Cable Impedance and Structural Return Loss Measurement Methodologies

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Introduction

Two critical electrical specifications for CATV cable are well known: cable impedance and structural return loss. However, as common as these specifications are, the specifications associated with any cable depend upon both the specification definitions and the measurement methodology.

This paper introduces exact definitions for cable impedance and structural return loss alongasfg with several measurement methodologies. Several enhancements to traditional measurement methods are introduced which compensate for the largest source of errors. The uncertainties associated with each method are discussed.

Definitions of Cable Impedance and Structural Return Loss

In the most general terms, cable impedance is the ratio of the voltage to current of a signal traveling in one direction down the cable. In coaxial cable, the value of the impedance will depend upon the ratio of the inner and outer conductor diameters, and the dielectric constant of the material between the inner and outer conductors. The value of the conductivity will affect the impedance to the extent that RF signals do not travel on the surface of the conductor, but propagate into the conductor by what is known as the skin depth. The finite conductivity also causes losses that increase with RF frequency, and this can change the effective cable impedance. Finally, the construction of the cable can change along the length of the cable, with differences in conductor thickness, dielectric material and outer conductor diameter changing due to limitations in manufacturing. Thus the cable impedance can vary along the length of the cable.

The extent to which the manufacturing imperfections degrade cable performance is characterized by the specification *Structural Return Loss* (or SRL). Structural return loss is the ratio of incident signal to reflected signal in a cable. This definition implies a known incident and reflected signal. In practice, the SRL is loosely defined as the reflection coefficient of a cable referenced to the cable's impedance. The reflection seen at the input of a cable, which contributes to SRL, is the sum of all the tiny reflections along the length of the cable. In terms of cable impedance, the SRL can be defined mathematically as:

$$\rho_{SRL}(\omega) = \frac{Z_{in}(\omega) - Z_{cable}}{Z_{in}(\omega) + Z_{cable}} \qquad \text{eq. 1}$$

Z_{in} is the impedance seen at the input of the cable, and Z_{cable} is the nominal cable impedance.

Cable impedance is a specification that is defined only at a discrete point along the cable, and at a discrete frequency. However, when commonly referred to, the impedance of the cable is some average of the impedance over the frequency of interest. Structural return loss, on the other hand, is the cumulative result of reflections along a cable as seen from the input of the cable. The above definitions need to be expressed in a more rigorous form in order to apply a measurement methodology.

One definition of cable impedance is that impedance which results in minimum measured values for SRL reflections over the frequency of interest. This is equivalent to measuring a cable with a return loss bridge that can vary its reference impedance. The value of reference impedance that results in minimum reflection, where minimum must now be defined in some sense, is the cable impedance. Mathematically, this is equivalent to finding a cable impedance Z_{cable} such that:

$$\frac{\partial[\bar{\rho}(\omega, Z_{cable})]}{\partial(Z_{cable})} = 0 \qquad \text{eq. 2}$$

where $\bar{\rho}(\omega)$ is some mean reflection coefficient. Thus, cable impedance and SRL are somewhat inter-related; the value of SRL depends upon the cable impedance, and the cable impedance is chosen to give a minimum SRL value.

An alternate definition of cable impedance is the average impedance presented at the input of the cable over a desired span. This can be represented as

$$Z_{avg} = \frac{\int_{F_{\min}}^{F_{\max}} Z_{in}(\omega)\, d\omega}{2\pi(F_{\max} - F_{\min})} \qquad \text{eq. 3}$$

The value found for Z_{avg} would be substituted for Z_{cable} in equation (1) to obtain the structural return loss from the cable impedance measurement.

Understanding cable construction, defects and faults.

Any discourse on cable measurements should include a discussion of the unique qualities of cables that make measurements so challenging. Because cables are electrically very long, and very low loss, the effect of any periodic defect in the cable will be greatly multiplied.

Periodic faults and SRL

SRL is a reflection of incident energy that is caused by disturbances (bumps) in the cable which are distributed throughout the cable length. These bumps may take the form of a small dent, or a change in diameter of the cable. These bumps are caused by periodic effects on the cable while in the manufacturing process. For example, consider a turn-around wheel with a rough spot on a bearing. The rough spot can cause a slight tug for each rotation of the wheel. As the cable is passed around the wheel, a small imperfection can be created periodically corresponding to the tug from the bad bearing.

Each of these small variations within the cable causes a small amount of energy to reflect back to the source due to the non-uniformity of the cable diameter. Each bump reflects so little energy that it is too small to observe with fault location techniques. However, reflections from the individual bumps can sum up and reflect enough energy to be detected as SRL. As the bumps get larger and larger, or more of them are present, the SRL values will also increase. The energy reflected by these bumps can appear in the return loss measurement as a reflection spike at the frequency that corresponds to the spacing of the bumps. The spacing between the bumps is one half the wavelength of the reflection spike and is described by equations.

$$\text{wavelength} = c / f \qquad c = \text{speed of light}, \quad f = \text{frequency} \qquad \text{eq. 4}$$

$$\text{wavelength} / 2 = \text{spacing between the bumps} \qquad \text{eq. 5}$$

The wavelength/2 spacing corresponds to the frequency at which down and back reflections will add coherently (in- phase). The reflections produce a very narrow response on the analyzer display that is directly related to the spacing of the bumps. We observe the amount of reflected energy as return loss. When this return loss measurement is normalized to the cable impedance, the return loss becomes structural return loss.

Figure 1. diagrams reflections from bumps in a cable. We can combine the energy reflected by each bump in a cable and make a few basic assumptions, to mathematically describe SRL by the series shown in equation (6).

$$\mathrm{P}_{ref} = [P_{in}L\Gamma L] + [P_{in}L(1-\Gamma)L\Gamma LL] + [P_{in}L(1-\Gamma)L(1-\Gamma)L\Gamma LLL] + \ldots \qquad \text{eq. 6}$$

P_{ref} is the reflected Power. P_{in} is the incident Power. L is the cable loss. Γ is the reflection coefficient of the bumps. The bumps are assumed to be uniform in reflection and spaced by a wavelength/2 separation.

