



Dramatic Noise Reduction using Guard Traces with Optimized Shorting Vias

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Abstract

Guard traces are sometimes used in high-speed digital and mixed signal applications to reduce the noise coupled from an aggressor transmission line to a victim line. Sometimes guard traces are effective, and sometime they are not, depending on the topology and end connections to the guard trace.

Optimized design guidelines for using guard traces in both microstrip and stripline transmission line topologies are identified based on the mechanisms by which they reduce cross talk. By correct management of the ends of the guard trace, a guard trace can reduce coupled noise on a victim line by an order of magnitude over not having the guard trace present. However, if the guard trace is not optimized, the cross talk on the victim line can also be larger with the guard trace, than without.

Author(s) Biography

Eric Bogatin received his BS in physics from MIT and MS and PhD in physics from the University of Arizona in Tucson. He has held senior engineering and management positions at Bell Labs, Raychem, Sun Microsystems, Ansoft and Interconnect Devices. Eric has written 6 books on signal integrity and interconnect design and over 300 papers. His latest book, *Signal and Power Integrity- Simplified*, was published in 2009 by Prentice Hall. He is currently a signal integrity evangelist with Bogatin Enterprises, a wholly owned subsidiary of Teledyne LeCroy. He is also an Adjunct Associate Professor in the ECEE department of University of Colorado, Boulder. Many of his papers and columns are posted on the www.BeTheSignal.com web site.

Lambert (Bert) Simonovich graduated in 1976 from Mohawk College of Applied Arts and Technology, Hamilton, Ontario Canada, as an Electronic Engineering Technologist. Over a 32-year career, working at Bell Northern Research/Nortel, in Ottawa, Canada, he helped pioneer several advanced technology solutions into products. He has held a variety of engineering, research and development positions, eventually specializing in high-speed signal integrity and backplane architectures. After leaving Nortel in 2009, he founded Lamsim Enterprises Inc., where he continues to provide innovative signal integrity and backplane solutions as a consultant. With three patent applications, and two patent grants to his name, he has also authored and coauthored several publications; posted on his web site at www.lamsimenterprises.com. His current research interests include: high-speed signal integrity, modeling and characterization of high-speed serial link architectures.



Introduction

Guard traces are important elements in many low noise designs. In low frequency analog designs, guard traces are critical to prevent surface leakage noise currents flowing to a very sensitive high-impedance victim receiver. The design guidelines are simple in these applications: surround the sensitive victim line with a guard trace and bias it to the same DC voltage as the victim line.

Guard traces are also sometimes used in high-speed digital and mixed signal applications to reduce the noise coupled from an aggressor transmission line to a victim line, with very different design guidelines. Sometimes guard traces are effective, and sometimes they are not, depending on the topology and end connections to the guard trace.

It is important to note that in most high speed digital applications, -50 dB isolation is perfectly adequate and there is never a need for a guard trace. It is only when more than -60 dB isolation at high interconnect density is critical should a guard trace be considered.

In this paper the optimized design guidelines for using guard traces in both microstrip and stripline transmission line geometries are identified based on the mechanisms by which they reduce cross talk. We show there are two mechanisms by which guard traces can reduce, and in some cases, increase, crosstalk between two transmission lines: by affecting the fringe electric and magnetic field coupling directly between aggressor and victim lines and by “re-infecting” or “polluting” the victim line from noise which is coupled onto the guard trace.

We further show that how the ends of the guard trace are implemented: open, terminated or shorted, dramatically affects the reflections of the induced noise on the guard trace, and this in turn can have a dramatic impact on the total noise induced on the victim line. In fact, by correct management of the ends, a guard trace can reduce coupled noise on a victim line by an order of magnitude over not having the guard trace present. However, if the guard trace is not optimized, the cross talk on the victim line can also be larger with the guard trace, than without.

Design guidelines for using guard traces offered in application notes and in discussion groups are more often based on folklore than engineering. This is mostly due to confusion, misconceptions, and just plain incorrect physics applied to the mechanisms to explain how guard traces can lower cross talk.

Many transient simulators with integrated 2D field solvers can simulate the impact of a guard trace on near and far end cross talk. However, without an understanding of the



mechanism by which a guard trace affects the crosstalk, the results are little more than an empirical observation of a specific configuration.

In this paper, we show how to analyze and separate the two mechanisms by which guard traces affect aggressor-victim crosstalk. Using simulated S-parameters from both 3D planar field solvers and 2D field solvers, we show how to use the capacitance and inductance per unit length matrix elements and how these aggressor-victim matrix elements are affected by a guard trace.

The values of the aggressor-to-victim matrix elements vary with geometry. By comparing the matrix elements with and without a guard trace present, the specific contribution to electric and magnetic field coupling can be separated for microstrip and stripline geometries. From the capacitance and inductance matrix elements, the near and far end cross talk coefficients can be estimated.

Any noise induced on the guard trace will act as a signal source to re-infect the victim line. The magnitude and direction of propagation of this noise on the guard trace has a profound effect on the noise induced on the victim line. Based on the direction of propagation of the noise on the guard trace, the total noise on the victim line can be calculated.

This paper analyzes the magnitude of these two mechanisms, the absolute benefit of a guard trace, and the optimized end configuration. We show in what topologies a guard trace offers no advantage, but considerable risk, and when high isolation is important, how to successfully implement guard traces.

Finally, we explore the impact on the via model used to short the ends of the guard trace and the impact of distributed shorting vias down the length of the guard trace. The results are rather surprising.

Discussion

Near-end and Far-end Crosstalk

There will be cross talk between two uniform transmission lines having a wide return path, such as a plane [1]. Because the signature of the noise at the two ends of the victim line look very different, we label the ends differentially. The signal on the aggressor defines the forward direction. The end of the victim line, near the source, is the backward end, while the other end is the forward end, which is far from the source, as seen in Figure 1.

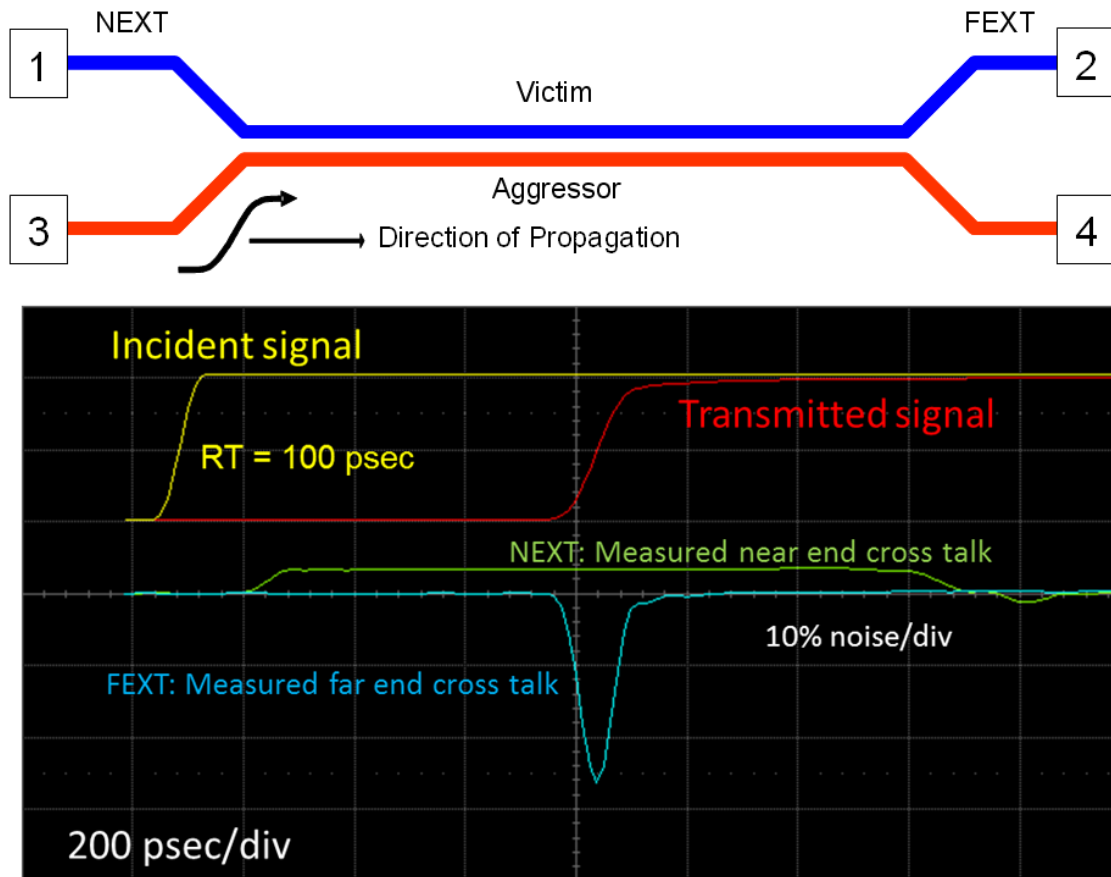


Figure 1 Illustration of the near and far end cross talk and an example of the noise signatures in closely coupled microstrip traces, measured with a Teledyne LeCroy SPARQ Signal Integrity Network Analyzer. Incident and transmitted waveforms 0.5V/div. NEXT and FEXT waveforms 100 mV/div. As the aggressor (incident) signal propagates from port 3 to port 4, near end noise appears on port 1 initially and far end noise appears on port 2 after one Time Delay (TD) of the coupled length.

In this measured example of two closely coupled microstrips, each about 5 mils wide and 5 mil spaced, with a coupled length of about 4 inches, the near end noise is about 4% of the incident signal and the far end noise peak value is about 25% of the transmitted signal.

Many 2D field solver tools allow the calculation of the coupling between two uniform transmission lines. In this paper, Agilent’s EEsofEDA, Advanced Design System (ADS)[5], which has an integrated boundary element field solver, was used to simulate the near and far end noise under a variety of situations.

