

## WIDEBAND MEASUREMENT OF NONSTANDARD TRANSMISSION PATHS

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## ABSTRACT

This paper presents a means of interpreting the measurements of attenuation of non-50-ohm transmission paths when the measurements are made on a 50-ohm system. Nonstandard transmission paths are modeled as lossy lengths of transmission line. Equations are derived to calculate the transmission parameters of a nonstandard transmission path derived from its scalar  $S_{21}$  parameters when measured on a 50-ohm scalar analyzer. The parameters can then be used for calculating the response of the path interfacing other impedances.

## INTRODUCTION

In both radio frequency interference (RFI) and electromagnetic pulse (EMP) assessment technologies, it is necessary to find the rf attenuation of the transmission path from the exterior of an electronic system to an interior damageable or upsettable component. The undesired electromagnetic energy is coupled either to an antenna out of band or to an unshielded wire, which acts as an antenna; in either case, the "antenna" is exterior to the system. The interior damageable or upsettable component is typically a receiver mixer, amplifier, or buffer amplifier associated with the wire exiting the system housing; this component is usually a semiconductor junction. The transmission paths are typically wires in a bundle or printed circuit conductors; generally, these have been analyzed theoretically to give characteristic impedances in the 100- to 200-ohm region and appear quite lossy because of their poor dielectrics and irregularities in structure. At lower frequencies the transmission path can be represented by lumped-circuit elements, but at higher frequencies parasitics of the discrete components dominate the transmission characteristics; thus, other measurement and computational methods must be used to accurately represent the coupling paths.

Since network analyzers measure transmission path characteristics with reference to 50 ohms, these characteristics do not change when the transmission path interfaces with other 50-ohm

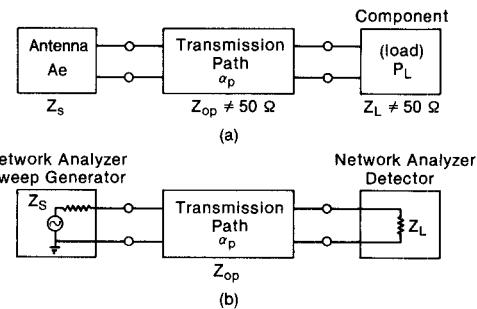


Figure 1. Block diagram showing (a) typical system transmission path and (b) network analyzer set up to measure transmission loss.

circuits; however, most coupling structures (input ports) tend to be in the 25- to 100-ohm range, semiconductor components (output ports) tend to be in the 5- to 20-ohm range, and the transmission paths (wires and circuit boards) tend to be in the 100- to 200-ohm range. The characteristics of transmission paths normalized to 50 ohms are not therefore directly usable. Despite the problems that arise from mismatched characteristic impedances, the typical approach in RFI assessments is to use the attenuation measured with respect to 50 ohms in coupling calculations, with the hope that the errors of mismatching characteristic impedances are not large enough to introduce large errors in the assessment.

Presented here is a means of interpreting measurements of attenuation through non-50-ohm paths when the measurements are made on a 50-ohm system. The results are used to calculate the errors from approximations made ignoring mismatches, and to set forth a simple means for improving the accuracy of assessments.

Figure 1a depicts the three major areas of the system transmission path: the energy collector or "antenna," the transmission path, and the critical component that affects the system operation. To determine the exterior radiation power density required to affect the critical system component, we must know the power threshold of the component,  $P_L$ , at which the damage or upset

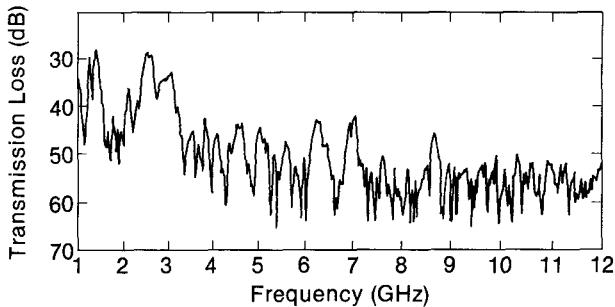


Figure 2. Transmission loss for a typical radio receiver out-of-band.

is induced; the transmission path loss,  $\alpha_p$ ; and the effective aperture (area),  $A_e$ , of the energy collector. With these three parameters characterized as a function of the incident radiated frequency polarization, modulation, and illumination angle, it is possible to calculate the radiation power density required to degrade the system.

Although each of the three parameters is important to characterize the susceptibility threshold of a system, the largest contributor is normally  $\alpha_p$ , the transmission loss of the path from the antenna output to the component input. The transmission loss is critical because it is a direct measure of the amount of undesired rf that can reach the critical system components and potentially damage or upset them.