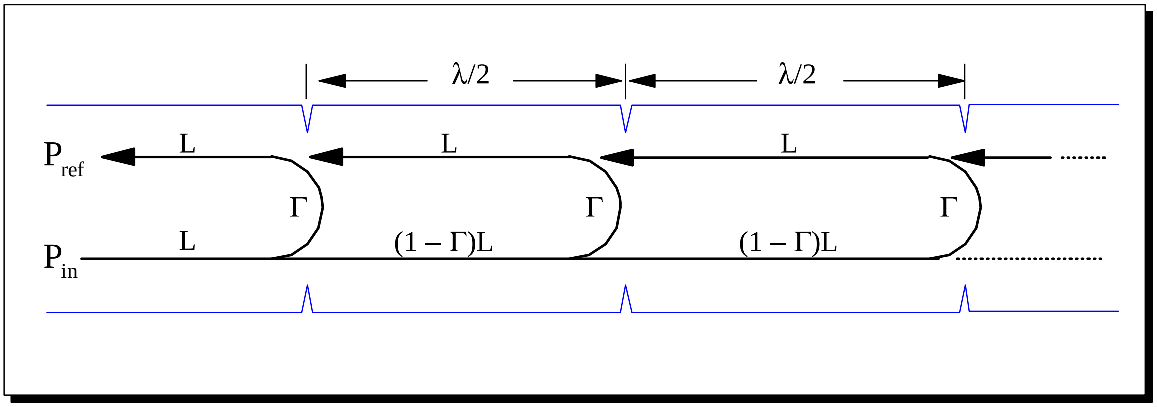


Figure 1. Periodic bumps in a cable

The series may be reduced to a simple form to leave us with the relationship shown in equation (7). The derivation for the simplified relationship is reproduced in appendix A. The term *L* is a function of the loss of the cable at a specific frequency and the wavelength at that frequency.

$$SRL = \frac{P_{ref}}{P_{in}} = \Gamma\left(\frac{L^2}{1-L^2}\right) \qquad \text{eq. 7}$$

The term $L^2/(1-L^2)$ can be thought of as the number of bumps that are contributing to SRL. It represents a balance between the contribution of loss in a single bump and further bumps in the cable for the specified frequency and cable loss. Calculate the distance into the cable by multiplying the term $L^2/(1-L^2)$ by the distance between bumps.

Table 1.1 illustrates some calculated values for a typical trunk cable. From the table, bumps spaced 1.5 meters apart out to 307 meters will contribute to SRL. The calculations to obtain the table values are shown in Appendix B.

Table 1.1 SRL Equation Constant

Frequency	Spacing (λ/2)m	Loss /m (dB)	dB/bump	bumps $L^2/(1-L^2)$	Distance (m)
100 MHz	1.5	0.01	-0.02	205	307
500 MHz	0.6	0.02	-0.02	220	132
1 GHz	0.3	0.05	-0.08	591	89

In actual cables, the reflections from the bumps and the spacing of the bumps may vary widely. The worst case, or best case for a minimum SRL, is that the bumps are totally random and very small. The effects are scattered throughout the frequency range and are small. Real world examples are somewhere in between the uniform bumps and the scattered case. As the sizes of the bumps, their spacing and the number of bumps vary within the manufacturing process, varying amounts of SRL are observed.

Discrete cable faults and SRL

Reflections from faults within the cable will also increase the level of SRL measured. The energy reflected from a fault will sum with the energy reflected from the individual bumps and provide a higher reflection level at the measurement interface. Examining the cable for faults before the SRL measurement is a worthwhile procedure. The time required to perform the measurement is small compared to the time spent in performing an SRL measurement scan.

A fault within the cable will provide the same type of effect as a bad connector. If the fault is present within the near end of the cable, the effect will be noticed throughout the entire frequency range. As the fault is located further into the cable, the cable attenuation will reduce the effect at higher frequencies. The reflected energy travels further through the cable at lower frequencies where the cable attenuation is lower.

Traditional measurement methods, variable bridge

A variable impedance bridge can be used to measure cable impedance and structural return loss. The variable impedance bridge consists of a return loss bridge that can vary its nominal impedance. The nominal impedance is the impedance for which zero reflection occurs, usually from about 70 to 80 ohms. Also, there is compensation for connector mismatch in the form of a variable capacitance term at the bridge test port, with a typical range of ±1.5 picofarads. In recent years, the variable impedance bridge method has been used with a vector network analyzer taking advantage of the increased dynamic range, synthesized source, and advanced features such as markers, limit lines and vector error correction. Measurement methods have been described in the Society for Cable Television Engineers (SCTE) Interface Practices Subcommittee standards for cable impedance and structural return loss (IPS 406 and 407)

To use a variable impedance bridge, a measurement is set up with the source going into power splitter, then into the reference channel of the network analyzer as shown in Figure 2. This is needed for phase-lock of the source to the receiver, but also greatly enhances the source match of the measurement system in ratio measurements, such as the ratio of reflected to incident power. A 50-75 ohm match pad can be used before the input of the variable impedance bridge, and another on the reflection port output of the bridge to the measurement channel of the network analyzer. The frequency span should be set to the desired range, 5 MHz to 1 GHz for CATV cable. Next, if a vector network analyzer is used, a vector 1-port (open, short, load) calibration can be performed to remove effects such as tracking (also known as frequency response), source match, and directivity. For this, the bridge must be set to exactly 75 ohms, and 0 pF, before the calibration is performed.

After the calibration, the bridge will be nearly ideal measuring exactly 75 ohms, and thus impedance measurements will be much better than if no calibration is performed. Even when the impedance is changed on the bridge, any residual errors due to changing the reference impedance will be smaller than if no calibration had been performed.

To measure cable impedance and structural return loss, the bridge impedance is varied while watching the trace on the screen to get the flattest trace that is lowest in level.

Sometimes, there is a trade off between varying the impedance and varying the compensating capacitor. If a cable does not meet specifications, it may be because the connector to the cable has too high of return loss. The connector may be manually "tweaked" by sliding it back and forth slightly, or twisting it, while watching the trace.

When the best trace has been achieved, the value of the impedance dial on the variable bridge is considered the cable impedance. This is a physical realization of equation 2, where the operator minimizes cable reflection coefficient by varying Z to get the minimum value. Then, the value of Z is the cable impedance. There are two difficulties here, both related to operator craft and judgment: 1) The value of impedance depends upon the operator's judgment of minimum reflection. Thus, the result can be different for the exact same cable and setup conditions, if a different operator performs the test. 2) The value depends upon the connection, and the manner in which the operator adjusts the connector and adjusts the capacitor compensation. Sometimes, the value for cable impedance is determined by judging only the low frequency trace response where the effect of the connector is not significant. Note that the impedance measurement is a single number, which is obtained by some interpretation of return loss data over frequency, and that the cable impedance is only truly defined at one spot along the cable.