Figure 2 is an example of the simulated near and far end cross talk of a similar structure as measured: two 50 Ohm microstrips, 5 mil wide, 5 mil space, 4 inch coupled length and a rise time of 100 psec.

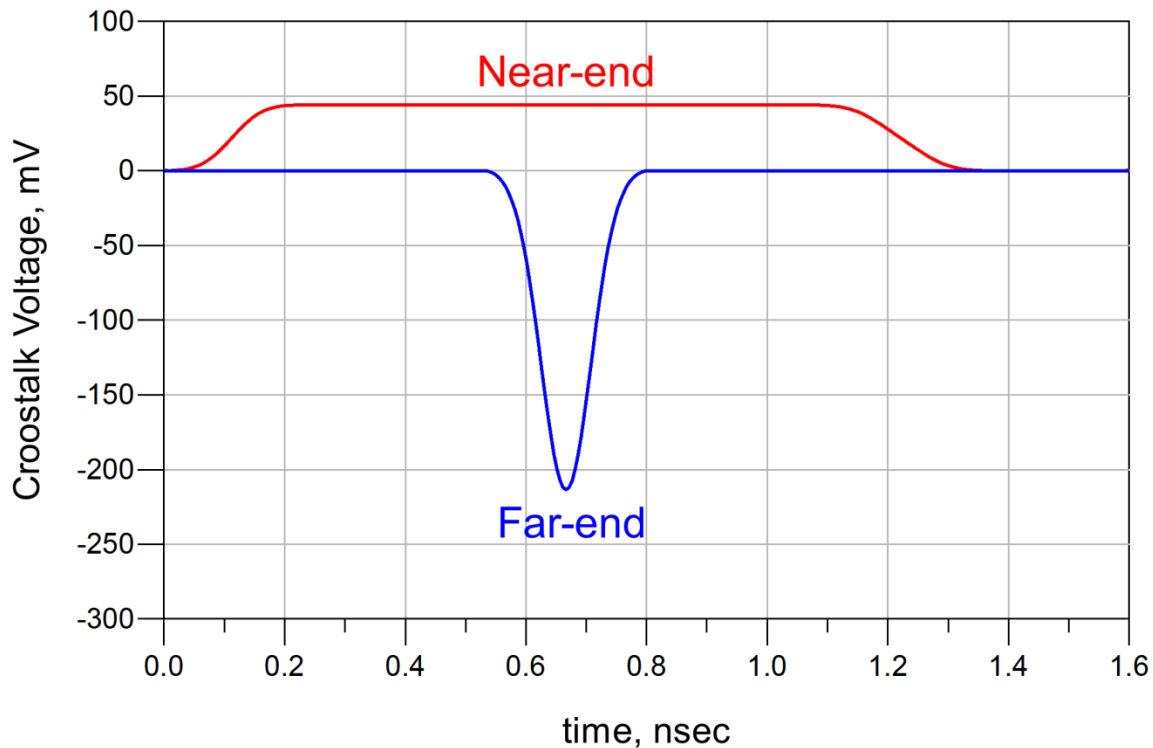


Figure 2. Near and far end cross talk simulated with ADS with an aggressor signal of 1 V at Port 3.

The ADS simulation reproduces the general features of the measured near end noise: the turn on with the rise time of the aggressor, saturating in value after 1 rise time, and lasting for a round trip time, $2 \times TD$. The magnitude of the near end noise is closely matched at about 4% of the incident signal value of 1V.

The far end features are also reproduced in the simulation: the far end noise coming out of port 2, $1 \times TD$ later and the sharp dip with a magnitude of about 22% of the signal value. Since the far end is linearly sensitive to rise time, matching the same rise time between measurement and simulation is always a challenge.

These noise signatures are due to the combination of two important essential principles [2]:

- At any instant in time, the only place noise is induced from the aggressor to the victim is where the transitioning edge is on the aggressor line.
- Any signal, once on a transmission line, will propagate down the line.

These principles mean that once induced, noise on the victim line propagates on the victim line to arrive at the two ends on the victim line. It is not static, but just as dynamic as the signal on the aggressor. The noise seen at the near end of the victim line has been propagating in the backward direction on the victim line. The noise seen at the far end of the victim line has been propagating in the forward direction on the victim line. Using these simple principles the role of guard traces can be easily understood.

The Guard Trace

By definition, a guard trace is a trace routed coplanar between two transmission lines. Since it is a common practice, as a design rule, to specify the minimum spacing to be the same as the line width, the separation needs to be at least three times the line width in order to fit a guard trace. In this paper, a line width of 5 mils and minimum space of 5 mils is used as a baseline.

The guard trace can be left floating, terminated at each end in its characteristic impedance, or shorted to ground. Design guidelines, offered in application notes and in discussion groups, often cite the guard trace should be shorted to ground, at regular intervals along its length, using stitching vias, spaced at 1/10th of a wavelength of the highest frequency component of the aggressor's signal, as illustrated in Figure 3.

In this paper we show that this design guideline comes with caveats, and that in some cases, we show that there is no benefit to stitching the guard trace at all.

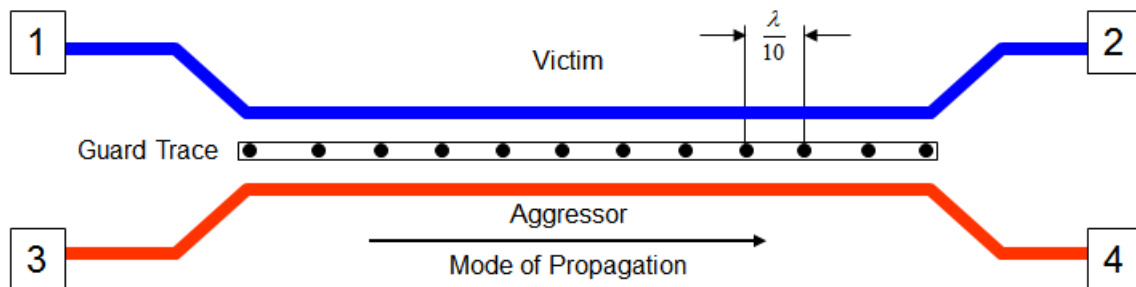


Figure 3 Illustration of guard trace with stitching vias spaced at $\lambda/10$ between aggressor and victim traces.

Building Simple Scalable Circuit-based Models

Agilent's ADS was used exclusively to model and simulate the various topologies. The TLines-Multilayer pallet is a 2D field solver with a variety of coupled transmission line models. These models are implemented as the solution of Maxwell's Equations using the

boundary element method for the two-dimensional cross-section geometry that is defined by the model parameters.

Modeling Methodology

The methodology used for this study was to build four parameterized coupled transmission line topologies:

- Topology 1 - Microstrip without a guard trace
- Topology 2 - Microstrip with a guard trace
- Topology 3 - Stripline without a guard trace
- Topology 4 - Stripline with a guard trace

In order to simulate a guard trace, with ideal stitching vias, topologies 2 and 4 were built with 8 sections of ML3CTL_V (3 Coupled Lines, Variable Width and Spacing) transmission line models as shown in Figure 4. The length of each section was parameterized to facilitate changing the spacing. The ground stitching and the end-termination resistors can be deactivated and/or shorted as required. A 0-2 v VtPulse source, with a 0.1 nsec 10-90 rise time, was used for the aggressor in transient analysis, with a 50 Ohm source impedance so the signal launched on the aggressor, at Port 3 was exactly 1 V.

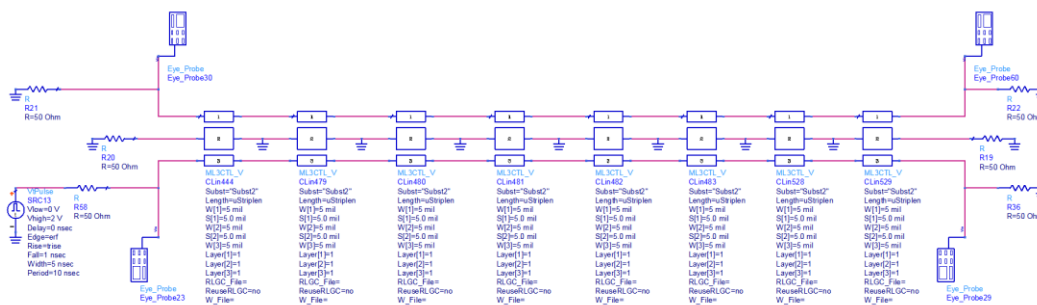


Figure 4 Example of generic circuit model for topologies with guard traces.

Topologies 1 and 3, with no guard traces, were built with 8 sections of ML2CTL_V (2 Coupled Lines, Variable Width and Spacing) transmission line models as shown in Figure 5. Both the length and spacing between tracks were parameterized in order to easily adjust the topologies for comparisons.

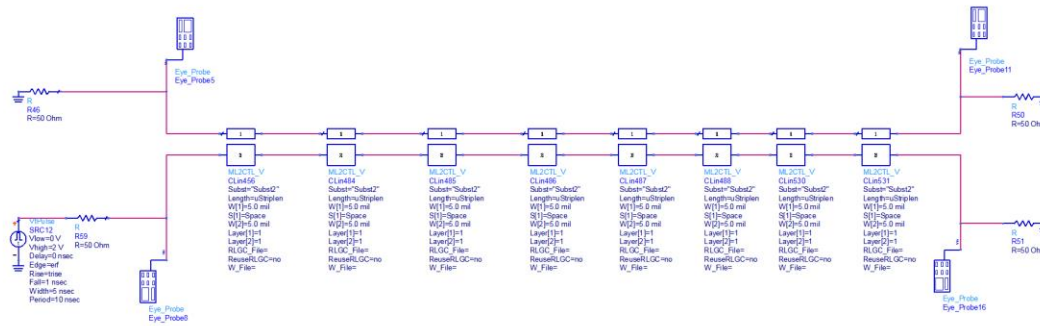


Figure 5 Example of generic circuit model for topologies without guard traces.

