

**Rigorous Evaluation of Worst Case Total
Crosstalk in the Time Domain
Using Frequency Domain Scattering
Parameters**

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Abstract

Total crosstalk is the sum of all crosstalk waveforms due to input waveforms simultaneously present on all input ports of a circuit. Worst case crosstalk is typically evaluated by means of multiple analyses in the time domain. However, this requires either fabrication and physical measurement, or careful development of a (typically lumped) model. As frequencies become higher, the various lumped model approximations lose accuracy and physical measurements become difficult and expensive.

In this paper, maximum crosstalk is evaluated in the frequency domain. Each crosstalk waveform is viewed as a sum of sinusoidal waveforms, or spectrum. The worst case occurs when all sinusoidal waveforms add in phase. The magnitudes of the crosstalk spectral components are determined by means of an electromagnetic analysis. The electromagnetic analysis is based purely on Maxwell's equations and the circuit geometry and inherently includes all capacitance, inductance, resistance, substrate conductivity, and coupling between all lines regardless of orientation. Given knowledge of the absolute worst-case crosstalk, the high-speed digital designer can design the critical portions of a circuit so that it is impossible for a given level of crosstalk to be exceeded.

Authors/Speakers

James C. Rautio received a BSEE from Cornell in 1978, a MS Systems Engineering from University of Pennsylvania in 1982, and a Ph. D. in electrical engineering from Syracuse University in 1986. From 1978 to 1986, he worked for General Electric, first at the Valley Forge Space Division, then at the Syracuse Electronics Laboratory. At this time he developed microwave design and measurement software, and designed microwave circuits on Alumina and on GaAs. From 1986 to 1988, he was a visiting professor at Syracuse University and at Cornell. In 1988 he went full time with Sonnet Software, a company he had founded in 1983. In 1995, Sonnet was listed on the Inc. 500 list of the fastest growing privately held US companies, the first microwave software company ever to be so listed. Today, Sonnet is the leading vendor of 3-D planar high frequency electromagnetic analysis software. Dr. Rautio was recently elected an IEEE Fellow and has been awarded the 2001 IEEE MTT Applications Award for his work in high frequency electromagnetics.

Introduction

With large-scale digital system clock speeds approaching and exceeding 1 GHz, crosstalk threatens signal integrity. The usual approach to quantification of this problem is to first develop a lumped model of a critical circuit, then analyze it in the time-domain for one or more specific input signals. The circuit is then modified so that crosstalk for the specific cases examined is below a desired threshold.

This approach has several difficulties. First, creation of a lumped model can be difficult. Once created, the model might not properly include transmission line or dispersive effects. For example, inductance and capacitance are functions of frequency.

Coupling between non-parallel lines might not be included. These errors can become large at high frequency, where crosstalk coupling is most significant. In addition, while ignoring one or more crosstalk mechanisms (like mutual inductance) might be valid for a particular clock speed/process, such simplifying assumptions might fail for higher clock speeds or for different processes. Finally, the number of time domain analyses required increases linearly with the number of possible aggressor lines.

This paper describes the calculation of worst case total crosstalk in the frequency domain. Although certainly possible, we do not calculate the actual crosstalk waveform with this approach. Thus, unless appropriately modified, this approach should not be used if worst case crosstalk is not a concern. For example, one may simply use a clock speed slow enough that all crosstalk settles out prior to the time when valid data is needed. In this case, crosstalk analysis is not needed at all.

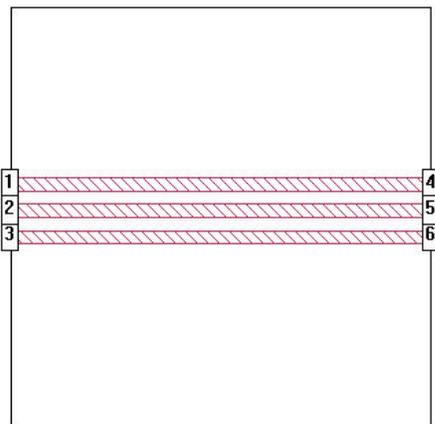


Figure 1. Three parallel coupled microstrip lines form the first circuit used to illustrate the calculation of maximum possible crosstalk.

When a slower clock speed is not an acceptable solution to reducing the effect of crosstalk, then this approach may be used. Analysis is performed only at a few frequencies regardless of the circuit complexity. No lumped models or fabrication is needed. The only input needed for this approach is the geometry of the circuit. The only approximation is the discretization of the circuit metal required by the electromagnetic analysis. Then, thanks to Maxwell's equations, all capacitance, inductance, resistance, coupling between all conductors at all orientations, and conducting substrate effects are completely and exactly included.

The Crosstalk Spectrum

All input waveforms and all resulting crosstalk waveforms have a spectrum. If the waveforms are periodic, the spectrum is simply a sum of sinusoids at the fundamental and harmonic frequencies.