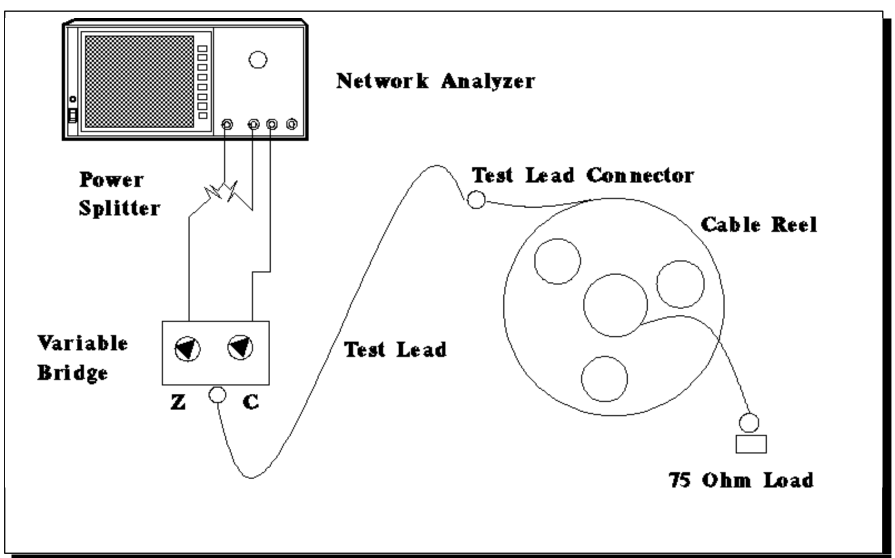


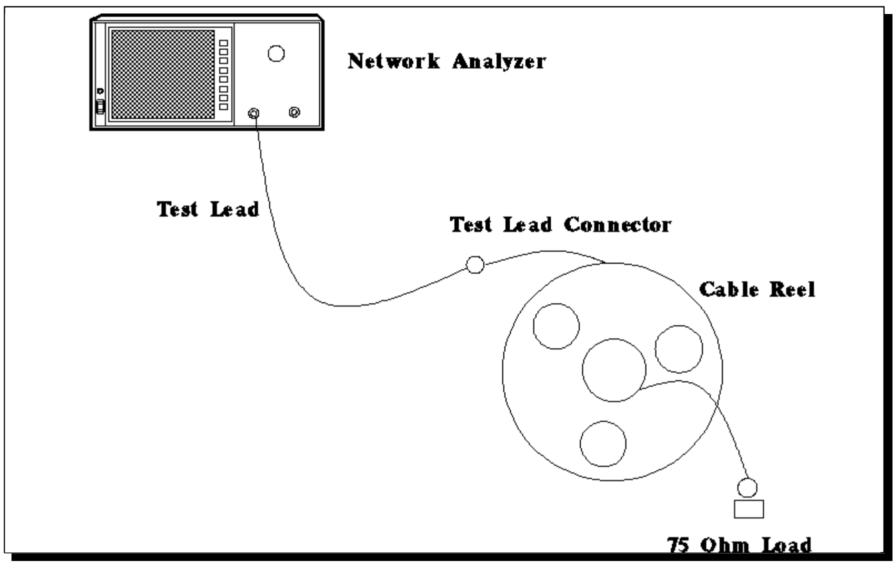
Figure 2. SRL test system setup with variable bridge

Structural return loss, however, is a measurement made over the entire frequency range of the cable. A typical report shows the worst several frequency points, along with their value for SRL. After finding the cable impedance, the operator should re-measure the cable with a finer resolution, because structural return loss can have very narrow, high-Q peaks in the response. For a 2500 foot cable, the minimum spacing between points should be less than 200 kHz.

Fixed bridge method with connector compensation

Another technique for measuring structural return loss involves a vector network analyzer, a set of calibration standards, and a technique for emulating a variable bridge with calculations. The calculations give the average impedance of the cable and a C value for connector compensation.

The fixed bridge measurement setup is shown in Figure 3. The source output from the network analyzer is connected to the cable being tested. A test lead cable may be used between



the analyzer and the end of the cable being tested for convenience.

Figure 3. SRL test system setup with fixed bridge

Perform a vector 1-port (open, short, load) calibration at the end of the test lead cable to correct for the bridge directivity, the frequency response, the test lead cable, and the measurement system port matches.

The standards used for this calibration are an open, a short, a load, and a thru. Each standard is traceable to the National Institute of Standards (NIST). This means that the measurements taken with a calibrated system are traceable to national standards.

To measure cable impedance and structural return loss, the frequency span should be set to the desired range, 5 MHz to 1 GHz for CATV cable. Begin by making low resolution measurements with fast update rates to determine the impedance of the cable and verify the setup. The measured return loss data is normalized to the Z-average impedance of the cable mathematically by the analyzer. The mathematics to do this calculation emulate the action of balancing the variable bridge Z impedance. A connector compensation can also be mathematically applied which emulates the adjustment of the C value on the variable impedance bridge.

The impedance and C compensation values may be entered manually or automatically derived by the analyzer. Once the values for the impedance and the connector compensation are determined, re-measure the cable at higher resolution. The analyzer can scan the cable at resolutions less than 100 kHz, then process the measured results and graph the worst responses.

The mathematics for the Z-averatge normalization are shown below. The mathematics for the connector compensation are shown in the next section.

$$Z_{in}(\omega) = 75 * \frac{(1+\rho(\omega))}{(1-\rho(\omega))} \qquad \text{eq. 8}$$

$$Z_{cable} = abs\left(\frac{\sum Z_{in}(\omega)}{N}\right) \qquad \text{eq. 9}$$

$$\rho_{SRL}(\omega) = \frac{Z_{in}(\omega) - Z_{cable}}{Z_{in}(\omega) + Z_{cable}} \qquad \text{eq. 10}$$

In equation (8), $\rho(\omega)$ is the reflection coefficient from the analyzer measured at each frequency and $Z_{in}(\omega)$ is the impedance of the cable for that measured reflection coefficient. The calculation of Z_{cable}, described in equation (9) is the Z-average impedance of the cable over the frequency range. Equation (10) is the structural return loss for the cable. This calculation can be done by the analyzer or an external computer.

Techniques for removing connector effects

Connector effects on SRL

When measuring spools of cable, typically two connectors are used: the test lead connector and the termination connector. These connectors provide the cable interface and are measured as part of the cable data.

Often, slight changes in the test lead connector can cause significant changes in the values of structural return loss measured at high frequencies. This is because the reflection from a connector increases for high frequencies. In fact, the return loss of a test lead connector can dominate the SRL response at frequencies above 500 MHz. This is where training, good measurement practices, and precision cable connectors are needed, especially for measurements up to 1 GHz. Precision connectors are required to provide repeatability over multiple connections. Slip-on connectors are used to provide rapid connections to the cables, but require careful attention in obtaining good measurement data. Repeatability of measurement data is directly affected by the connector's ability to provide a consistently good connection. This is the major cause of repeatability problems in SRL measurements.