The cross section was selected using a $Dk = 3.6$ and thicknesses adjusted for 50 Ohm impedance lines in both stripline and microstrip. In each case the trace was 0.7 mils thick, corresponding to half ounce copper.

The total length of each line was 1.5 inches. For the case of the stripline, the Dk was 3.6. For the case of the microstrip, the effective Dk , based on the contribution of fringe field lines in air, was 2.7.

Analysis of Direct Coupling Between the Aggressor and Victim Lines

Cross talk between two transmission lines, driven by the fringe electric and magnetic fields between them, is described by the Maxwell capacitance and inductance coupling matrices.

The capacitance matrix elements are defined as:

$$C_{ij} = \frac{Q_i}{V_j}$$

Where:

C_{ij} = the Maxwell capacitance matrix element

Q_i = the charge on conductor i when all other conductors are grounded

V_j = the voltage on conductor j when the voltage on all other conductors is 0 v.

In this matrix, the diagonal elements are the “loaded capacitance”, the capacitance between the conductor and ground, when all the other conductors are also grounded. The



off-diagonal elements are the coupling capacitances. These are all negative, indicating that when a +1 V is applied to one conductor, the induced charge on the adjacent conductors is negative.

The inductance matrix elements are defined by:

$$L_{ij} = \frac{V_i}{\left(\frac{dI_j}{dt}\right)}$$

Where:

L_{ij} = the inductance matrix element

V_i = the voltage induced on the i^{th} conductor when current flows only in the j^{th} conductor

dI_j/dt = the changing current in the j^{th} conductor

Ultimately, the near and far end cross talk can be described in terms of the relative size of the matrix elements [3].

$$k_{ne} = \frac{1}{4} \left(\frac{C_{ij}}{C_{ii}} + \frac{L_{ij}}{L_{ii}} \right)$$

And:

$$k_{fe} = \frac{1}{2} \left(\frac{C_{ij}}{C_{ii}} - \frac{L_{ij}}{L_{ii}} \right)$$

Where:

k_{ne} is the near end coupling coefficient

k_{fe} is the far end coupling coefficient

and the C_{ij} matrix elements are taken as positive.

These coupling coefficients can be used to estimate the near and far end crosstalk voltages when the signal on the aggressor is a positive step voltage. The near end cross talk voltage is given by:

$$V_{ne} = V_{\text{signal}} \times k_{ne}$$



The far end cross talk voltage is given by:

$$V_{fe} = V_{signal} \times \left\{ \frac{Len}{RT} \frac{1}{v} \times k_{fe} \right\} = V_{signal} \times \left\{ \frac{Len}{RT} \frac{\sqrt{Dk_{eff}}}{c} \times k_{fe} \right\} = V_{signal} \times \left\{ \frac{1.5}{0.1} \frac{\sqrt{2.7}}{11.8} \times k_{fe} \right\}$$
$$= V_{signal} \times 2.09 \times k_{fe}$$

Where:

V_{ne} = the saturated voltage on the near end of the victim line

V_{fe} = the peak value of far end noise on the victim line

V_{signal} = the magnitude of the signal on the aggressor

Len = the coupled length = 1.5 inches in these examples

RT = the 10-90% rise-time = 0.1 nsec in these examples

k_{ne} = the near end coupling coefficient

k_{fe} = the far end coupling coefficient;

v = the speed of light in the material

c = speed of light in air = 11.8 inch/nsec

Dk_{eff} = the effective dielectric constant the signal will see = 2.7 for this microstrip example

These simple relationships can be used to evaluate the impact from changes in the fringe field coupling directly between two transmissions lines as their spacing is increased and a guard trace is added.

Using the built in 2D boundary element field solver in ADS, the matrix elements and coupling coefficients were calculated for both the 50 Ohm microstrip and stripline aggressor to victim pairs under the three cases:

- Tightly coupled, spacing = 5 mil
- Loosely coupled, spacing = 15 mils
- Loosely coupled with a guard trace inserted between them



For microstrip, the matrix elements and coupling coefficients were calculated with ADS as:

Table 1 Microstrip Matrix Elements

	Cii (pF/in)	Cij (pF/in)	Cij/Cii	Lii (nH/in)	Lij (nH/in)	Lij/Lii	kne	kfe
Tight coupling	2.77	0.116	0.0419	6.97	0.772	0.1108	0.0382	-0.0344
3x spacing, no guard	2.77	0.0177	0.0064	7.00	0.188	0.0269	0.0083	-0.0102
With guard	2.77	0.0136	0.0049	6.97	0.200	0.0287	0.0084	-0.0119

This calculation points out four important observations:

1. Just increasing the separation between the traces, the capacitive coupling between the victim and aggressor drops to less than 15% of the tightly coupled value.
2. Adding a guard trace between the two lines decreases the direct capacitive coupling between the aggressor and victim line slightly.
3. The inductive coupling is decreased to 24% of the tightly coupled value by just increasing the spacing.
4. Adding a guard trace actually increases the inductive coupling between the aggressor and victim line slightly.

In microstrip, the impact on directly coupled noise on the victim line with and without the guard trace is:

1. Adding the guard trace actually increases the near end coupling coefficient by 1%, a negligible amount.
2. Adding the guard trace increases the far end coupling coefficient between the aggressor and victim lines by about 17%.

In a counter-intuitive way, the reduced capacitive coupling, with guard, actually increases the far end coupling coefficient. This is because the far end coupling coefficient is the difference between the relative capacitive and inductive coupling. There is less capacitive coupling to subtract from the inductive coupling.



The directly coupled peak far end noise without a guard trace would be:

$$V_{fe} = V_{signal} \times 2.09 \times k_{fe} = V_{signal} \times 2.09 \times (-0.0102)$$

$$= -V_{signal} \times 2.1\%$$

The directly coupled peak far end noise with a guard trace would be:

$$V_{fe} = V_{signal} \times 2.09 \times k_{fe} = V_{signal} \times 2.09 \times (-0.0119)$$

$$= -V_{signal} \times 2.5\%$$

The same coupling coefficients between the aggressor and victim lines were simulated by ADS for the case of stripline traces:

Table 2 Stripline Matrix Elements

	Cii (pF/in)	Cij (pF/in)	Cij/Cii	Lii (nH/in)	Lij (nH/in)	Lij/Lii	kne	kfe
Tight coupling	3.213	0.333	0.1036	8.119	0.841	0.1036	0.0518	0.0000
3x spacing, no guard	3.162	0.020	0.0063	8.162	0.053	0.0064	0.0032	-0.0001
With guard	3.213	0.002	0.0006	8.118	0.091	0.0112	0.0029	-0.0053

The analysis in stripline points out that:

1. Increasing the separation between the traces, the capacitive coupling between the victim and aggressor drops to 6% of the tightly coupled value.
2. Adding a guard trace between the two lines decreases the capacitive coupling even further, by a factor of 10. This is due to the “thieving” of the aggressor’s field lines by the guard trace that would normally couple to the victim line.
3. The inductive coupling is decreased to about 6% of the tightly coupled value by just increasing the spacing.
4. Adding a guard trace between the aggressor and victim lines actually increases the inductive coupling by almost 2x. The fringe magnetic field lines from the aggressor are distorted by the presence of the guard conductor and are pushed



closer to the victim line. In stripline, with a guard trace present, cross talk will be inductance dominated.

In stripline, the impact on directly coupled noise on the victim line, with and without the guard trace, is:

1. Adding the guard trace has a very slight reduction of less than 10% on the near end coupling coefficient, a negligible amount.
2. Where there is no far end cross talk in just stripline, adding a guard trace will now generate far end cross talk of an amount on the order of half that in microstrip. This is a significant impact.

The peak far end noise expected in stripline with a guard trace is:

$$\begin{aligned}V_{fe} &= V_{\text{signal}} \times 2.09 \times k_{fe} = V_{\text{signal}} \times 2.09 \times (-0.0053) \\ &= -V_{\text{signal}} \times 1.1\%\end{aligned}$$

Often, when guard trace analysis is done, it's only the directly coupled noise from the aggressor to the victim line, as represented by these matrix elements, that is noted. In fact, the additional noise on the victim line, due to re-infection from noise on the guard trace, has a significant impact on the total noise on the victim line.

Analysis of Re-infection between the Guard Trace and Victim on Microstrip

Manually keeping track of the noise induced on the guard trace, and its re-infection onto the victim line, is extremely tedious. It involves two steps. First is identifying the directly coupled re-infected backward and forward noise on the victim line from the voltage on the guard trace. Second is keeping track of the multiple reflections of the noise on the guard trace, based on its end terminations and how the reflected voltages will re-infect the victim line.

When the guard trace is terminated at 50 Ohms, the reflections from the ends play no role and the re-infected noise on the victim line is just from directly coupled re-infected noise on the guard.

The near end coupling and far end coupling between the guard and the victim lines will be the same as represented by the matrix elements above for two closely spaced traces. There are three sources of voltage noise on the guard trace which may contribute to backward and forward noise on the victim line:

1. The initial backward propagating step edge of near end noise on the guard trace.
2. The forward propagating increasingly negative pulse of far end noise on the guard trace.
3. The induced voltage disturbance on the guard trace, coincident with the aggressor's edge.

