

ABSTRACT

CATV system bandwidths are increasing to 750 MHz and 1 GHz. New measurement techniques are needed to facilitate testing to these higher frequencies. One problem with the higher frequencies is the increased mismatch problems due to the shorter wavelengths. Testing the basic properties of long 75 ohm coaxial transmission lines at these higher frequencies, such as insertion loss, structural return loss (SRL), and impedance is more difficult. This paper will discuss the concept of vector error correction using a fixed bridge for these measurements and will compare this technique to the variable return loss bridge technique currently being used by the CATV industry. The theoretical basis for this fixed bridge technique is covered in detail. Data is presented from the results of an automatic transmission line testing program to 1 GHz and is compared to variable bridge measurements. These new testing procedures are important for measuring 75 ohm transmission lines especially as system bandwidths increase to 1 GHz, as new HDTV requirements unfold, and as hybrid fiber/cable systems become commonplace.

INTRODUCTION

As the CATV industry moves forward, we must be continually looking out for better ways of doing things. This is the case with cable measurements as we push the frequency range up to 1 GHz. What is proposed requires the next generation of test equipment for making measurements on the next generation of cable. The advantages are numerous. With the past technique, measurements to 1 GHz are difficult, tedious, and prone to errors. With the proposed technique, these problems are virtually eliminated, with the result, a cable that will enhance the value of the system in which it is used.

ELECTRICAL PROPERTIES OF CABLE

Insertion Loss

The insertion loss or attenuation of the cable describes how a signal loses energy as it travels through the cable. This loss is usually described in terms of a power ratio in dB and increases with the signal frequency. For coaxial cables these losses are attributed to the conductors and to the dielectric. The electrical properties of these materials are well known; thus the insertion loss is predictable from DC to well over 1 GHz.

The attenuation of typical CATV cables at 1 GHz is shown in Table 1. The cable must be measured in long production lengths (greater than 2000 feet) so the total loss per reel is also given in Table 1.

Many of the cables have losses in excess of 60 dB for normal reel lengths, but up to 96 dB of loss per reel is possible. The challenge for measuring attenuation is that the test equipment must have sufficient dynamic range to measure the losses through these long lengths of cable.

Impedance

The cable characteristic impedance is the ratio of the voltage to current for a wave traveling in the cable. Ideally coaxial cable impedance appears purely resistive across the frequency band and CATV coaxial cables are designed to have 75 ohm impedance, the standard used by the CATV industry. Seventy five ohms is nearly the optimum impedance for the lowest attenuation. For higher frequencies, greater than 5 MHz, the coaxial cable impedance is related to the ratio of inner to outer conductor dimensions and the dielectric material between them. Unfortunately, the cable impedance is not exactly 75 ohms across the frequency band and is generally within ± 2 ohms from 75 for trunk and feeder cable and within ± 3 ohms from 75 for drop cable.

Table 1.

| Attenuation at 1 GHz | | | | | | | | |
|----------------------|-------------|---------|---------------|-------------|---------|-------------|-------------|---------|
| Trunk Cables | | | Feeder Cables | | | Drop Cables | | |
| Cable Size | Attenuation | | Cable Size | Attenuation | | Cable Size | Attenuation | |
| | dB/100 feet | dB/reel | | dB/100 feet | dB/reel | | dB/100 feet | dB/reel |
| T10 - 750 | 1.74 | 43.5 | T10 - 412 | 3.10 | 96.1 | 59 Series | 7.92 | 79.2 |
| T10 - 874 | 1.53 | 38.3 | T10 - 500 | 2.53 | 63.3 | 6 Series | 6.42 | 64.2 |
| T10 - 1000 | 1.44 | 36.0 | T10 - 625 | 2.11 | 52.8 | 7 Series | 5.41 | 54.1 |
| TX10 - 840 | 1.53 | 38.3 | TX10 - 565 | 2.17 | 54.3 | 11 Series | 4.31 | 43.1 |
| TX10 - 1160 | 1.20 | 30.0 | | | | | | |

Return Loss

When the cable impedance is not exactly 75 ohms, there will be an impedance mismatch and a reflection of energy if it is connected to an ideal 75 ohm signal source. This reflection can be quantified in terms of the return loss:

$$RL = 20 \text{ LOG } \left[\frac{Z_{\text{DEVICE}} - Z_0}{Z_{\text{DEVICE}} + Z_0} \right] \quad (1)$$

where Z_{DEVICE} is the complex characteristic impedance of the device (ohms) and Z_0 is 75 ohms for CATV systems.