Effects of the test lead connector at the measurement interface are observed as a slope in the noise floor at higher frequencies. By observing the SRL measurement display and slightly moving the connector, the effects of the connection can be observed at the higher frequencies. The test lead connector should be positioned to obtain the lowest possible signal level and the flattest display versus frequency. The mechanical interface typically provides an increasing slope with frequency and flattens out as the connection is made better.

It is also possible to gate the test lead connector reflections from the measurement data or to compute the effects of the connector and compensate these effects from a connector model. The topics of gating and compensating for test lead connector effects are discussed in the next section.

The termination connector may also effect the SRL measurement if the cable termination connector and load provide a significant amount of reflection and the cable is short enough. As longer lengths of cable are measured, the cable attenuation provides isolation from the termination on the far end. Use a time domain reflection measurement technique to observe the reflection from the termination at the far end of the cable. If the termination is shown as a fault, the reflection from the terminating connector is contributing to the reflection from the cable. A more suitable termination is required or a longer section of cable must be measured. The cable must provide sufficient attenuation to remove the effects of the connector and load for a good SRL measurement. Performing a good measurement on a short length of cable is quite difficult and requires connectors with very low reflections to be effective.

Connector effects can be removed by requiring a good connection so that the SRL response is flat or, with the variable impedance bridge method, by adjusting the compensating C value for the flattest response. Two additional methods are introduced to do the same thing. One method uses the advanced technique of time domain gating and the other method is a fixed bridge method with connector compensation.

Time domain gating to remove connector effects

The complex (magnitude and phase) frequency response of reflection can be transformed to the time domain, through the inverse Fourier transform. The result is a time domain response that is similar to a time domain reflectometer, with reflections presented as distance down a cable. This technique is commonly used for fault location in cable testing. An advanced capability, called gating, may provide a technique to remove or greatly reduce the degradation and uncertainty caused by the connector to cable interface.

For time domain measurement, the maximum range (distance) is limited to the data point frequency spacing. The resolution (ability to resolve two closely spaced reflections) is limited to the maximum frequency span of the response data. The time domain response of a typical cable shows the connector as the initial large reflection, and the cable as more, much smaller reflections. Time domain gating numerically removes (sets to zero) the response between the start and stop of gate. In general, the gating is used to measure connector interfaces, where the start is before the connector and the stop is beyond it, somewhere in the cable. With the gating turned on, the time response can be converted back to frequency response with only the connector response shown. In this way, reflections from the cable are removed from the connector measurement. However, if the gate start is set after the connector, and the gate stop is set before the connector, the time response of the connector only will be set to zero, leaving the response of the rest of the cable. This time response can be converted back to the frequency domain. The question is: does this twice converted response represent the structural return loss of the cable, or is some information lost? That is, will time domain gating remove the error caused by a poor connection, but leave the cable response intact. This question arises because the time response of any reflections following a large reflection will be smaller than normal, since the large reflection does not pass all of the "impulse" energy. Thus, the gated result will not have as high a reflection as the actual cable. Also, since the gating function is numerically derived from the limited frequency response data, gating time widths may have unexpected affects in the frequency response.

The gated response may still be used to determine cable quality. One technique proposed is to gate in the connector, convert that back the frequency range, and use the resultant reflection as a "correction factor" to be applied to the response with connector gated out. For example, if a connector has a reflection coefficient of 0.05 at 500 MHz, and 0.1 at 1 GHz, then the response of the cable with connector gated out should be divided by 0.95 at 500 MHz and 0.9 at 1 GHz. There are many other factors that must be considered before time domain gating is used, including understanding the affects of frequency sampling points, gating windows, and how the effects of a variable bridge add into the measurement uncertainty. Time domain gating promises to be an effective tool in removing a major cause of repeatability problems, but more work is needed to prove its performance in real world tests.

Fixed bridge with connector compensation.

Vector error correction is used to provide the most accurate measurements up to the calibration plane defined by the calibration standards. Additional corrections can also be used to minimize the affects of the test lead connector on the measured SRL response.

The error corrections done for a fixed bridge can also include connector compensation. The fixed bridge method with connector compensation technique mathematically removes the effects of the test lead connector by compensating the predicted connector response given by a connector model. With a connector model, the adjustment of the C value given in the variable bridge technique can be emulated. This will reduce the requirements on the performance of the connector.

One model that can be used for the cable connector is the shunt C connector model. The shunt C connector model assumes the discontinuity at the interface is abrupt and much smaller than a half wavelength of the highest frequency of measurement. With this assumption, the discontinuity can be modeled as a single shunt susceptance, where C= Co + second and third order terms.

Intuitively this is the right model to choose because the effects of a typical poor connector on structural return loss measurement is an upward sloping response, typically worst at the high frequencies.

Using a shunt C to model the connector, a value of the susceptance, -C, may be chosen by the network analyzer to cancel the equivalent C of the connector and mathematically minimize the effect of the connector on the response measurement.

The equations for computing structural return loss and the average cable impedance with capacitive compensation are described below.

$$Z_{in}^{/}(\omega) = \frac{Z_{in}(\omega) * \frac{1}{j\omega C}}{Z_{in}(\omega) + \frac{1}{j\omega C}} \qquad \text{eq. 11}$$

$$Z_{cable}^{/} = abs\left(\frac{\Sigma Z_{in}^{/}(\omega)}{N}\right) \qquad \text{eq. 12}$$

$$\rho_{\mathrm{SRL}}^{/}(\omega) = \frac{Z_{in}^{/}(\omega) - Z_{cable}^{/}}{Z_{in}^{/}(\omega) + Z_{cable}^{/}} \qquad \text{eq. 13}$$

In equation (11), $Z_{in}(\omega)$ is calculated from the measured return loss as described in equation (8), previously. The primed values are the new calculation values using the capacitive compensation. With these equations, the network analyzer can compute values for the cable impedance and mathematically compensate for the connector mismatch with a given value of C connector compensation.

Deriving the connector C value

There are two ways to derive a value for the C connector compensation. The first way to do this is similar to the variable bridge method. Observe the SRL response, then allow the operator to choose a value of C that best flattens the response. The second way to determine the value is to use the computational power of the network analyzer to choose an optimal value of C to achieve the flattest response. The optimization performed is based on the predicted behavior given by the connector model.

Analyzer based optimization eliminates operator interaction and provides a consistent solution to enable less skilled operators to make SRL measurements.

CAE simulations

The network analyzer can use modern CAE techniques to compute the optimum values for the connector model. CAE tools can also be used verify the validity of the model. Use CAE to simulate a typical structural return loss measurement by modeling a cable as lengths of transmission line and the cable connector as a connector mismatch.