The initial backward edge of near end noise on the guard will be a step edge with magnitude $V_{\text{ne-guard}} = V_{\text{signal}} \times K_{\text{ne}}$. If it were to reflect from the end of the guard trace, this forward propagating edge would couple near end noise to the victim line of:

$$\begin{aligned} V_{23\text{-ne}} &= V_{\text{signal}} \times k_{\text{ne}} \times k_{\text{ne}} = V_{\text{signal}} \times k_{\text{ne}}^2 = V_{\text{signal}} \times 0.038^2 \\ &= V_{\text{signal}} \times 0.14\% \end{aligned}$$

The peak far end contribution on the victim line, from the re-infection of the reflected near end noise on the guard trace would be:

$$\begin{aligned} V_{23\text{-fe}} &= (V_{\text{signal}} \times k_{\text{ne}}) \times 2.09 \times k_{\text{fe}} = V_{\text{signal}} \times 0.038 \times 2.09 \times (-0.034) \\ &= V_{\text{signal}} \times (-0.56\%) \end{aligned}$$

The far end noise on the guard trace could reflect from the ends of the guard trace and contribute forward noise on the victim line. The signature would be a derivative of the far end noise, with a magnitude on the order of:

$$\begin{aligned} V_{23\text{-fe}} &= (V_{\text{signal}} \times 2.09 \times k_{\text{fe}}) \times 2.09 \times k_{\text{fe}} = (V_{\text{signal}} \times 2.09 \times 0.034) \times 2.09 \times 0.034 \\ &= V_{\text{signal}} \times 0.5\% \end{aligned}$$

The third source of noise on the guard trace is of a different character. As the aggressor signal propagates from left to right, it induces noise on the guard trace which splits in half. Half the current propagates in the forward direction as far end noise and half propagates in the backward direction as near end noise. While these two propagating noise sources directly re-infect the victim, the voltage disturbance on the guard trace coincident with the aggressor signal can also independently re-infect the victim line.

The dV/dt signal on the guard trace will induce capacitively coupled current on the victim line. The dI/dt induced on the guard trace will in turn, induce a counter circulating current loop on the victim line. These two currents will split and propagate on the victim line to generate an effective near end and effective far end noise. These currents are illustrated in Figure 6.

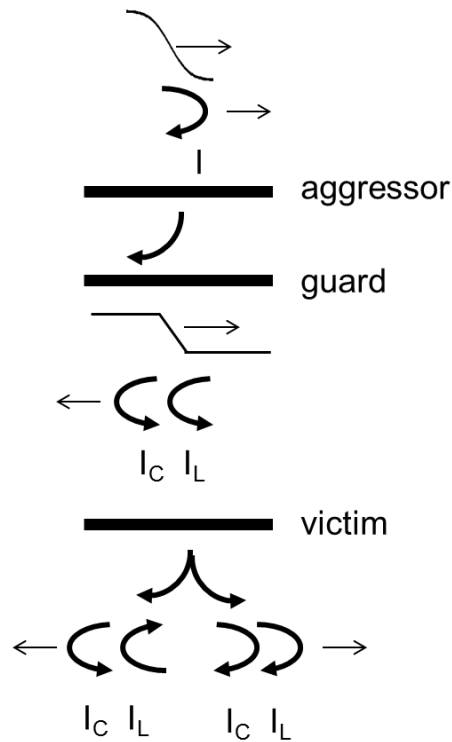


Figure 6 Diagram illustrating just the leading edge of the near end noise from the aggressor to the guard trace, which then re-infects the victim line with an effective near and far end noise.

Based on the generation of the currents, the effective near and far end coupling coefficients are:

$$k_{ne-eff} = \frac{1}{4} \left(\frac{C_{ij}}{C_{ii}} - \frac{L_{ij}}{L_{ii}} \right) = \frac{1}{4} (4.2\% - 11\%) = -1.7\%$$

And:

$$k_{fe-eff} = \frac{1}{2} \left(\frac{C_{ij}}{C_{ii}} + \frac{L_{ij}}{L_{ii}} \right) = \frac{1}{2} (4.2\% + 11\%) = +7.6\%$$

The voltage that drives these noise signatures on the victim line is the leading edge of the near end noise on the guard trace, which is a positive step edge equal to $V_{signal} \times k_{ne}$. The expected magnitude of re-infected, effective near and far end noise is:

$$\begin{aligned} V_{23-ne-eff} &= V_{signal} \times k_{ne} \times k_{ne-eff} = V_{signal} \times 0.038 \times (-0.017) \\ &= -V_{signal} \times 0.06\% \end{aligned}$$



And:

$$\begin{aligned} V_{23-fe-eff} &= (V_{signal} \times k_{ne}) \times 2.09 \times k_{fe-eff} = V_{signal} \times 0.038 \times 2.09 \times (0.076) \\ &= V_{signal} \times 0.84\% \end{aligned}$$

To summarize, in microstrip, the magnitude of noise on the victim line is:

Near end type noise:

No guard, direct aggressor to victim (V_{ne}):	0.83%
With guard, direct aggressor to victim (V_{ne}):	0.84%
Re-infected from guard (V_{23-ne}):	0.14%
Re-infected from guard, effective ($V_{23-ne-eff}$):	-0.06%

Far end type noise:

No guard, direct aggressor to victim (V_{fe}):	-2.1%
With guard, direct aggressor to victim (V_{fe}):	-2.5%
Re-infected from guard (V_{23-fe}):	+0.5%
Re-infected from guard, effective ($V_{23-fe-eff}$):	+0.84%

Depending on the nature of the termination, the re-infected noise from the guard trace can add or subtract to the directly coupled noise on the victim line. This will often make the net noise on the victim line, with a guard present, worse than without a guard trace.

To complete the analysis of microstrip cross talk, the near and far end cross talk was simulated in a transient simulation for the three cases of 50 Ohm termination on the guard, open at the ends and shorted at the ends. The results are shown in Figure 7.

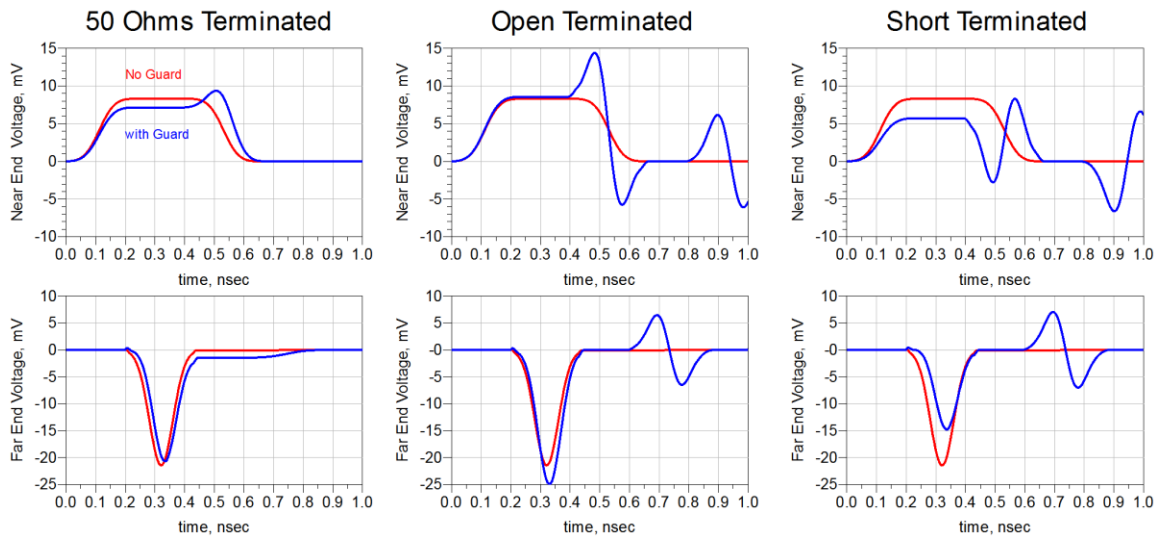


Figure 7. Transient simulation in microstrip of the near and far end noise on the victim line, with and without a guard trace.

In general, the near end noise, with a guard trace, is on the order of the near end noise with a guard trace terminated, plus and minus the typical 0.14% of the aggressor signal, or approximately 8mV +/-1.4 mV.

The far end cross talk on the victim line, with a guard trace, is also on the order of the noise with a guard trace terminated, plus or minus 0.5% of the aggressor signal, or roughly 20mV +/- 5 mV.

However there are two important features to note. The lowest near end peak noise on the victim is when the guard is shorted at its ends. However, the far end noise on the guard is able to reflect at each end, and re-infect the victim line. If the coupling length were longer, or rise time shorter, there would be even more far end noise, and it could easily exceed the slightly reduced near end noise.

In addition, the far end noise on the guard will rattle around for a long time, continually re-infecting the victim line. As an example, Figure 8 shows the near and far end noise on the victim line for a longer time, showing how the rattling far end noise on the guard trace re-infects the victim line. This can have a far worse impact than the short duration near end noise without a guard trace.

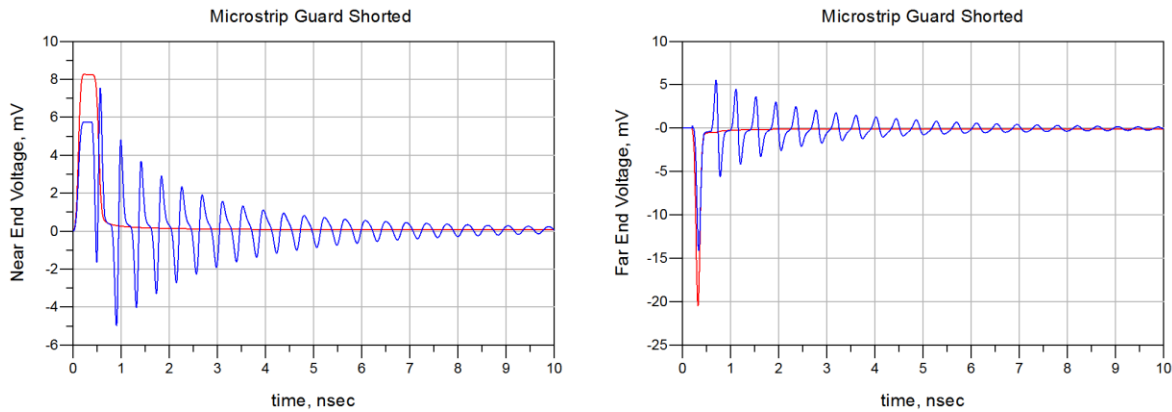


Figure 8. Near and far end noise on microstrip with a guard trace shorted on the ends showing how long the re-infected noise from the guard traces lasts. The conductor and dielectric losses were turned on in this simulation to account for realistic damping.