Since the cable impedance is within a few ohms of 75, the return loss, as opposed to the cable's structural return loss, is very good and usually better than 37 dB. The structural return loss, which deals with return loss at particular frequencies, will be discussed next.

Structural Return Loss

As coaxial cable is manufactured, a number of variables can cause the impedance to change. Recall, the cable's impedance is a function of the cable's physical properties (conductor diameters, insulation's dielectric constant), and if any of these properties change, the impedance will change. For example, the dielectric material is extruded over the center conductor during the manufacturing process. As the dielectric is extruded, its diameter or dielectric constant can change and cause the impedance to change. This impedance change is extremely small and difficult to measure. If only one of these impedance changes occurs in the cable or if they occur at random intervals, the return loss will be good; but due to manufacturing processes, there may be many evenly spaced impedance changes and return loss problems will arise. Reflections from these evenly spaced impedance changes add together at a frequency corresponding to a half wavelength spacing. Although, each impedance change may be very small, when they all add together, they cause a return loss "spike". These spikes can be narrower than 200 KHz. The return loss from these impedance changes is called the structural return loss because the impedance variations are due to structural nonuniformities in the cable. Although structural return loss measurements are described below, the challenge for measuring cable to 1 GHz is that the test equipment must have extended bandwidth (greater than 600 MHz) without sacrificing the ability to resolve and accurately measure these sharp SRL spikes.

Test Techniques

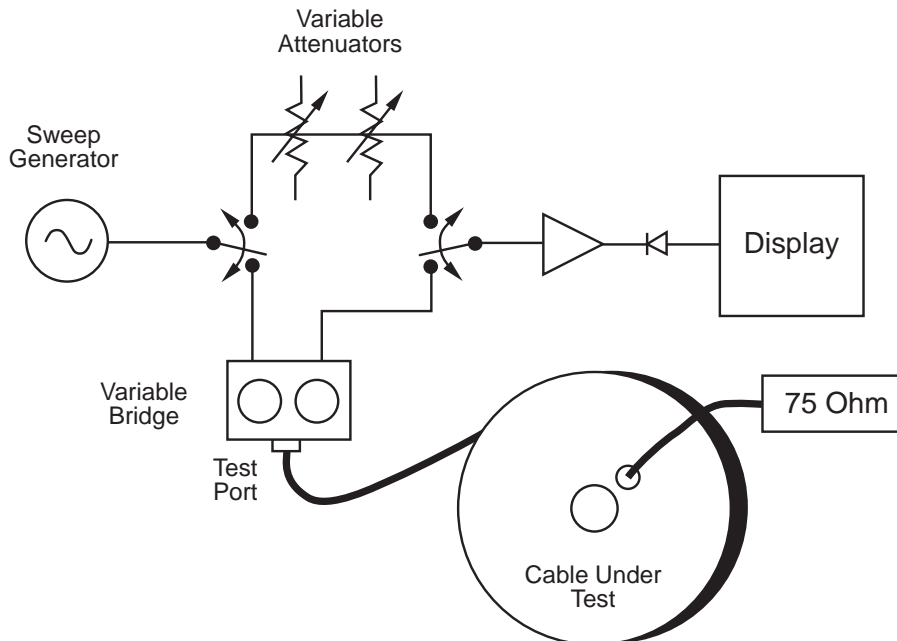
Testing the insertion loss, impedance, and return loss of 75 ohm cable requires defined test techniques for making repeatable and accurate measurements. This section of the paper will present two test techniques for making impedance and structural return loss measurements. The first technique involves the use of a variable bridge and is the currently accepted method for doing this type of cable testing. The second technique involves a fixed bridge, a network analyzer, a set of calibration standards, and a technique for simulating a variable bridge with calculations to perform these cable tests.

Variable Bridge Technique

The variable bridge testing technique block diagram for measuring SRL is shown in Figure 1. This block diagram shows that one end of the cable under test is connected directly to the variable bridge while the other end is connected to a 75 ohm load. To perform a measurement, the tester connects the top of the cable under test to the variable bridge and the bottom to the 75 ohm load, adjusts the variable bridge for the best match (i.e., CRT trace is adjusted for the lowest possible baseline without regard to "sharp spikes" when looking at return loss), and takes the measurements. An RMS voltmeter is sometimes used as a null indicator to help balance the bridge and improve repeatability. The connections are switched and the process is repeated for the bottom of the cable under test. During the measurements the tester is required to locate the worst case structural losses and report their amplitudes and frequencies. This requires the tester to locate these spikes with the help of the frequency markers in the sweep generator and determine their magnitude with an external variable attenuator. In order to see very narrow bandwidth return loss spikes, the sweep generator's sweep time must be increased or the sweep generator's frequency bandwidth must be decreased. This method of testing is currently an industry practice and is widely accepted for making SRL measurements.