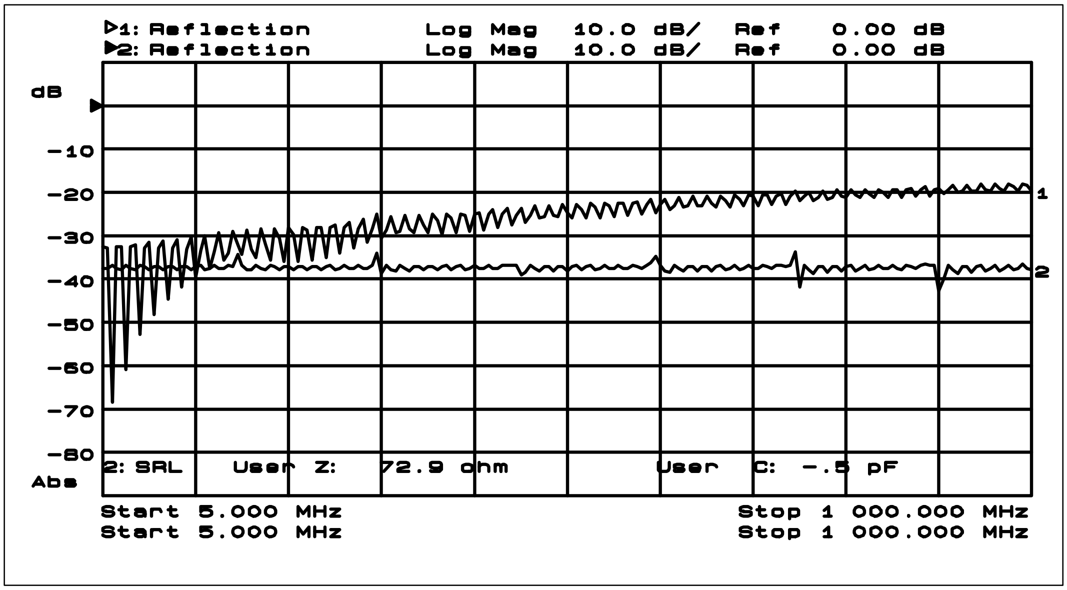


Figure 4. 500 meter cable SRL with fixed bridge and connector compensation

Figure 4 displays a simulation (CAE) of a 500 meter length of transmission line with the connector modeled as a shunt capacitance of .5pF. Trace 1 displays the return loss response as would be measured by a fixed bridge with no impedance normalization and no connector compensation. Trace 2 shows the structural return loss measurement now normalized to an average measured impedance of 72.9 ohms with -.5pF capacitive reactance mathematically removed. Notice the 12 dB response improvement at high frequency. The response improvement at high frequency is mainly caused by removing the effects of the connector mismatch mathematically.

Figure 5 displays a simulation (CAE) of a 1000 meter length of transmission line with a connector mismatch modeled as an 8 mm length of 88 ohm line. Trace 1 displays the uncompensated return loss measurement. Trace 2 displays the response after the network analyzer has mathematically calculated the response including a 0.11 pF shunt capacitance compensation and normalizing to a 75.93 ohm cable impedance. Notice an 8 dB improvement at high frequency but a worse response at lower frequency in this example.

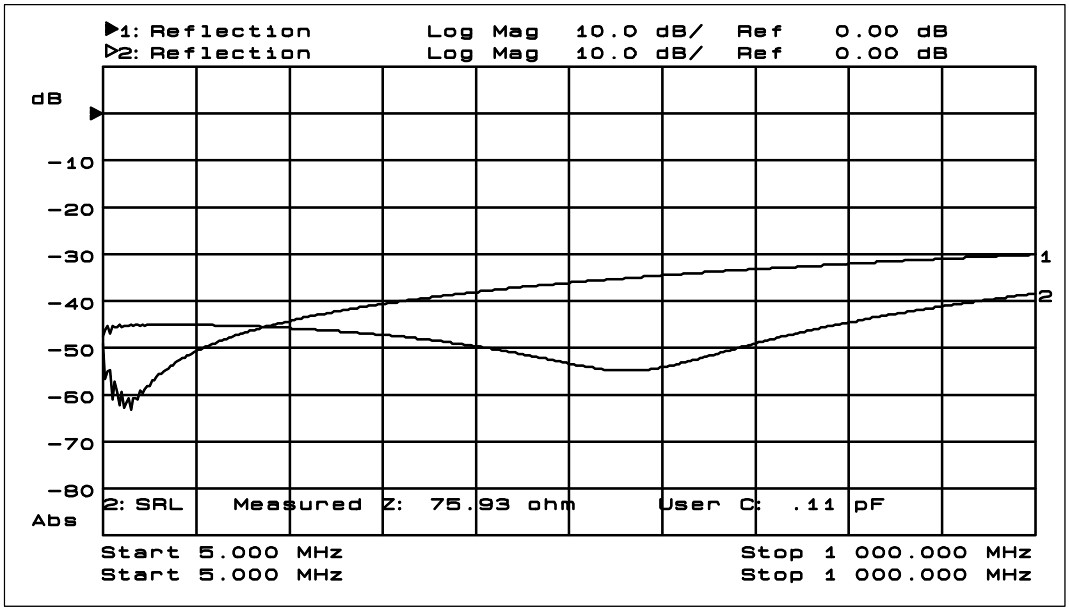
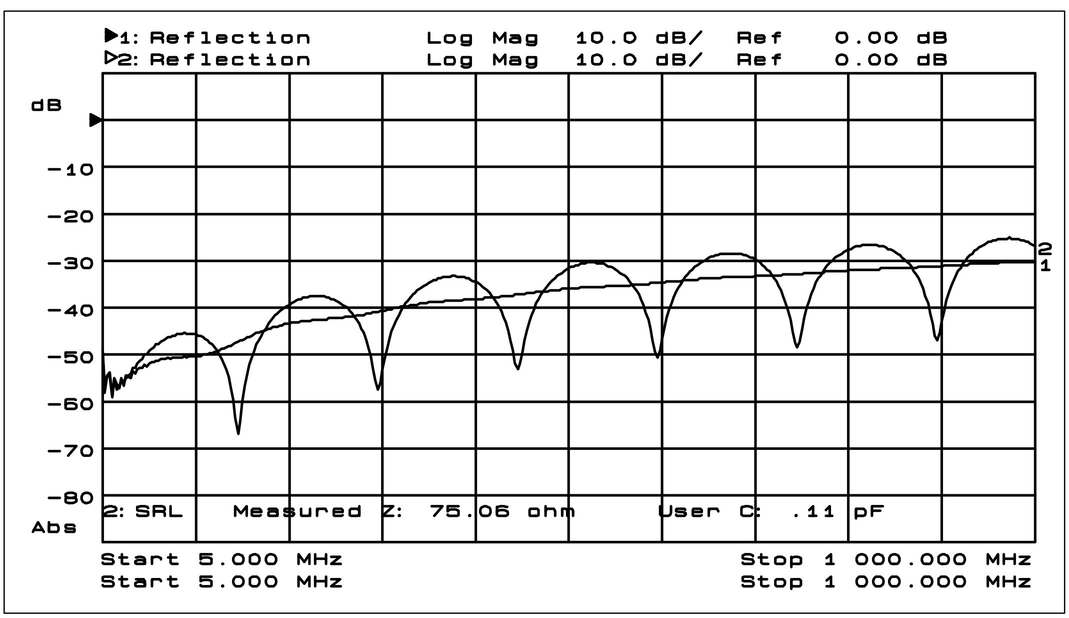


Figure 5. 1000 meter cable with connector mismatch.