The maximum value of crosstalk is realized when input waveforms are present on all input ports and the sum of sinusoids from each resulting crosstalk waveform all add in phase. When a signal consists of a large number of sine waves, it is highly unlikely that they will all add in phase. At least a few will tend to cancel. However, remember that with, for example, a 1GHz clock, there are 1,000,000,000 chances every second for the sine waves to add in phase. With this many "rolls of the die", even very low probability events can occur with unacceptable frequency.

Now the problem is how to calculate the amplitude of each sinusoid of each crosstalk waveform caused by each input waveform. This is where high frequency electromagnetic analysis is used. In wide use in high frequency and microwave design for over a decade, electromagnetic analysis software can evaluate a circuit including all electromagnetic effects completely. There are many types of analyses

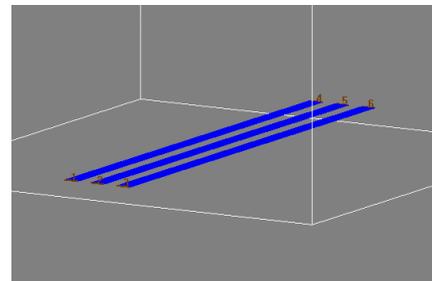


Figure 2. A 3-D view of the Figure 1 circuit.

available. For planar circuits it is best to use a surface meshing tool. Volume meshing tools mesh the entire volume of a circuit and are usually best used when at least a portion of the circuit is non-planar.

A surface meshing analysis first divides the metal of a circuit into small subsections. Then, the analysis fills a large matrix with the coupling between each subsection based on Maxwell's equations. If there are N subsections, the matrix is NxN. Then the matrix is inverted. The usual result is a text file full of numbers called "S-parameters". With a small amount of mathematical manipulation, S-parameters tell us how much output voltage appears on each port when a 1.0 Volt signal (single frequency sine wave) is applied to a given input port. For example, S_{51} is directly related to how much voltage appears on port 5 when there is an input voltage on port 1.

S-parameters are calculated on a frequency-by-frequency basis. For example, S-parameters for a circuit calculated at 1 GHz, tell us about the crosstalk only at 1 GHz. Since a periodic waveform is a sum of sine waves at the fundamental frequency and at all harmonics, a complete set of S-parameters should be calculated for each important frequency.

For examples described here we use the Sonnet[®] electromagnetic analysis, from Sonnet Software, Inc., Liverpool, NY. A free version of the analysis, called Sonnet Lite is available at <http://www.sonnetusa.com>. The free version can

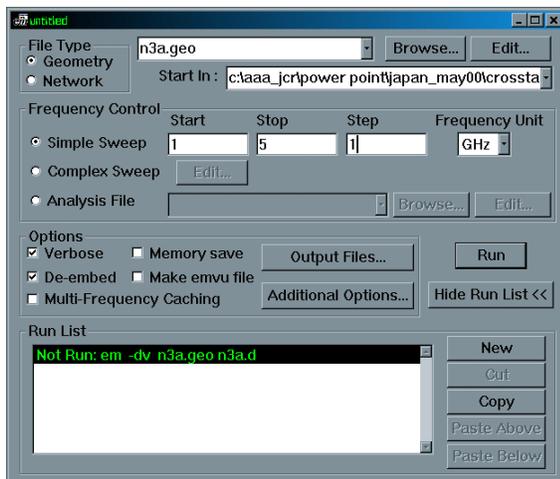


Figure 3. The Sonnet analysis control window allows specification of analysis options.

analyze up to four ports. It is practical to analyze circuits with hundreds of ports using the full version.

An Example Circuit

Figures 1 and 2 show an example circuit. It is a three line bus captured and displayed using Sonnet's xgeom graphical editor. The circuit could also have been imported from existing GDSII Stream or AutoCAD dxf files. The 3-D view of the circuit in Figure 2 comes from a free program developed by Muehlhaus Hochfrequenztechnik. It can be downloaded from <http://www.muehlhaus.com> or <http://www.sonnetusa.com>.

Ports 1-3 are input ports and ports 4-6 are output ports. This circuit is analyzed using Sonnet's[®] analysis. The circuit should be analyzed at the fundamental clock frequency and at all significant harmonics.

Performing the Analysis

Figure 3 shows the control window for the Sonnet analysis. Since we are assuming a 1 GHz clock, we make the first analysis frequency 1 GHz. Then, we include 4 harmonics by specifying a stop frequency of 5 GHz and a step of 1 GHz.

The "De-embed" check-off is important. There is a small shunt capacitance (usually a few tenths of a pF) associated with each port. The De-embed option automatically removes the effect of this "port discontinuity" from the data.

The result of the EM analysis is one matrix at each frequency. These results are based directly on

	A
1	First Step
2	Load S-Parameter File
3	
4	Click Here
5	Load
6	S-parameters
7	
8	
9	
10	Circuit has
11	6
12	ports.
13	
14	Data is available for
15	5
16	frequencies.
17	
18	
19	

Figure 4. The S-parameters are loaded into the spreadsheet in the first step.