Analysis of Re-infection Between the Guard Trace and Victim in Stripline

The analysis in stripline is identical as in microstrip, but with two small differences. The specific near and far end coupling coefficients are different in stripline contributing to different noise levels. Also, in stripline without a guard, there is no far end cross talk. These two changes result in the following expected re-infected noise levels from the guard trace:

The initial backward edge of near end noise on the guard will be a step edge with magnitude $V_{ne-guard} = V_{signal} \times K_{ne}$. If it were to reflect from the end of the guard trace, this forward propagating edge would couple near end noise to the victim line of:

$$\begin{aligned} V_{23-ne} &= V_{signal} \times k_{ne} \times k_{ne} = V_{signal} \times k_{ne}^2 = V_{signal} \times 0.052^2 \\ &= V_{signal} \times 0.27\% \end{aligned}$$

The peak far end contribution on the victim line, from the re-infection of the reflected near end noise on the guard trace would be:

$$V_{23-fe} = (V_{signal} \times k_{ne}) \times 2.09 \times k_{fe} = V_{signal} \times 0.038 \times 2.09 \times (0) = 0$$

There will be no far end noise on the guard trace to re-infect the victim. However, there will be a voltage disturbance on the guard under the aggressor signal which will re-infect the victim line.



Based on the generation of the currents, the effective near and far end coupling coefficients are:

$$k_{ne-eff} = \frac{1}{4} \left(\frac{C_{ij}}{C_{ii}} - \frac{L_{ij}}{L_{ii}} \right) = \frac{1}{4} (10.4\% - 10.4\%) = 0$$

And:

$$k_{fe-eff} = \frac{1}{2} \left(\frac{C_{ij}}{C_{ii}} + \frac{L_{ij}}{L_{ii}} \right) = \frac{1}{2} (10.4\% + 10.4\%) = +10.4\%$$

The voltage that drives these noise signatures on the victim line is the leading edge of the near end noise on the guard trace, which is a positive step edge equal to $V_{signal} \times k_{ne}$. The expected magnitude of re-infected, effective near and far end noise in stripline is:

$$V_{23-ne-eff} = V_{signal} \times k_{ne} \times k_{ne-eff} = V_{signal} \times 0.038 \times 0 = 0$$

And:

$$\begin{aligned} V_{23-fe-eff} &= (V_{signal} \times k_{ne}) \times 2.09 \times k_{fe-eff} = V_{signal} \times 0.052 \times 2.09 \times (0.104) \\ &= V_{signal} \times 1.1\% \end{aligned}$$

To summarize, in stripline, the magnitude of noise on the victim line is:

Near end type noise:

No guard, direct aggressor to victim (V_{ne}):	0.32%
With guard, direct aggressor to victim (V_{ne}):	0.29%
Re-infected from guard (V_{23-ne}):	0.27%
Re-infected from guard, effective (V_{23-fe}):	0%

Far end type noise:

No guard, direct aggressor to victim (V_{fe}):	0%
With guard, direct aggressor to victim (V_{fe}):	-1.1%
Re-infected from guard ($V_{23-ne-eff}$):	0%
Re-infected from guard, effective ($V_{23-fe-eff}$):	+1.1%

Depending on the nature of the termination, the re-infected noise from the guard trace can add or subtract to the directly coupled noise on the victim line. This will often make the net noise on the victim line with a guard present, worse than without a guard trace.

To complete the analysis of stripline cross talk, the near and far end cross talk was simulated in a transient simulation for the three cases of 50 Ohm termination on the guard, open at the ends and shorted at the ends. The results are shown in Figure 9.

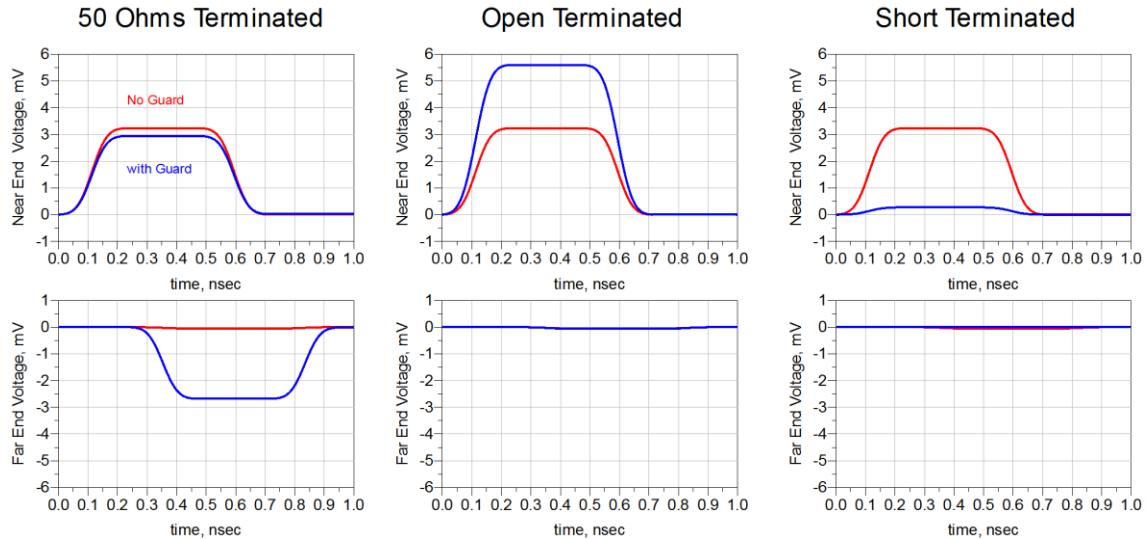


Figure 9. Transient simulation in stripline of the near and far end noise on the victim line with and without a guard trace.

When the guard is terminated, the near end noise on the victim is observed to be 2.9mV. The far end noise on victim line is -2.7 mV. This is due to the backward propagating falling near end edge on the guard trace re-infecting the far end with a negative near end noise signature starting at 1TD.

When the guard trace ends are open, the initial near end noise on the guard reflects as a positive going edge which re-infects the victim with additional 2.7 mV of near end noise. The reflected near end noise and backward propagating near end on the guard trace cancel out and contribute no far end noise on the victim line.

In either case, with the guard trace terminated in 50 ohms or left open, the far end or near end noise on the victim line is larger with a guard trace than without.

The real potential advantage of a guard trace is seen when the ends of the guard trace are shorted to ground. In this unique case, the near end noise is dramatically reduced. The directly coupled near end noise, from guard to victim line, is 0.29%. Because the guard trace is shorted, the initial near end noise on the guard trace is reflected immediately as a



negative going edge, coincident with the forward propagating positive signal edge on the aggressor. The re-infected noise from the guard trace contributes 0.27% negative noise, and when combined with the aggressor-coupled positive noise of 0.29%, results in a net near end noise on the victim of 0.02%, or about 0.2 mV.

Based on the matrix elements, the directly coupled far end noise on the victim line, when a guard trace is present, should be -1.1% or -11 mV of noise. However, the voltage disturbance from the aggressor on the victim contributes a far end contribution of exactly + 1.1% or +11 mV with a signature of far end noise. These two voltages cancel out leaving no net far end noise on stripline.

Important Implications for Cross Talk Reduction with a Guard Trace

The most effective use of a guard trace is in stripline with the ends of the guard trace shorted to the return path. This results in a dramatic reduction in near end noise from 0.3% without a guard trace to 0.02%.

The far end noise without a guard trace is 0 and with a guard trace, is still 0. Even though the coupling coefficients suggest there should be far end noise, the re-infection from the guard trace is a happy coincident and cancels this out resulting in no net far end noise.

In the ultimate case, when the guard trace is completely shorted along its length, the inductance matrix elements between the aggressor and victim lines change. Of course, when calculating the capacitance matrix elements between the aggressor and victim line, by definition, the guard trace is connected to ground. There will be no change to the capacitance matrix elements with a grounded guard trace.

However, in the case of the inductance matrix elements, in their definition, all other conductors are left open to have no current while current is forced on the aggressor and the induced voltage is measured on the victim line.

When the guard trace is “well” grounded, the inductance matrix elements for microstrip with a guard trace present are reduced:

$$L_{ii} = 6.97 \text{ nH/in} \quad \rightarrow \quad 6.88 \text{ nH/inch}$$

$$L_{ij} = 0.2 \text{ nH/in} \quad \rightarrow \quad 0.12 \text{ nH/inch}$$

$$L_{ii}/L_{ij} = 0.029 \quad \rightarrow \quad 0.017$$

$$k_{ne} = 0.0084 \quad \rightarrow \quad 0.0055$$



$$k_{fe} = -0.012 \quad \rightarrow -0.006$$

This results in a reduction of both the near and far end cross talk coupling coefficients.

In stripline, when the guard trace is “well” grounded, the inductance matrix elements with a guard trace present are reduced:

$$L_{ii} = 8.118 \text{ nH/in} \quad \rightarrow 8.032 \text{ nH/inch}$$

$$L_{ij} = 0.09 \text{ nH/in} \quad \rightarrow 0.0044 \text{ nH/inch}$$

$$L_{ii}/L_{ij} = 0.011 \quad \rightarrow 0.0005$$

$$k_{ne} = 0.003 \quad \rightarrow 0.0003$$

$$k_{fe} = -0.005 \quad \rightarrow 0.00004$$

In effect, the induced current on the grounded guard trace cancels out most of the magnetic field around the victim line from the aggressor line. The combination of reduced capacitive coupling and inductive coupling makes the grounded guard trace very effective at “guarding” the victim line from the aggressor.