Ideally, the attenuation of the transmission path from the antenna output to the component input should be measured with instrumentation that has the same impedances as the system interfaces and therefore introduces no mismatch errors in the transmission loss measurement. However, because the incident rf energy may in fact be anywhere over a wide band of frequencies, the transmission path attenuation of the system must be measured over that wide bandwidth. The interfaces between the system and the instrumentations are not designed for these frequencies, and so are typically not matched to each other. A typical setup used to measure the outside-band transmission loss of a system is shown in figure 1b.

Figure 2 shows the transmission loss of a typical radio receiver as a function of frequency. The transmission loss has an uncertainty associated with it, as shown by the random fluctuations in the attenuation (see figure 3). The problem is that when the transmission loss of a system is measured with instrumentation not matched to it (typically 50 ohms), we do not know the uncertainty between the attenuation measured,  $\alpha_p(\text{meas})$ , and the actual system transmission loss,  $\alpha_p(\text{syst})$ . Ideally this uncertainty should be added to that observed in the measured transmission loss, and any adjustments in average level should be made. Uncertainties add as the root of the sum of their squares, causing the largest one to overpower the smaller ones.

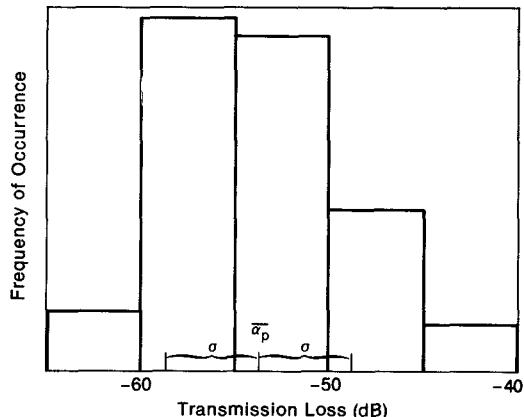


Figure 3. Distribution of transmission loss of figure 2 for frequencies above 3.3 GHz.

#### APPROACH

The approach taken in the study was to determine the amount of measurement error

$$\text{Error} = \frac{S_{21}(\text{syst})}{S_{21}(\text{meas})} \quad (1)$$

that could occur using a nonmatched instrumentation system to measure the transmission loss of a system; we then determined the impact of this measurement error on the power density estimates used for the electromagnetic vulnerability assessments. The error is dictated by the source,  $Z_s$ , and load,  $Z_L$ , impedances of the system, and the effective characteristic impedance of the transmission path,  $Z_{Op}$ .

The forward transmission coefficient  $S_{21}$  for a section of lossy TEM transmission line can be derived using ABCD parameters and is given by [ref. 1]

$$S_{21} = \sqrt{Z_s/Z_L} \frac{2}{\eta \cosh \gamma l + \epsilon \sinh \gamma l} \quad (2)$$

where

$Z_{Op}$  = line characteristic impedance,

$Z_s$  = source impedance,

$Z_L$  = load impedance,

$\gamma$  =  $\alpha' + j\beta$ ,

$\alpha'$  = attenuation in nepers per unit length,

$\beta$  = propagation constant ( $2\pi/\lambda$ ),

$\lambda$  = wavelength on the transmission line,

$l$  = length of transmission line, and

$$\eta = \frac{1}{2} \left[ 1 + \frac{Z_s}{Z_L} \right] \quad ; \quad \epsilon = \frac{1}{2} \left[ \frac{Z_{Op}}{Z_L} + \frac{Z_L}{Z_{Op}} \right]. \quad (3)$$

In general, the value of  $S_{21}$  oscillates between upper and lower boundary curves as a function of frequency. If the value of  $S_{21}$  is needed only at the transmission peaks, equation (1) reduces to

$$S_{21} = \frac{(-1)^n}{\eta \cosh \alpha' l + \epsilon \sinh \alpha' l} \quad (4)$$

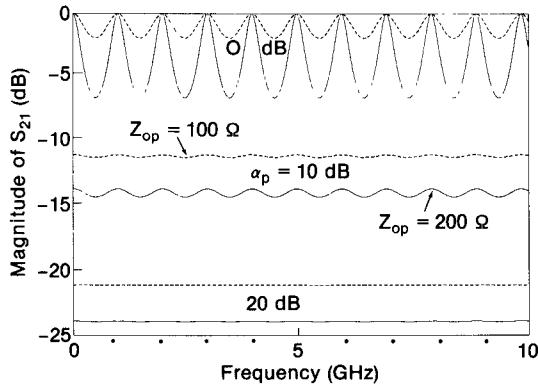


Figure 4. Calculated transmission path loss for low values of path loss.

where  $n = 0, 1, 2, 3 \dots$  when the line is  $0, \frac{1}{2}, 1, 1 \frac{1}{2}$  wavelengths long. The error is then given by

$$\text{Error(dB)} = 20 \log_{10} \frac{\cosh \alpha' l + \epsilon_{50\Omega} \sinh \alpha' l}{\eta_{\text{syst}} \cosh \alpha' l + \epsilon_{\text{syst}} \sinh \alpha' l} \quad (5)$$

The error is the difference in decibels between the measured value of  $S_{21}$  and the value of  $S_{21}$  in the real system at the peaks of  $S_{21}$ . The error can also be derived for the minimum transmission peaks.

