passes through the filter a second time in the reverse direction after being reflected from the open. For this example, the bandpass filter is masking the reflected response from the open.
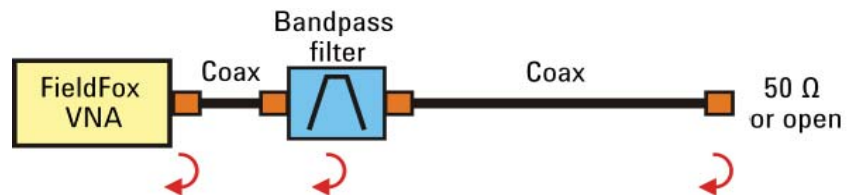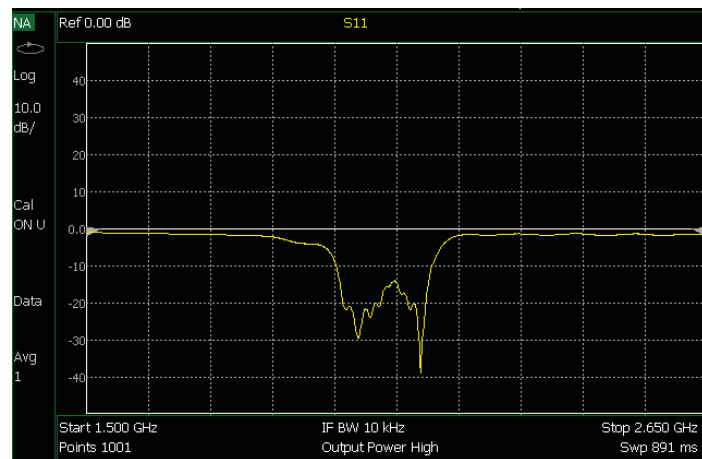

Figure 9. Test configuration for a system that includes two coaxial cables interconnected with a bandpass filter and terminated in either an open or a 50-ohm load
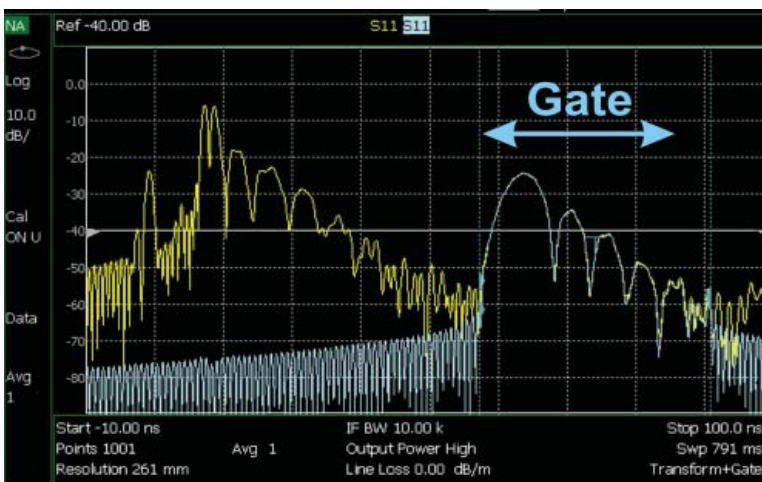

(a) Frequency response

(b) Time response

Figure 10. Measured frequency domain response of S11 (10a) and (10b) measured time domain response showing the reflection characteristics from the input connector, filter and open ended cable

Measurement example with bandpass filter

To examine the effects of masking through the inline bandpass filter shown in this example, figure 11 shows the time and frequency response of this system with a gate function applied around the reflected signal from the open. Figure 11a shows the time domain response with and without the gate. The blue curve shows the time response with the gate centered over the reflection from the open ended cable. Figure 11b shows the frequency domain response of gated signal from the open. This response shows that the system's inline filter is masking the ideal response from the open ended cable. In this case, the frequency domain response shows a typical bandpass transmission response. As mentioned, the gated response around the open shows the results when the signal passes twice through the filter, once in the forward direction and once in the reverse direction after reflecting from the open. This type of measurement would be useful when verifying that system components have been properly installed and when the user has access to only one end of the system.

It should be noted that in figure 11b, the edges of the gated frequency response have increasing amplitude. This increase is not a function of the inline bandpass filter but rather an artifact of the signal processing involved in the gating function. It may be possible to reduce the edge effects in the frequency domain by adjusting the characteristics of the gate function from the front panel of the FieldFox VNA. Details on optimizing the gate window are described in the FieldFox User's Guide and the Agilent Time Domain Application Note 1287-12 [1].