In practically implementing a “grounded” guard trace, there are four important considerations. The first is how close should the shorting vias in the guard trace be to make the guard trace look like ground? A rough rule of thumb suggests the spacing should be at least every 1/10 the wavelength of the highest frequency content of the signal.

For a Gaussian edge, the -3 dB bandwidth is:

$$BW = \frac{0.338}{RT}$$

At this frequency, the $\lambda/10$ spacing is given by:

$$S_{vias} = \frac{1}{10} \times \frac{v}{BW} = \frac{1}{10} \times \frac{\left(\frac{11.8}{\sqrt{Dk_{eff}}} \right)}{\left(\frac{0.338}{RT} \right)} = \frac{3.5}{\sqrt{Dk_{eff}}} \times RT$$

Where:

S_{vias} = the closest required spacing between vias to meet the $\lambda/10$ criterion, in inches



v = the speed of the signal on the transmission line in in/nsec

BW = the bandwidth of the signal in GHz

Dk_{eff} = the effective dielectric constant the signal sees

RT = the 10-90 rise time of the signal in nsec.

For a 0.1 nsec rise time and stripline, the $\lambda/10$ spacing is 0.18 inches. The transmission line examples in this study were 1.5 inches long. For a via spacing of 0.18 inches, this is a total of about 9 vias. Figure 10 is a transient simulation comparing the cases of a microstrip and stripline aggressor and victim line spaced 15 mils apart with:

- no guard trace
- a guard trace shorted only at both ends
- a guard trace with 3 distributed shorting vias
- a guard trace with 5 distributed shorting vias
- a guard trace with 9 distributed shorting vias

There was no difference with more than 9 shorting vias.

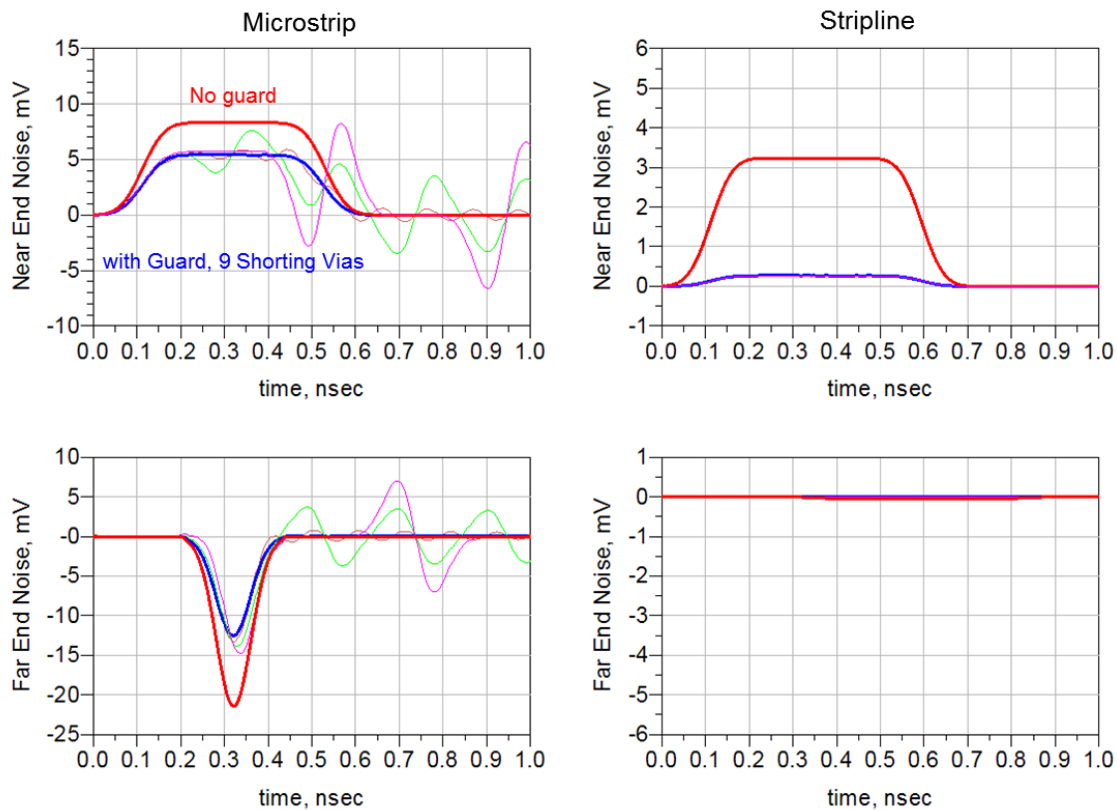


Figure 10. Near and far end noise in microstrip and stripline with guard trace having just 2, 3, 5 and 9 shorting vias, compared with same spacing but no guard trace.

This transient analysis points out that using a spacing of $1/10^{\text{th}} \lambda$ between shorting vias is the minimum spacing to achieve the same impact as ideal shorting of the guard trace. When the guard trace is shorted with fewer vias, there is still considerable noise on the guard trace which can re-infect the victim line.

When the guard trace is suitably grounded, all the noise on the victim line is from direct coupling between the aggressor and victim, with no re-infection from the guard trace. The reduced noise is due to the reduced matrix elements.

The near end noise on the victim line in microstrip is reduced to 0.55%, in agreement with the value suggested by the matrix elements. The far end noise on the victim line in microstrip is reduced from 21 mV to 12 mV, or 57%, which is close to the 50% expected value from the matrix elements.

In the best case for microstrip, with the guard trace having multiple shorting vias down its length, the near end noise is still 65% of its value with no guard trace and the far end



noise is 57% of its value with a guard trace. This is of small incremental value, and as is shown later, difficult to achieve in practice.

In the case of stripline, having two shorting vias or 100 shorting vias has the same result. This indicates, when using stripline, there is no need for multiple shorting vias, other than at the end of the guard trace. This dramatically simplifies the use of guard traces in stripline.

Practical Design Considerations

Three additional design issues must be included in this analysis: the finite inductance of the vias, the impact on the line to line spacing with shorting vias and the extension of the guard trace compared to the coupled length.

The finite via impedance will prevent complete suppression of the noise on the guard trace. Some noise will still be present to re-infect the victim line, depending on the inductance of the vias.

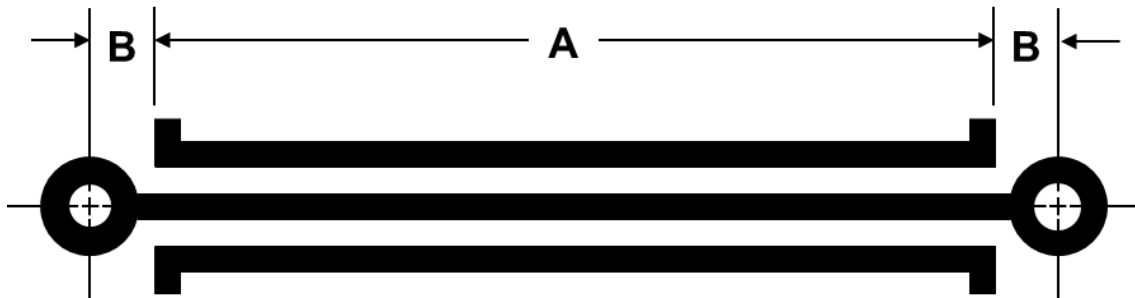
Vias have some total inductance, on the order of 10 nH/inch. In stripline, if the length of the via to the top and bottom plane were each 20 mils the parallel inductance of each pair of vias might be on the order of 0.1 nH. In microstrip, the length of a shorting via to the return plane might be on the order of 10 mil, with a total inductance of about 0.1 nH.

Even at a rise time of 0.1 nsec, and signal bandwidth of 3.5 GHz, the impedance of a 0.1 nH via is about 2 Ohms. This is much lower than the 50 Ohm impedance of the line, and is still an effective short. Even though the finite impedance of a typical vias will have only a small impact, these issues should be evaluated in each candidate design.

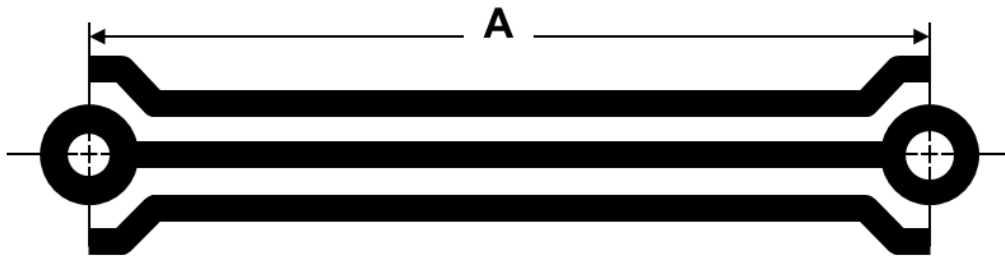
Of potentially bigger impact is the size of the via. When adding vias to a design, there are manufacturing design rules set a limit to the smallest via and capture pad.

The smallest mechanical drill size for a through-hole via most PCB vendors will spec is 8 mils. The minimum capture pad diameter is usually 10 mils over drill size. For an 8 mil drill, the minimum pad diameter would be 18 mils. The minimum pad to copper spacing is generally 5 mils. Therefore a minimum space between the aggressor and victim lines would have to be at least 28 mils just to fit a guard trace with grounding vias down its length. If the two signal lines were to be increased to 28 mils, the reduction in cross talk from just the added separation would be more significant than adding the shorted guard trace in microstrip and stripline.

The above analysis suggests that to gain the dramatic reduction in cross talk with a shorted guard trace in stripline does not require stitching vias along the guard trace, but just at the ends. This means that the minimum space to fit a guard trace can remain at 3 times the line width as long as the guard trace is extended, by dimension B, as shown in Figure 11(a). Alternatively, the guard trace can be made equal to the coupled length as illustrated in Figure 11(b).