Figure 6. 1000 meter cable with mismatch at 1 meter



Adding connector compensation should only correct for connector mismatches and not for cable defects. Figure 6 shows the best compensation for a cable with a cable defect at 1 meters away from the connector. Again the defect is modeled as an 8 mm length of 88 ohm line. The response is improved at some frequencies but made worse at other frequencies. The maximum response is higher than the response of the cable return loss without compensation, for any value of compensation C. The capacitance compensation cannot improve the response of a defect greater than a half wavelength down the length of the cable primarily because the summed vector responses from the defects down the length of the cable can not be canceled by a simple reactance.

Measurement uncertainty in SRL measurements and cable impedance.

In any comparison of cable impedance or structural return loss data, it is important to understand the measurement uncertainty involved in each type of measurement. This is critical for manufacturers, who often use the most sophisticated techniques to reduce manufacturing guard bands. It is also important in field measurements that users choose the proper equipment for their needs, and understand the differences that can occur between manufactures' data and field data. Also, note that measurement uncertainty is usually quoted as the worst case result if the sources of error are at some maximum value. This is not the same as error in the measurement, but rather a way to determine measurement guard band, and to understand how closely to expect measurements to compare on objects measured on different systems.

The errors that can occur in a reflection measurement are reflection tracking (or frequency response), T, source match, Γ_M, and directivity, D. The total error in a measurement can be shown to be:

$$\Gamma_{\text{MEAS}} = T \bullet \left[D + \frac{(\Gamma_{\text{DUT}})}{(1 - \Gamma_M \ \Gamma_{\text{DUT}})} \right] \qquad \text{eq. 14}$$

Error correction techniques can effectively remove the effects of tracking. Also, source match effects are small if Γ_{DUT} is small. This leaves directivity as the largest error term in the reflection measurement. The causes and effects of these error terms will be described for each of the measurement methodologies.

For variable bridge measurements, the directivity of the bridge is the major error term. One-port vector error correction reduces the effects of tracking and source match, and improves directivity. The directivity after error correction is set by the return loss of the precision load, specified to be better than 49 dB at 1 GHz. However, the directivity is only well known at precisely 75 ohms, and the directivity at other impedances should be assumed to be that specified by the manufacturer. For best performance, the bridge should be connected directly to the cable connector, with no intervening cable in between.

The directivity of the bridge could be determined at impedances other than 75 ohms, by changing the impedance and measuring the resulting values. With a vector network analyzer, this can be done by changing the reference impedance to the new value, say 76 ohms, changing the bridge to that value, and measuring the impedance on a Smith chart display. The difference from exactly 75 ohms represents the directivity at that impedance.

For fixed bridge methods, the reflection port is often connected to the cable connector through a length of test lead. A one-port calibration is performed at the end of the test lead. The directivity will again be set by the load, but any change in return loss of the test lead due to flexing will degrade the directivity of the measurement system. In both fixed and variable bridge measurements, the repeatability and noise floor of the analyzer may limit the system measurement. A convenient way to determine the limitation of the measurement system is to perform a calibration, make the desired measurement, then re-connect the load to check the effective directivity. A very good result will be better than -80 dB return loss of the load. Typically, flexure in the test leads, connector repeatability, or noise floor in the network analyzer will limit the result to between -60 to -40 dB. If the result is better than -49 dB, then the system repeats better than the load specification for the best available 75 ohm loads. Thus, the effective directivity should be taken to be the load spec of -49 dB. It is possible to reduce this limitation by having loads certified for better return loss.

Measurement Uncertainty for Impedance Measurements

The fixed bridge method calculates the cable impedance by averaging the impedance of the cable over frequency. The variable bridge uses a reading of the impedance from the dial on the bridge. The directivity at any impedance can be determined, as stated earlier, but only to the limit of the return loss of the load, and the system repeatability. Table 1.2 shows the effect of directivity on cable impedance measurement uncertainty.

z_{DUT}	Directivity		P_m	Z_m	Error
74	-.01	40 dB	-.0167	72.5	±1.5Ω
74	+.01		+.0032	75.5	
74	-.00562	45 dB	-.0123	73.2	±0.8Ω
74	+.00562		-.0011	74.8	
74	-.004	48 dB	-.0107	73.4	±0.6Ω
74	+.004		-.0027	74.6	

Table 1.2 Effect of directivity on cable impedance

The cable to connector adapter can have a significant effect on the impedance measurement. With the variable bridge method, the operator determines what is the appropriate setting, taking into account the capacitive tuning adjustment. With the fixed bridge method, it is also possible to compensate somewhat for the connector. However, it is often the case that the cable impedance is determined by the low frequency response, up to perhaps 200 MHz to 500 MHz, where the connector mismatch effects are still small. The choice of frequency span to measure cable impedance can itself affect the value obtained for cable impedance. In general, as the connector return loss becomes worse, it will have a greater effect on the resulting impedance measurement. The uncertainty caused by the connector is difficult to predict, but large errors could occur if the low frequency return loss is compromised to achieve better high frequency structural return loss.

Finally, note that since both methods average, in some way, the measurement over the entire frequency range, it is probable that the worst case error will never occur at all frequencies, and with the same phase. In fact, it is more likely that the errors will cancel to some extent in cable impedance measurements. Also, the loads that are used will invariably be somewhat better than specified, especially over the low frequency range. From this, it is reasonable to assume that the errors in impedance measurements are at least 50% less than listed in the above table.

Measurement Uncertainty for Structural Return Loss

The same factors that effect cable impedance - directivity, system and test lead stability, and cable connector mismatch - also affect structural return loss. However, since structural return loss is measured at all frequencies, it is much more likely that a worst case condition can occur at any one frequency. For that reason, the measurement uncertainty must include the full effect of the above listed errors. Figure 5 shows a graph of measurement uncertainty curves for a -40 dB error term applied to various return loss values. The upper trace is return loss plus error, the bottom term is return loss minus error, and the middle curve, which must be a straight line, is simply the return loss with no error. The x-axis is the value of the return loss, and the y-axis is the value measured, with the error added or subtracted.