If the attenuation of the transmission line is sufficiently high, equation (5) reduces to

$$\text{Error(dB)} =$$

$$20 \log_{10} \frac{\sqrt{Z_s Z_L}}{50} \frac{[Z_{0p} + 50]^2}{(Z_{0p} + Z_s)(Z_{0p} + Z_L)} \quad (6)$$

and is a function of the source, line, and load impedances alone.

#### CALCULATIONS

The transmission loss for a wide range of source impedances, path characteristic impedances, and load impedances was calculated to determine the general performance parameters of the error function. For low path loss there was a periodic fluctuation in the path loss due to the interaction of the mismatches at the ends. For high path loss there was no interaction, and the loss tended to remain constant over the full frequency range of the calculations. For high path loss the system loss could be fully accounted for by the path attenuation and the mismatch losses at each end.

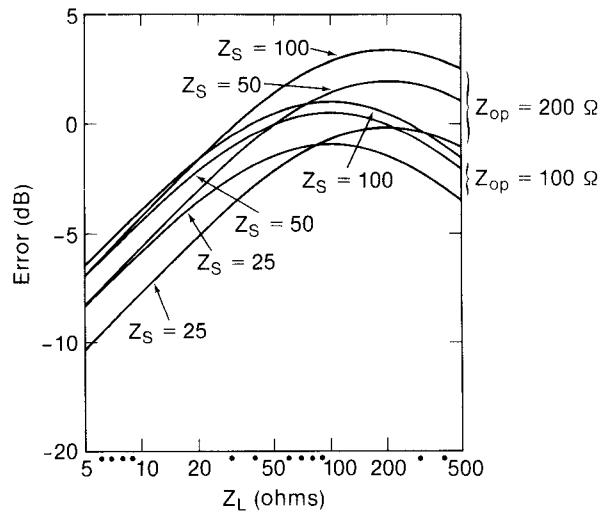


Figure 5. Errors for transmission loss of a path in a system for a range of system parameters for path loss higher than 20 dB.

Figure 4 shows the calculated loss of a transmission path 6 in. long and having 0-, 10-, and 20-dB attenuation as it would be measured in a 50-ohm network analyzer. The differences between the curves and the 0-, 10-, and 20-dB attenuations are ascribed to the mismatches to the 50-ohm network analyzer and their interactions. Significantly, when the transmission loss is 20 dB or higher, the fluctuations in transmission loss due to the interactions of the mismatches at the ends are obscured by the loss of the path, and the path loss is dominated by the attenuation of the line and the individual mismatches at the ends of the lines. Therefore, the representation of the path is considerably simplified for those paths having 20 dB or more of loss.

The errors for lines with high attenuation were calculated for the range of parameters expected in systems, giving the errors shown in figure 5. For systems having semiconductor junctions as their damageable/upsettable load (5 to 20 ohms), the error is bracketed by -2 and -10 dB. Two-thirds of the area ( $\pm 1$  sigma) is between -4 and -8 dB, giving the distribution of  $-6 \pm 2$  dB.

The path loss measured in a typical system, given in figures 2 and 3, was  $53 \pm 5$  dB. Solving equation (3) for  $S_{21}(\text{syst})$  gives

$$S_{21}(\text{syst}) = S_{21}(\text{meas}) + \text{Error} \quad (7)$$

$$\begin{aligned} S_{21}(\text{syst}) &= (-53 \pm 5) + (-6 \pm 2) \\ &= -59 \pm 5.4 \text{ dB} \end{aligned}$$

The increase in uncertainty is insignificant and only the average amount of mismatch needs to be added to the attenuation measured.

#### CONCLUSIONS

When nonstandard transmission lines are measured on a 50-ohm network analyzer or scalar analyzer, their mismatches contribute to errors in measurements. The uncertainty in these errors is small when the attenuation of the line is higher than 10 dB and insignificant when the attenuation is higher than 20 dB. The error from average mismatch, however, should be factored in, to correct the parameters measured. Most paths that show low losses will be standard characteristic impedances, and they can be measured with the correct input and output characteristic impedances, producing no additional error from mismatches. Should a low-loss path be a nonstandard characteristic impedance, the only way to characterize it would be to use the full complex parameters measured on the network analyzer for the path and for items connected to each end of the path, and combine them using complex arithmetic.

#### REFERENCE:

- (1) R. W. Beatty and D. M. Kerns, "Relationships Between Different Kinds of Network Parameters Not Assuming Reciprocity or Equality of the Waveguide or Transmission Line Characteristic Impedances," Proceedings of the IEEE, January 1964, Vol. 52, p. 84.