(a)



(b)

Figure 11 Two examples of adding a grounded guard trace with minimum spacing of 3 x line width. **Figure(a):** guard trace is extended past the coupled length (A) by dimension B on both sides in order to satisfy minimum 5 mil pad-track spacing requirements. **Figure (b):** guard trace is equal to coupled length by separating the traces at each ends.

If the guard trace is extended beyond the coupled region, with just shorting vias on the ends of the guard trace, there will be an impact on the cancellation of noise on the guard trace and there will be re-infected noise onto the victim line.

To explore and quantify the implications vias have on guard trace noise refection, Agilent's ADS Momentum planar 3D field solver was used to build stripline models per Figure 11. A third model, not shown, was also built, including just the aggressor and victim lines as a reference. The coupled length (A) was set to 1.1 inches.

Figure 12 shows a portion of the 3D model of the left end of the topologies shown in Figure 11. The reference planes are not shown for clarity. The via diameter is 8 mils; with a pad diameter of 18 mils. The guard trace B dimension was extended 12 mils to maintain minimum 5 mils pad-track clearance. The trace widths remained at 5 mils with 5 mils spaces.

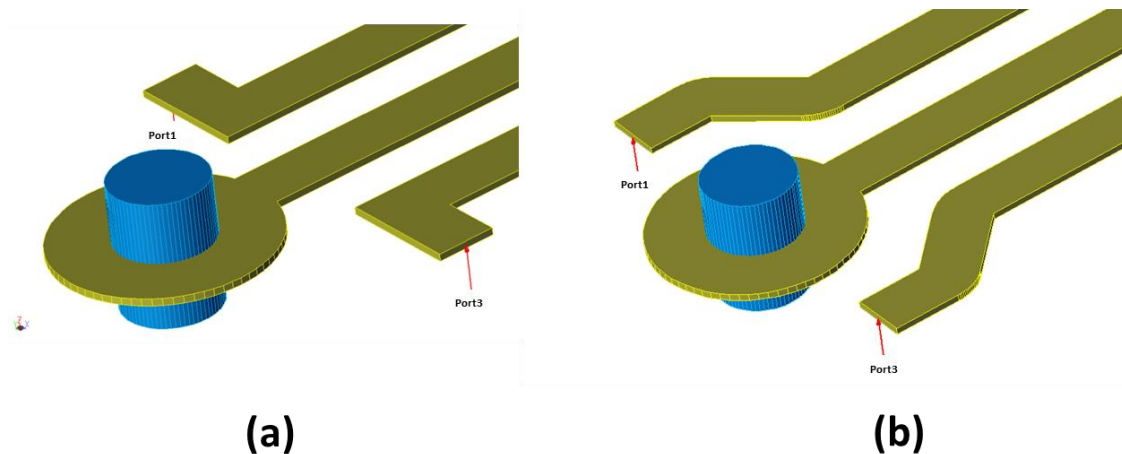


Figure 12 Two examples of left end of guard trace shorting via and pad with respect to near end coupled line. **Figure(a):** guard trace is extended past the coupled length (A) by dimension B in order to satisfy minimum 5 mil track to pad spacing requirements. **Figure (b):** guard trace is equal to coupled length by separating the traces. Via diameter is 8 mils with 18 mil diameter pad, modeled in Agilent Momentum 3D field solver. Reference planes are not shown for clarity.

After simulation, the data was saved in Touchstone format and brought into ADS for transient simulation analysis and comparison. A 0-2V VtPulse source, with erf edge and a 10-90%, 100 psec rise time, was used for the aggressor in transient analysis to yield a 0-1V aggressor signal on Port 3. The near end crosstalk was measured on Port 1.

The waveforms are shown in Figure 13. The results are consistent with ADS circuit simulations described earlier.

The red and blue waveforms are when B=12 mils and 0 mils respectively. The blue waveform shows that even when B is 0 mils, there is still a small amount of noise due to the inductive length of the vias to the reference plane. Of course, the impact of the inductance of the shorting vias will depend on the rise time of the signal and the length of

the via. In this case, the via length is 5 mils to each plane and the rise time is 100 psec. The impact of the finite inductance of the shorting vias is to increase the noise in stripline, thereby reducing the effectiveness of the guard trace. In extreme cases of longer shorting vias or shorter rise time, the noise with a shorted guard trace may in fact be worse than not using a guard trace.

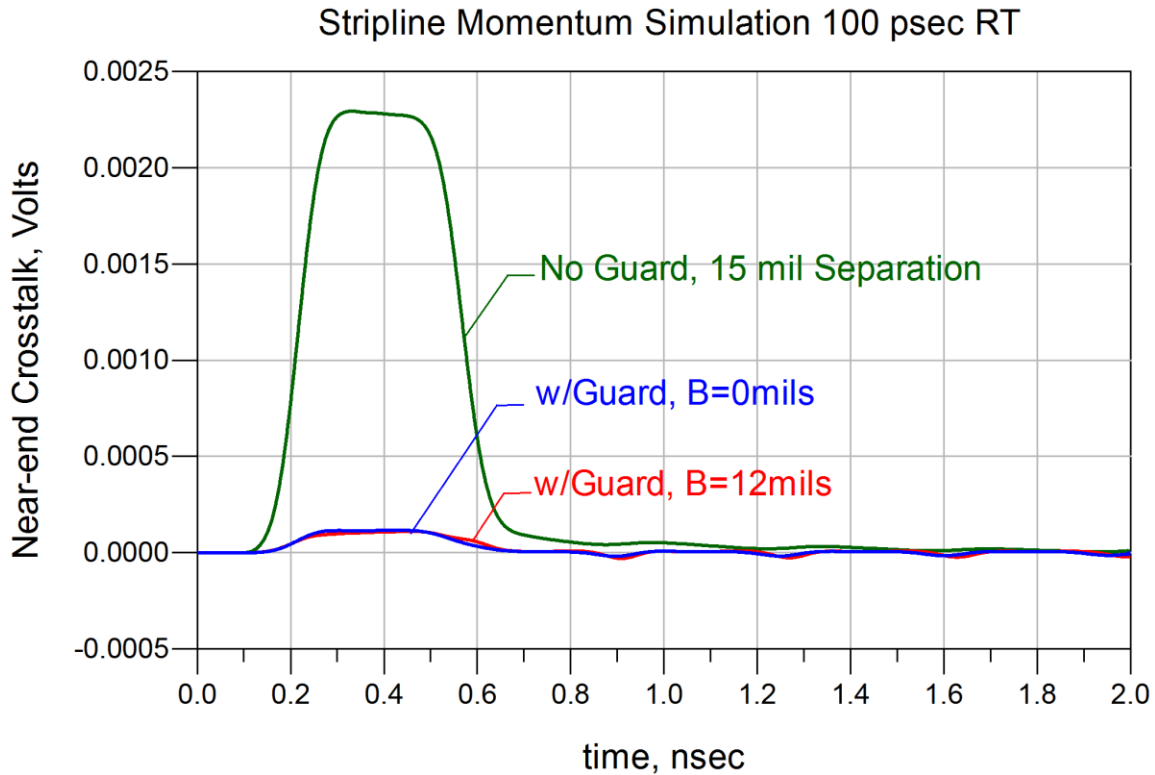


Figure 13 Momentum simulation results comparing near end crosstalk at Port 1 when aggressor voltage was applied to Port 3. The red and blue waveforms are with a guard trace. The green waveform is with no guard and 15 mils separation. Aggressor voltage = 1V, 100 psec erf rise time.

It is a well-known fact that technology advancements over time results in faster and faster rise times. If you have engineered your design on the technology of the day, any future substitution of parts, with faster rise time, may cause your product to fail, or worse be intermittent. Figure 14 shows an example of the increased noise ripple when the rise time is reduced to 50 ps.

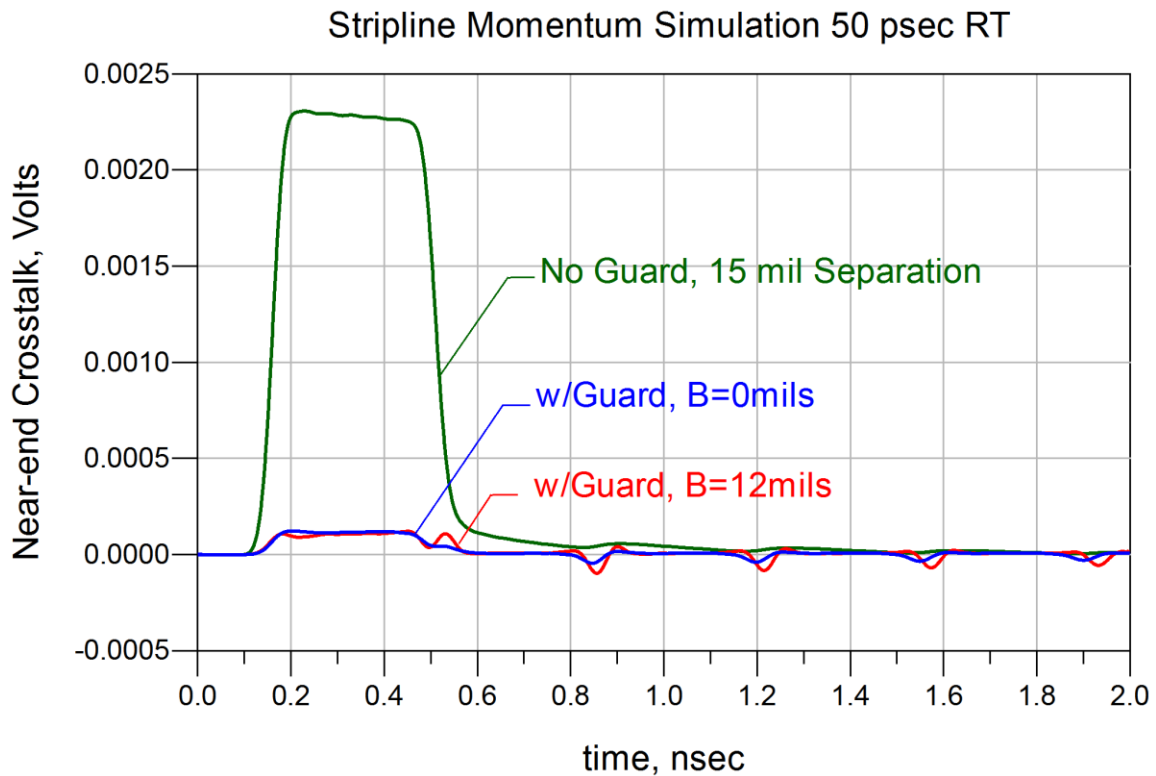


Figure 14 Momentum simulation results comparing near end crosstalk at Port 1 when aggressor voltage was applied to Port 3. The red and blue waveforms are with a guard trace. The green waveform is with no guard and 15 mils separation. Aggressor voltage = 1V, 50 psec erf rise time.