(a) Time response

(b) Frequency response

Figure 11. time domain response of the transmission system with an inline bandpass filter (11a) and (11b) frequency domain response of the gated signal from the open ended cable having a masking effect

Relating time measurements to physical distance

Once it has been determined that a system's insertion loss is higher than expected or the return loss and associated VSWR are out of spec, it becomes necessary to find the physical location of the fault(s) along the transmission system. If the velocity at which the signal travels in the cable is known, then the physical location of the damage can be calculated from a reflection measurement and using the following equation.

$$DTF\ (meters) = \left(\frac{t_{RT}}{2}\right)\left(v_{cable}\right)$$

Where v_{cable} = (VF)(c) in meters/second and VF = $1/\sqrt{\varepsilon_r}$

With a VNA such as the FieldFox, a marker placed on a peak in the time domain response represents the round trip travel time, t_{RT}. The round trip time is divided by two for an estimate of the one-way travel time to the associated discontinuity. The measured DTF is the one-way time multiplied by the velocity of the signal, vcable, in the medium. The velocity is given in meter/second but may also be calculated in feet/second. It is known that the signal velocity in a vacuum is equal to the speed of light, c. The signal velocity in a medium is the speed of light, c, multiplied by the Velocity Factor (VF) which is a value less than or equal to 1. The VF is inversely related to the square root of the dielectric constant, ε_r, of the transmission line. For example, a coaxial cable that uses solid PTFE as the dielectric will have a VF of 0.7 as the dielectric constant of PTFE is 2.1. When using a VNA to measure the location of faults, it is important to accurately enter the velocity factor into the VNA. When using a FieldFox VNA to measure DTF, once the VF is correctly entered, the FieldFox marker displays both the time and the corrected one-way distance to the discontinuity. Also, when using a FieldFox configured in CAT mode, all time domain display parameters are automatically converted to distance. The Agilent Application Note [6] provides additional information on estimating the velocity factor for an unknown cable.

Relationship between frequency span and pulse width

When a VNA measures the S-parameters of a component or system in the frequency domain, the data is measured across a user-selectable frequency range (span).

When operating in the time domain mode, the pulse width of the impulse is approximately related to the inverse of the frequency span.

$$Pulse\ width\ (seconds) \approx \frac{1}{Frequency\ span}$$

A wider span will result in more detail, or resolution, in the time domain. This is especially useful when attempting to identify two closely spaced discontinuities in the time domain. The equation is approximate due to the fact that a window is applied to the measured data in order to improve the dynamic range of the time domain response which slightly increases or decreases the pulse width. Additional details concerning the window function can be found in Agilent Time Domain Application Note 1287-12 [1].

As an example, figure 12 shows the measured time domain response of two coaxial cables connected together with a coaxial adapter and terminated in a 50-ohm load. Figure 12a shows the time response using a VNA configured with a 500 MHz span. Here the individual discontinuities are not observable due to the wide pulse width in the time domain. Figure 12b shows the measurement when the frequency span is increased to 4 GHz. In this case the individual discontinuities are clearly observed using a narrower pulse width.

While having a large frequency span improves the time domain resolution, it has a negative effect on the total time span or maximum range that can be measured. The next section discusses the relationship between frequency span and the maximum measurable time.
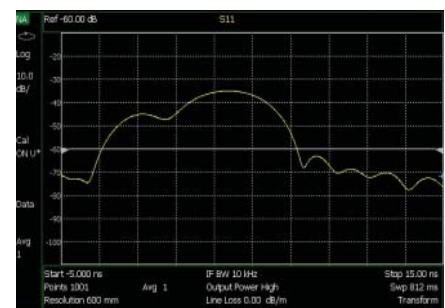
(a) Time response with 500 MHz span
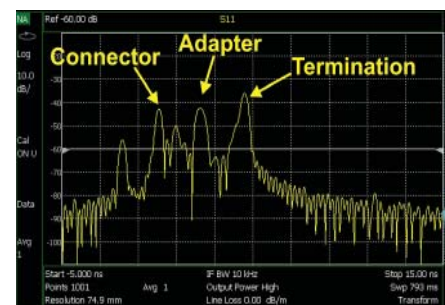
(b) Time response with 4 GHz span

Figure 12. Measured time domain response of two coaxial cables connected together with a coaxial adapter and terminated in a 50-ohm load

Relationship between frequency span and time span

When a VNA measures the S-parameters of a component or system in the frequency domain, the data is measured across a selected frequency range (span) and stored at discrete points across this span. The frequency spacing between data points, Δf, is directly proportional to the frequency span and inversely proportional to the total number of measurement points, **Points**, as shown in the following equation. saturating.

$$\Delta f = \frac{Frequency\ span}{(Points-1)}$$

Along with the frequency span, the number of points is also selectable by the user. The frequency spacing, Δf, is then automatically calculated by the VNA. The FieldFox VNA can be configured with the number of points set from 101 to 10,001. For example, using a span of 1 GHz and 101 points, the data is then measured every 10 MHz $=\Delta f$.