Notice as the return loss gets larger (closer to 0 dB) the effect of the error is smaller. Figure 6 is the same plot, shown for a -49 dB error term. One use for this graph is to determine the measurement guard band needed to specify cable performance. If the cable is to meet a -30 dB spec., with -49 dB system, then the value of -31 dB must be measured to guarantee - 30 dB. Graphically, if the a spec line is drawn vertically through the x-axis at -30 dB, the lower uncertainty trace shows the value on the y-axis that must be measured to guarantee the spec.

Conversely, if a cable is shipped with value of -35 dB for structural return loss, the value that might be measured by a second system in the field can be determined by drawing a vertical line through the x-axis at -35 dB. The upper and lower traces show, on the y-axis, the limits with which the cable SRL can be determined. For this example, the -35 dB cable could measure as bad as -33.5 dB, or as good as -37 dB. But this is not the whole picture. If the first measurement of the cable was performed on a similar system, it will have a similar uncertainty. For this example, a cable measured as -35 dB on the first system could be as bad as -31.5 dB. This could be measured on a second system as good as -35 dB (if the directivity error is exactly the same magnitude and phase as the first system), or as bad as -30.5 (where the directivity magnitude is the same, but the phase is opposite). Fortunately, as with impedance measurements, the directivities are unlikely to be worst case in magnitude at the same frequency and with opposite phase on two different systems.

Return Loss Uncertainty, -40 dB system

(-dB)

(-dB)

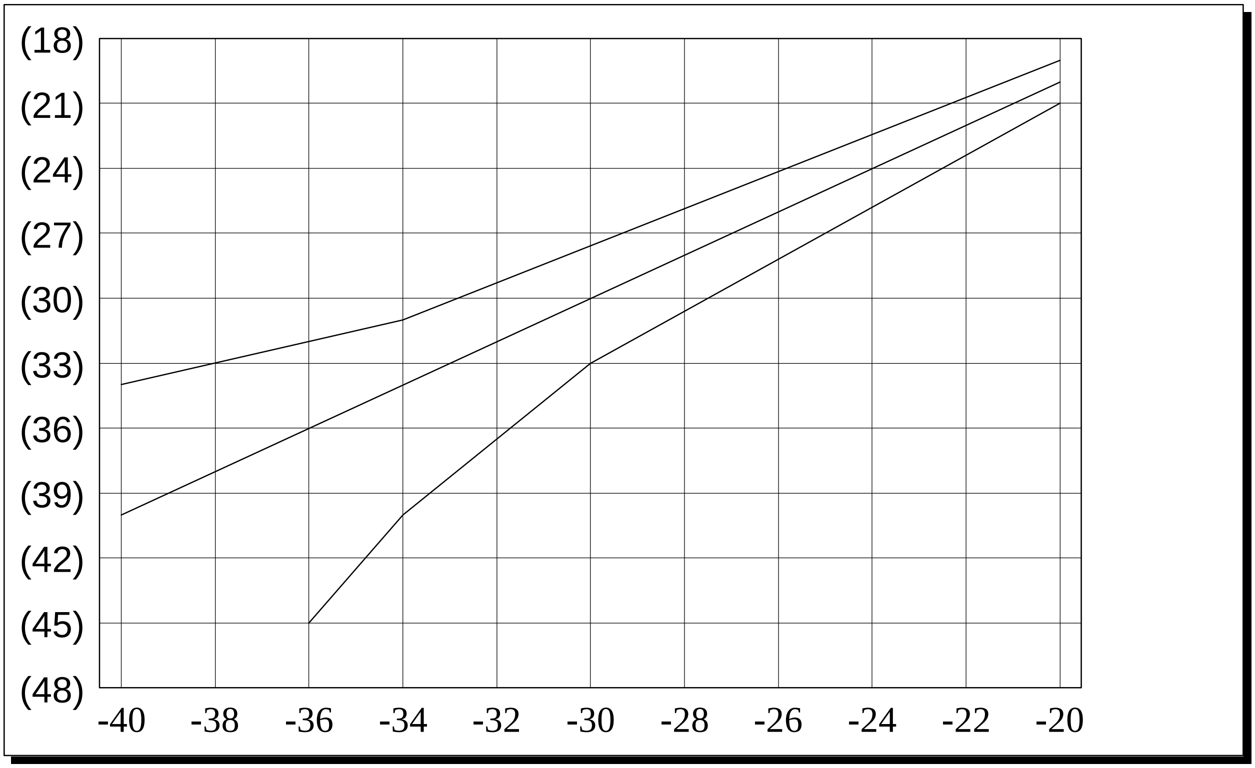


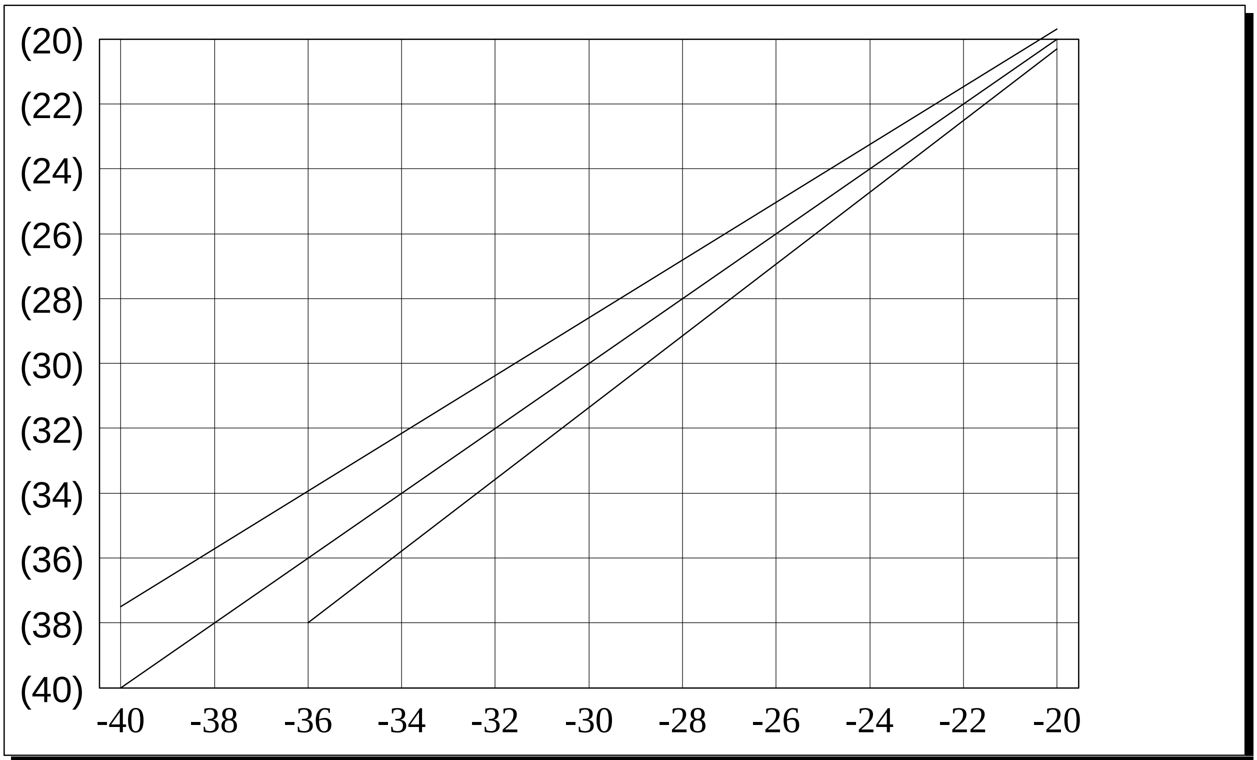
Figure 5. Return Loss of Device-Under-Test