In the variable bridge technique, there are three references that are used when making these cable measurements. The first involves the variable bridge. This bridge is used to determine the cable impedance and is calibrated to read out in ohms. This measurement requires a calibration process for determining the impedances for several variable bridge positions. By tuning this bridge to achieve the lowest trace on the CRT, the cable impedance can be read off the bridge directly. The variable return loss bridge has one disadvantage with

Figure 1.



broadband measurements, it is difficult to find a variable bridge with good directivity from 5 MHz to 1 GHz. The second reference used is the frequency markers on the sweep generator. These markers typically have a frequency accuracy of 0.005% and are used to find the location in frequency of the worst case accuracy loss spikes. The third reference is the variable attenuator. This attenuator determines the level of the return loss spikes and the insertion loss. The ability to know the level of this attenuator is critical, because it is the attenuator level that determines whether a cable passes or fails the structural return loss specification. All three of these references must be calibrated periodically so that the measurements can be made with confidence. The variable bridge technique relies heavily on operator interaction and the three references (bridge impedance, sweep markers, attenuator).

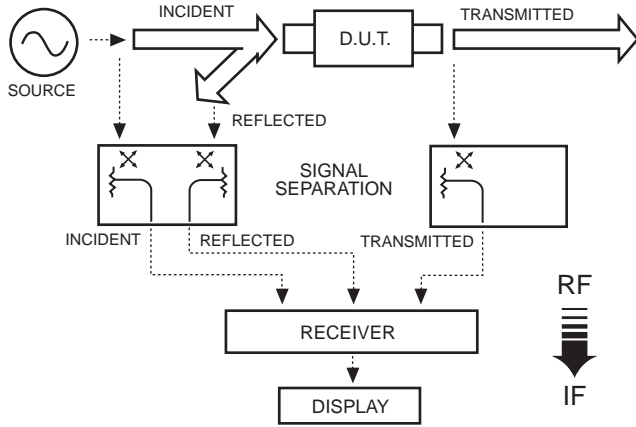
The measurement errors associated with the variable bridge technique can be attributed to three items: frequency tracking, mismatch, and directivity. The errors associated with the measurement system frequency response, otherwise known as frequency tracking, can be reduced to less than 0.5 dB by properly balancing the passive losses of the test set and the reference legs. The errors associated with cable mismatch can also be virtually eliminated by balancing the variable bridge for the best match between the bridge and the cable. The directivity errors are not easily eliminated and are due to the connector and the bridge itself. The directivity errors can be significant when measuring cables since the return

loss of the cable is generally greater than 30 dB. The best solution has been to specify a bridge that has a very low directivity specification for the test system. In the 5 to 600 MHz range, a bridge with 55 dB or better can be achieved. Above 600 MHz it is difficult to obtain a broadband variable bridge with much better than 45 dB directivity. Typically a directivity of 50 dB is desirable. In general, a directivity error of +2.5/-1.9 dB can be expected from a bridge whose directivity is 12 dB better than the measurement and a directivity error +1.2/-1.0 dB accuracy can be expected from a bridge with a directivity of a 18 dB better than the measurement.

Fixed Bridge Technique

The fixed bridge technique for measuring SRL is shown in Figure 2. This measurement technique has several advantages for measuring cable. The first advantage is the cable can be tested from both the top and bottom without being disconnected. This allows the measurement to be taken faster now that only one set of connections needs to be made. The other benefit of only one connection is reduced connector wear. The second characteristic of this technique is that the source is now a synthesized source. This allows for a much more repeatable measurement not only from sweep to sweep but from test stand to test stand. This synthesized source has a frequency accuracy of 10 KHz at 1 GHz and is phase locked to a 10 MHz frequency reference. The third characteristic is that no tuning need be done to get the measurements. There is no variable bridge to tune, and

Figure 2.
Fixed Bridge Testing Technique



no sweep generator to vary. This eliminates many of the operator errors and frees up the operator to do other tasks. The fourth characteristic, not shown in the block diagram, is the ability of this system to correct for the systematic errors that occur in the test system with calibration standards. These calibration standards are used to correct for the fixed bridge directivity, the measurement system frequency response, and the measurement system port matches. This calibration is done by measuring known standards and comparing the measured results to the theoretical results and calculating error vectors to correct the measurement. This fixed bridge technique can easily measure return loss, impedance, and insertion loss for the cable under test.