When measuring electrically long components and systems, it is important that the VNA is properly configured to measure all the way to the end of the transmission path. This is especially important when long cable runs are installed in a system such as in tower mounted antennas. We find that the maximum time span is directly proportional to the number of measurement points in the frequency domain and inversely proportional to the measured frequency span as shown in the following equation. Here, the divide by 2 is the result that reflection measurements are a round trip through the transmission system. For transmission measurements, such as S21 and S12, the divide by 2 is not required.

$$Maximum\ time \approx \frac{1}{2\Delta f} = \frac{(Points-1)}{2\,(Frequency\ span)}$$

Table 1. Time range as a function of measured frequency span when using 10,001 points and a velocity factor (VF) equal to 0.66

Span (GHz)	Max time (microseconds)	Range (meters)
2.5	2	396
5.0	1	198

Under some conditions, it may be possible to configure a VNA to display a time domain response beyond the calculated maximum time span. Under this condition, it is possible to observe a spurious response, also called an alias, which appears to be real response but is actually an artifact of the mathematical transformation from the frequency domain into the time domain. The FieldFox provides a table showing whether the current measurement is alias-free. When the FieldFox flags the possibility for an alias, there is a simple test to verify if a response is real. First, place a marker on the peak in question and note the time (distance) to the fault. Next, change the start or stop distance on the analyzer. A true time domain peak will not move in time (distance) but an alias response will appear to move. More information concerning aliases can be found in the FieldFox User's Guide and the Agilent Time Domain Application Note 1287-12 [1].

It is important to note that it is not possible to simultaneously optimize for narrow pulse width, discussed in the previous section, and maximum time range discussed here. A narrow pulse width requires a wide frequency span but a wide frequency span reduces the maximum time span. Therefore a tradeoff between the time resolution and the time span will need to be made. Fortunately for some types of devices, there is another time domain mode available on the FieldFox VNA that will further improve the time resolution without sacrificing time span and this mode will be introduced in the next section of this application note.

Configuring bandpass and lowpass time domain modes

The FieldFox VNA and CAT analyzers have two time domain mode selections for optimizing time measurements. The modes are lowpass and bandpass. The mode selection depends on the operating frequency range of the DUT. For example, when measuring broadband devices, such as coaxial cables and adapters, their operating frequency range extends from DC and into the RF and microwave frequency ranges. For these devices, the VNA is ideally operated in the lowpass mode for all time domain measurements. When the device is specified to operate over a narrow frequency range then the bandpass mode on the VNA will provide the best results. Bandpass mode is primarily used when filters, couplers, antennas and waveguide components are included as part of the transmission path.

When using bandpass mode, the instrument's start and stop frequency settings should be set to approximately the operating range of the DUT. When the DUT is broadband, the lowpass mode would be configured over a much larger frequency range. The lowpass mode extrapolates the measured frequency range down to DC and then mirrors the measured frequency range data about DC to greatly improve the time resolution capability. Additional information regarding these modes can be found in the FieldFox User's Guide and the Agilent Application Note 1287-12 [1].

Conclusion

The time domain feature on the FieldFox is a powerful tool for verifying and troubleshooting complex components and systems. Beyond the examples discussed in this note, there are numerous applications and instrument configurations for performing time domain measurements that are discussed in other Agilent application notes listed in the reference section of this note. Agilent will gladly supply these notes through the website or with live technical support. Agilent also provides local and on-site training for all handheld and benchtop VNA and CAT analyzers.

References

[1]   Agilent Application Note 1287-12, Time Domain Analysis Using a Network Analyzer, Literature Number 5989-5723EN, May 2012.

[2]   Brigham, E. Oran, The Fast Fourier Transform, Prentice-Hall, 1974.

[3]   Agilent Application Note 1304-2, Time Domain Reflectometry Theory, Literature Number 5966-4855E, May 2006.

[4]   Agilent Application Note 1287-8, Simplified Filter Tuning Using Time Domain, Literature Number 5968-5328E, July 2000.

[5]   Agilent Application Note 1287-10, Network Analysis Solutions Advanced Filter Tuning Using Time Domain Transforms, Literature Number 5980-2785EN, March 2001.

[6]   Agilent Application Note, Techniques for Precise Cable and Antenna Measurements in the Field, Literature Number 5991-0419EN, August 2012.

Carry precision with you.

Every piece of gear in your field kit had to prove its worth. Measuring up and earning a spot is the driving idea behind Agilent's FieldFox analyzers. They're equipped to handle routine maintenance, in-depth troubleshooting and anything in between. Better yet, FieldFox delivers Agilent-quality measurements - wherever you need to go. Add FieldFox to your kit and carry precision with you.

Related literature	Number
FieldFox Combination Analyzers, Technical Overview	5990-9780EN
FieldFox Microwave Spectrum Analyzers, Technical Overview	5990-9782EN
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