DUT R.L Measured	Minimum	Nominal	Maximum
-40.000	-313.071	-40.000	-33.979
-33.453	-38.977	-33.453	-30.103
-29.762	-32.956	-29.762	-27.432
-27.180	-29.435	-27.180	-25.393
-25.193	-26.936	-25.193	-23.742
-23.576	-24.998	-23.576	-22.355
-22.214	-23.414	-22.214	-21.160
-21.037	-22.075	-21.037	-20.109
-20.000	-20.915	-20.000	-19.172

Table 1.3 Uncertainty "window" for -40 dB directivity system

Return Loss Uncertainty, -49 dB system

(-dB)



DUT R.L Measured	Minimum	Nominal	Maximum
-40.000	-43.742	-40.000	-37.393
-32.041	-33.351	-32.041	-30.903
-27.959	-28.754	-27.959	-27.230
-25.193	-25.764	-25.193	-24.657
-23.098	-23.544	-23.098	-22.674
-21.412	-21.777	-21.412	-21.061
-20.000	-20.309	-20.000	-19.701

Table 1.4. Uncertainty for -49 dB directivity system

Appendix A. SRL Equations

P_{ref} = Reflected Power

P_{in} = Incident Power

L = Cable Loss

Γ = Reflection Coefficient of bump

$$P_{ref} = [P_{in}L\Gamma L] + [P_{in}L(1-\Gamma)L\Gamma LL] + [P_{in}L(1-\Gamma)L(1-\Gamma)L\Gamma LLL] + \ldots$$

$$P_{ref} = [P_{in}\Gamma L^2] + [P_{in}L^2(1-\Gamma)\Gamma L^2] + [P_{in}L^3(1-\Gamma)^2\Gamma L^3] + \ldots$$

$$P_{ref} = [P_{in}\Gamma L^2] + [P_{in}\Gamma(1-\Gamma)L^4] + [P_{in}\Gamma(1-\Gamma)^2 L^6] + [P_{in}\Gamma(1-\Gamma)^{n-1}L^{2n}] + \ldots$$

$$P_{ref} = \sum_{n=1}^{\infty} P_{in}\Gamma(1-\Gamma)^{n-1}L^{2n}$$

$$S_n = \sum_{n=1}^{n} P_{in}\Gamma(1-\Gamma)^{n-1}L^{2n}$$

$$S_n = P_{ref} = [P_{in}\Gamma L^2] + [P_{in}\Gamma(1-\Gamma)L^4] + [P_{in}\Gamma(1-\Gamma)^2 L^6] + \ldots [P_{in}\Gamma(1-\Gamma)^{n-1}L^{2n}]$$

$$(1-\Gamma)L^2 S_n = [P_{in}\Gamma(1-\Gamma)L^4] + [P_{in}\Gamma(1-\Gamma)^2 L^6] + \ldots [P_{in}\Gamma(1-\Gamma)^{n-1}L^{2n}] + [P_{in}\Gamma(1-\Gamma)^n L^{2(n+1)}]$$

$$S_n - (1-\Gamma)L^2 S_n = [P_{in}\Gamma L^2] - [P_{in}\Gamma(1-\Gamma)^n L^{2(n+1)}]$$

$$n \overset{\lim}{\rightarrow} \infty \; S_n[1-(1-\Gamma)L^2] = [P_{in}\Gamma L^2] - 0 \qquad L < 1,\ \Gamma < 1$$

$$P_{ref} = S_\infty[1-(1-\Gamma)L^2] = P_{in}\Gamma L^2$$

$$P_{ref} = \frac{P_{in}\Gamma L^2}{1-(1-\Gamma)L^2}$$

$$P_{ref} = \frac{P_{in}\Gamma L^2}{1-(1-\Gamma)(L^2)}$$

where $\Gamma \ll 1$ & $L \ll 1$

$$P_{ref} = \frac{P_{in}\Gamma L^2}{1-L^2}$$

$$\rho = \frac{P_{ref}}{P_{in}}$$

$$\rho_{SRL} = \frac{\Gamma L^2}{1-L^2}$$

$$P_{SRL} = \frac{\Gamma_{individual}L^2}{1-L^2}$$

$$L = \frac{Loss}{Length} \times \frac{Wavelength}{2}$$

Appendix B. Example calculations of SRL equation constants.

<u>TX 10 - 840 Cable @ 100 MHz</u>

-1.41 dB/100 m = -.0141 dB/m

$\lambda = \frac{c}{f} = \frac{3\times10^8 m}{1\times10^8} = 3m$

$\frac{\lambda}{2} = 1.5m$

$L = -.0141 dB/m \times 1.5m$

$L = -.0212 dB/bump$

$20\log(L) = -.0212$

L = .997568

$L^2 = .995142$

$1 - L^2 = .004858$

$\frac{L^2}{1-L^2} = 204.85$ Bumps

<u>TX 10 - 840 Cable @ 500 MHz</u>

.0328 dB/m   λ = .6m

$L = -.019680$ dB = .997737

$L^2 = .995479$

$1 - L^2$ = .004521

$\frac{L^2}{1-L^2} = 220.2$ Bumps

<u>TX 10 - 840 Cable @ 1 GHz</u>

4.89 dB/100m = .0489 dB/m

λ = .3 m

$\frac{\lambda}{2} = .15m$

L = -.077335 dB = .999156

L^2 = .998312

1 - L^2 = .001688

$\frac{L^2}{1-L^2} = 591.4 \ Bumps$

<u>Distance into cable</u>

591.4 bumps $\times \frac{\lambda}{2} =$ 88.7 m

220.2 bumps $\times \frac{\lambda}{2} =$ 132.1 m

204.8 bumps $\times$ 1.5k = 307 m