The process used to correct the measurements is known as vector error correction. Vector error correction is the process of measuring the magnitude and phase of defined standards, comparing these measurements to theoretical results and computing complex error vectors. The standards used for this calibration are an open, a short, a load, and a thru. Each standard is machined to tight tolerances and is traceable to the National Institute of Standards (NIST). This means that the measurements taken with a calibrated system are traceable to national standards.

Figure 3. Forward Flowgraph

| Forward Coefficients | | Reverse Coefficients |
|----------------------|-----------------------|----------------------|
| E_{DF} | Directivity | E_{DR} |
| E_{SF} | Source Match | E_{SR} |
| E_{RF} | Reflection Tracking | E_{RR} |
| E_{XF} | Isolation | E_{XR} |
| E_{LF} | Load Match | E_{LR} |
| E_{TF} | Transmission Response | E_{TR} |

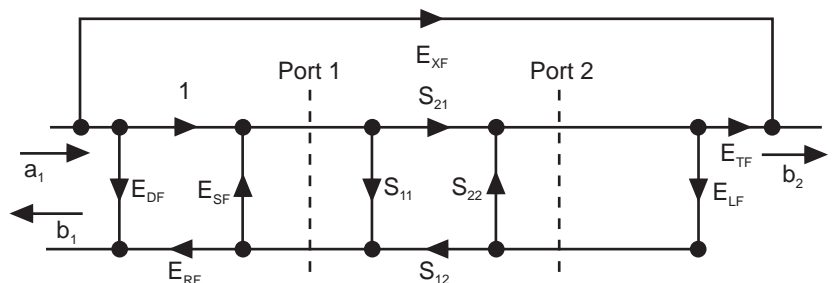


Figure 3 shows the error model for the test system. The cable under test is represented with S-parameters, where S_{11} and S_{22} are the input and output return loss (top and bottom) while S_{21} and S_{12} are the forward and reverse insertion loss for the cable. Around the S-parameters for the cable are the 6 forward error terms. These are the error terms for stimulating the cable from port 1, there are another 6 error terms for when the stimulus comes from port 2. In looking at Figure 3, the first three error terms have to do with port 1. Error term E_{df} has to do with the imperfections in the directional coupler, i.e., the directivity. This term is corrected for with the load calibration standard. Ideally, the directivity should be infinite. Error term E_{sf} is the source match error. This error is corrected for with both the short and open calibration standards. The source match error has to do with how well the test set is matched to 75 ohms. Ideally, the source at port 1 would be exactly 75 ohms and there would be no mismatch between the test set and the cable under test. Error term E_{rf} is the frequency tracking error. This term is also corrected for with both the short and open calibration standards. The frequency tracking error has to do with the frequency response of the test system including the loss through the test lead from the test port and back. Ideally, the frequency response of the test system should be zero and flat versus frequency. Error term E_{xf} is the isolation error. This error has to do with the rf leakage inside of the test set and becomes important for accurate measurements on cables with high loss. Ideally, this error is zero. Error term E_{lf} is the load match. This error term is corrected for by measuring the match of port 2. This error term is especially important at low frequencies when the loss thru the cable is less than 6 dB and the match of the cable is better than the match of port 2. Ideally, port 2 would look like a perfect 75 ohm load. Error term E_{tf} is the frequency tracking term for the transmission measurement. This error term is corrected for with the thru measurement, which includes the loss through both test leads. Ideally, this transmission frequency response should be zero and flat versus frequency. It is typically the first three error

terms that are needed when making the return loss measurements of the cable, unless the insertion loss of the cable is less than 6 dB then Elf must be taken into account.