As the guard trace gets longer at each end, the noise ripple grows in magnitude quite rapidly, as shown in Figure 15. The green waveform is the near end crosstalk voltage with no guard. The red, blue and magenta waveforms are the simulation results when dimension B is extended by 12 mils, 50 mils and 100 mils respectively. It is remarkable to note that when the guard trace is just 100 mils longer, at each end, the peak-peak amplitude of the noise just about equals the peak magnitude of the no guard case. This implies adding a guard trace, shorted at each end, has its caveats. Therefore, it is imperative to model and simulate the respected topology, preferably with a 3D field solver, before signing off on the design.

Stripline Momentum Simulation 100 psec RT

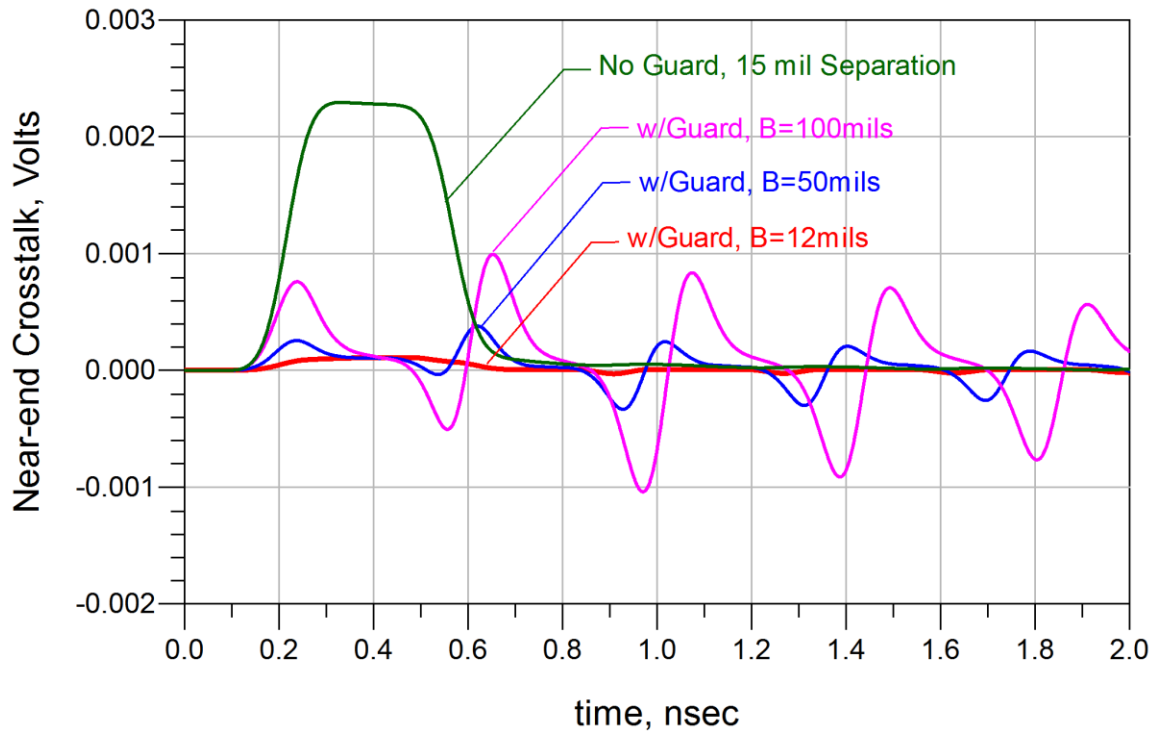


Figure 15 Momentum simulation results with guard trace extended. B = 12 mils (red), B = 50 mils (blue) and B = 100 mils (magenta) compared to no guard (green). Aggressor voltage = 1V, 100 psec erf rise time.

When the guard trace was shortened to equal the coupled length, as shown in Figure 12(b), the noise ripple was reduced by approximately one-third, as seen by the blue waveform, compared to the red waveform in Figure 16.

But when the guard trace was removed, and the space was increased to five times the line width, the near end crosstalk was reduced in magnitude and was approximately equal to both guard trace scenarios. Furthermore, because there is no guard trace, there is no additional noise coupled after the near end crosstalk pulse after 0.6 nsec. This supports the earlier assertion that by increasing the spacing to 28 mils to fit in an 18 mil via pad would further reduce the noise without the worry of guard trace re-infection.

Stripline Momentum Simulation 100 psec RT

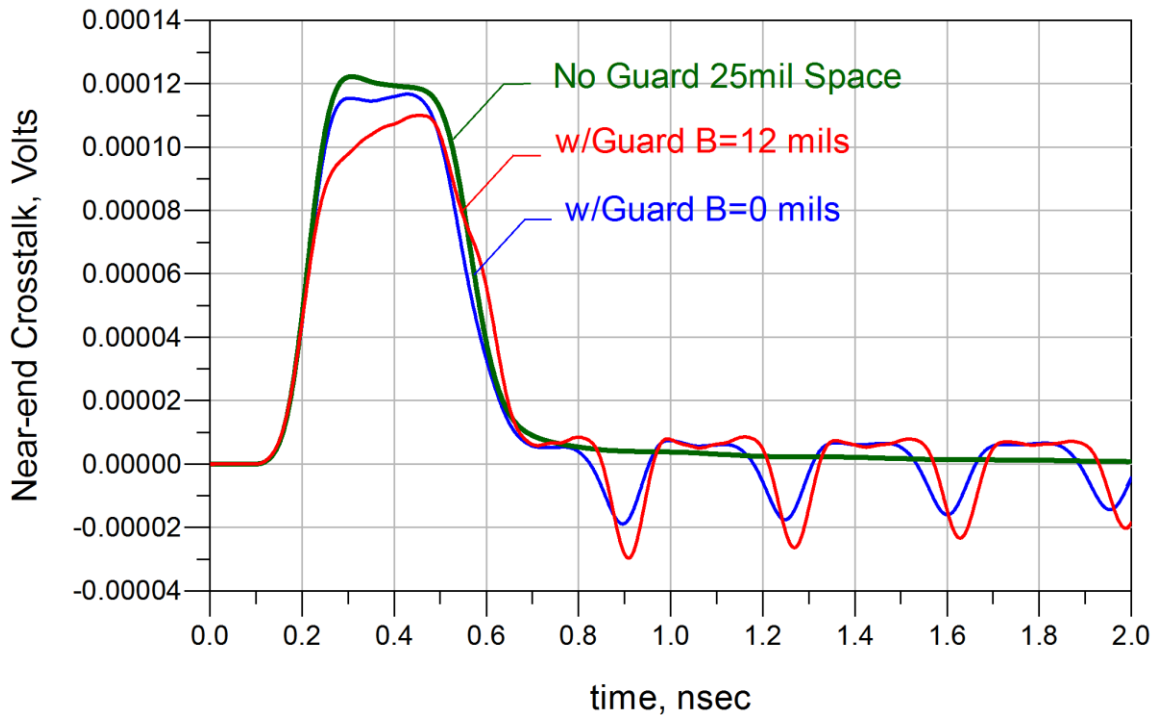


Figure 16 Momentum simulation results comparing near end crosstalk at Port 1 when aggressor voltage was applied to Port 3. The blue and red waveforms shows results, with guard trace extended lengths of 0 mils and 12 mils respectively. The green waveform shows the results of the non-guarded topology with 25 mil space. Aggressor voltage = 1V, 100 psec erf rise time.

Conclusions

1. In all high speed digital applications, where -50 dB cross talk is acceptable, there is never a need to implement a guard trace. This cross talk can be achieved in stripline traces by just increasing the spacing between aggressor and victim to fit a guard trace.
2. In microstrip, if a guard trace is used with the ends terminated open or shorted, the noise on the victim line can be higher than if the guard trace were not present.
3. A guard trace, even “well shorted”, has minimal advantage. To fit the required shorting vias means spacing the aggressor and victim lines very far apart which by itself reduces the cross talk more.
4. Using a guard trace with microstrip offers high risk of incorrect termination with little potential reward and should never be done. Rather sensitive lines should be buried in stripline



5. In stripline, never terminate the ends of the guard trace or leave them floating. The ends should be shorted with the lowest inductance via practical.
6. The optimum configuration for a guard trace is to use shorting vias on the ends, and match the length of the guard trace to the coupled region. When used in stripline structures, such a guard trace can result in near end cross talk of less than 0.03%, which is -70dB isolation, compared with -50 dB isolation for the same two lines without the guard trace. Far end cross talk can be eliminated.
7. Any extension of the guard trace outside the coupling region, with shorting vias on the ends, will reduce the effectiveness of the guard trace; due to the added length and finite inductance in the via. Because the details depend on the rise time and dimensions of the lines, a 3D simulation is the only way to quantify the actual benefit of a guard trace with vias in a practical situation.

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