1 GHZ TEST SETUP

Figure 4 shows the test setup used to make measurements on Times Fiber Communications semiflex cable. In Figure 4 the host controller is an HP Vectra. The HP 8753C RF Vector Network Analyzer is used to perform the measurements. This instrument has the capability to measure all four S-parameters, the input and output return loss, the insertion loss as well as do the necessary error corrections for making accurate measurements. The HP Vectra is a DOS based computer and is used to extract the data from the HP 8753C, perform some calculations, and store the data into a database. For structural return loss, the measurements are taken over the 5 MHz to 1 GHz frequency range in 5 measurement bands. In each one of these bands there are 1601 data points taken, which gives a frequency resolution of 125 KHz. This 125 KHz frequency resolution helps to locate the extremely narrow SRL spikes that can occur due to the periodic discontinuities in the 2000 plus feet of cable. The return loss data is normalized to the average impedance of the cable to give the reading of structural return

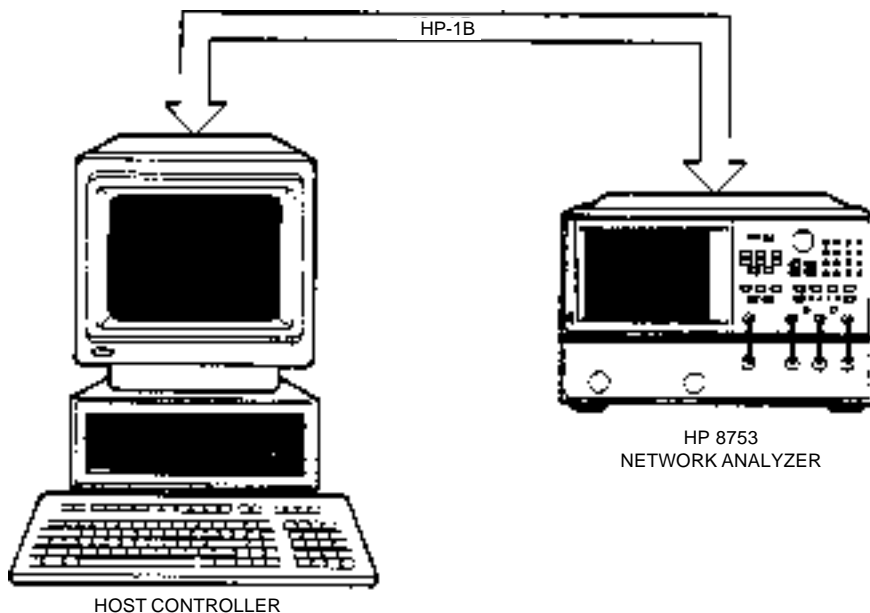
loss. This information is representative of the largest variation of impedance from the average impedance of the cable rather than 75 ohms, which is the data obtained from the network analyzer. The mathematics to do this calculation simulates the action of balancing the variable bridge with a fixed bridge format. The mathematics are shown below.

$$Z_{CABLE} = 75 \left[\frac{1 + \Gamma_M}{1 - \Gamma_M} \right] \tag{2}$$

$$\Gamma_{SRL} = \frac{Z_{CABLE} - Z_{AVG}}{Z_{CABLE} + Z_{AVG}} \tag{3}$$

In equation (2), Z_{CABLE} is the impedance of the cable and Γ_M is the reflection coefficient from the network analyzer as measured at each frequency. In equation (3) Z_{AVG} is the average impedance of the cable over the frequency range and Γ_{SRL} is the structural reflection coefficient for the cable. Γ_M is measured by the network analyzer and Z_{CABLE} is calculated. Z_{CABLE} is put in eq (3) and the value Γ_{SRL} results.

Figure 4.
Times Fiber Communications Measurement Setup



The other two measurements, impedance and insertion loss, are read directly from the network analyzer. The average impedance is measured by taking a single sweep from 5 MHz to 1 GHz with 101 points. The average is calculated from these data points and used in calculation of structural return loss. The insertion loss is measured at a number of specified frequencies.

TEST RESULTS

Structural Return Loss

Table 2 summarizes the results of test data collected on full reels of cable. These reels were tested with both a variable return loss bridge and a vector network analyzer (VNA) and then the results were compared. A large test sample consisted of T10500, 0.500 inch feeder cable, and T10750, 0.750 inch trunk cable, which were specially manufactured for 1 GHz applications. Table 2 shows the average of the worst case SRL spike.

Table 2.

| Average Structural Return Loss | |
|--------------------------------|----------|
| Variable Bridge | 33.99 dB |
| Network Analyzer | 33.92 dB |
| Difference Avg | 0.07 dB |
| Diff Std Dev | 2.10 dB |

The variable bridge structural return loss measurements were performed by a production tester. The network analyzer return loss measurements, being automated, required only the tester to connect the test leads to the cable reel. Once connected, the network analyzer test system performed all the measurements and recorded the data. After each reel was measured, the results were compared. Differences of approximately 2 dB were expected since the directivity of the variable bridge was only approximately 45 dB from 600 MHz to 1 GHz. This corresponds quite well with the difference standard deviation of 2.10 dB. With the exception of some small changes in the test leads, the directivity error on the VNA system is virtually eliminated while the directivity error of the variable bridge is left as an uncertainty.

In some cases a difference significantly greater than 2 dB was detected. Further analysis of these cases showed that the tester had missed an SRL spike. The tester missed these spikes because the display is linear and most of the cable is better than 32 dB; thus the operator had to adjust the display sensitivity to more accurately measure these lower levels. With this increased display

sensitivity, the top of 28 dB spikes go just beyond the top of the screen. Although the system had enough resolution to catch the spike, it is necessary to reduce the display sensitivity after each cable is measured. Since most of the cables are better than 32 dB, it is a challenge for the tester to continually reset the display sensitivity after each measurement is made when the cables with sharp SRL spikes occur only a few percent of the time. No significant change in the SRL average in Table 2 was noticed when the samples with the measurement errors were removed.

Impedance

The impedance measured from the variable return loss bridge compared favorably to the vector network analyzer, in light of the fact that the impedance is read off a dial indicator.

Table 3.

| Average Impedance | |
|-------------------|------------|
| Variable Bridge | 75.50 Ohms |
| Network Analyzer | 75.70 Ohms |
| Difference Avg | -0.20 |
| Diff Std Dev | 0.54 |

Attenuation

Because two groups of cable (500 and 750) were measured, it is appropriate to compare only the difference between the two attenuation measurements rather than their averages because the 500 has significantly different attenuation than 750. Combining them into one group would not be meaningful and perhaps misleading. The average difference in total attenuation was 0.20 dB (0.60%) at 400 MHz with a standard deviation of 0.15 dB. This type of correlation is quite good, given that the smallest increment on the variable attenuators for the variable bridge technique is 0.5 dB.

DISCUSSION

The accuracy of the variable bridge technique can be significantly improved by using a vector network analyzer and error correction. The variable bridge technique also requires a great deal of operator intervention which can add to the errors. The VNA mathematically corrects for the cable impedance and eliminates the possibility of missing sharp spikes. The vector network analyzer frees the operator to do other tasks while it does the actual measurements. Listed below are some other consider-

ations that are made when using a VNA to make cable measurements.

Lump Impedance Discontinuities

There are a few factors that need to be addressed with a vector network analyzer that are not as critical with the variable bridge measurement. The operator's ability to recognize problems associated with test connectors and the cable is lost to some extent with an automated system. If the cable is kinked or damaged in some way, it will have a lumped impedance discontinuity and the structural return loss trace will have a very distinct characteristic or pattern. Pattern recognition is difficult to do quickly with a computer, while the human eye can recognize patterns in a fraction of a second. Since test time is crucial, the operator's intervention is still needed when this type of problem occurs.

Test Connectors and Time Domain Capability

At 1 GHz, test connectors can introduce errors into the measurement because the system calibration is performed on the "N" type port at the end of the test lead. When a test connector is installed on the end of the test port, its impedance variations are introduced into the measurement. In order to minimize these problems, good connectors must be used. Over a period of time, the performance of the connectors degrade. Since the operator is no longer involved with the measurement, it is important for the system to recognize when problems with the connector arise. The automated VNA has such capability. By switching into the time domain mode, the VNA can measure the reflection coefficient of the interface. A program is written to analyze the data and notify the operator if a problem does arise. Use of the time domain mode can also be used to identify problems in the reels being tested.

Test Leads

The stability of the test leads must also be considered. In the case of the variable return loss bridge, the test leads are not part of the test circuit. In the case of the VNA system, they are. Small changes in the test leads after the calibration is performed can introduce errors into the measurement. It is therefore necessary to perform regular checks of the system performance. Special test leads that can endure repeated flexure and crushing forces from the operator walking on them or reels rolling over them limit the changes in impedance and phase that can degrade the system performance.

CONCLUSION

It has been shown that measurements of structural return loss, impedance, and insertion loss can be performed using a vector network analyzer and are in substantial agreement with the current industry accepted standard technique. Some factors are more critical with the new measurement technique, but with the proposed system, measurement errors are reduced in numerous ways including vector error correction. Although some human intervention is still necessary, the measurements are made and recorded directly by the automated system so most errors introduced by human intervention are eliminated. As the CATV industry moves forward toward the enhanced value of 1 GHz systems, the vector network analyzer technique using vector error correction and impedance normalization should be accepted as the new standard by which other techniques are compared.

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