Maxwell's equations. There is no dependency on approximate lumped models. The analysis, since it is based entirely on the solution of Maxwell's equations for the given geometry, inherently includes all capacitance, inductance, resistance, substrate conductance, and all possible couplings (not just parallel conductors). In short, you do not need to worry, when you go to a higher frequency or a more advanced process, whether or not the old assumptions (i.e., "inductance is not important") are still valid.

Since this is a six-port circuit, each matrix has 36 complex (magnitude and angle) numbers. Even for a small circuit like this, we suddenly have a lot of numbers to organize and process. If done manually, this process is tedious and error prone. For this reason, we have developed a Microsoft Excel spreadsheet so results can be processed quickly. The spreadsheet may be downloaded from <http://www.sonnetusa.com>.

Spreadsheet to the Rescue

When you first load the spreadsheet, you may be informed that the spreadsheet contains macros. If the macros are disabled, this spread sheet will not work.

Third Step		
Specify Input Ports		
Input Ports		
1		
2		
3		

Figure 6. The maximum possible cross-talk will be calculated with input signals connected to all input ports. Specify those ports in the third step.

Figure 4 shows the "First Step" of the spreadsheet. Clicking on "Load S-parameters" runs the first macro. The "*.d" file you created with the Sonnet analysis should be specified and loaded. The number of ports and analysis frequencies are listed.

In the "Second Step", Figure 5, specify the worst case (maximum) voltage amplitudes of the crosstalk spectrum. If you have fast rise and fall times, the amplitudes at high frequency are larger than if you have slow rise and

fall times. The most accurate way to get numbers for the spectral amplitudes is to view the spectrum of your actual digital signal on a spectrum analyzer. Only relative amplitudes are needed. For example, "1.0, 0.5, 0.25" yields the same results as "10.0, 5.0, 2.5".

Fourth Step		
Specify Thresholds		
Connection Threshold	0.9	
Flag Cross Talk Above	5%	

Figure 7. If V_{out}/V_{in} exceeds the connection threshold, then the two ports are assumed connected together. Later, when cross-talk is calculated, all cross-talk which exceeds the specified level is displayed in red.

Second Step		
Specify Harmonic Amplitudes		
GHz	Harmonic	Amplitude
1.0000	1	0.5
2.0000	2	0.2
3.0000	3	0.1
4.0000	4	0.05
5.0000	5	0.025

Figure 5. To calculate the maximum possible cross-talk, enter the worst case spectrum in the second step.

Fifth Step		
Find Connections to Input Ports		
Click Here		
Find Connections		
Port	Has Input	Vout/Vin
1	1	
2	2	
3	3	
4	1	1.00
5	2	1.00
6	3	1.00

Figure 8. All input/output connections are found in the fifth step. In addition, the maximum Vout/Vin is listed.

Final Step	
Calculate Max Crosstalk	
Click Here	
Calculate Crosstalk	
Port	Cross-Talk
1	4.07%
2	6.62%
3	4.07%
4	2.33%
5	3.24%
6	2.33%

Figure 9. In the final step, all cross-talk is calculated. The maximum possible cross-talk appearing on port 2 (due to input signals on ports 1 and 3) exceeds the design threshold.

The spectrum of a perfect periodic square wave is has spectral amplitudes of $1/N$, where N is the harmonic number, for all odd harmonics. For a non-zero rise/fall time, the spectrum falls off more

rapidly than $1/N$. For a random sequence of ones and zeros, the spectrum becomes continuous. In general, select a few frequencies that cover the worst case spectral bandwidth of the input waveforms. It is convenient to select harmonically related frequencies, but this is not necessary.

The “Third Step”, Figure 6, allows entry of input ports. A waveform with the worst case spectrum just specified will be connected to all input ports. The port numbers may be specified in any order. Non-existent port numbers are ignored.

In the “Fourth Step”, Figure 7, several thresholds are specified. The “Connection Threshold” is used by a macro in the next step to determine what ports are connected to the input ports. For example, with a connection threshold of 0.9, any input port that generates more than 0.9 volts on an output port (for 1.0 volts in) is assumed connected to that output port.

The “Flag Crosstalk Above” threshold causes all crosstalk above the given percentage to be displayed in red. This allows non-compliant ports to be easily spotted.

By clicking on “Find Connections” in the “Fifth Step”, Figure 8, a macro finds all input/output connections. If an output port has no connection, the entry “Has Input” is left blank. If a port is an input port, the same port number is displayed in the “Has Input” column. If a given output port is driven by more than one input port, an error message is displayed. Be sure to check all input/output connections. Circuit layout errors can be easily caught here.

In this case, we attach input signals to ports 1, 2, and 3. The spreadsheet determines that ports 4, 5, and 6 are output ports connected as we expected.

The final macro, in the “Final Step”, Figure 9, calculates maximum crosstalk. All crosstalk sinusoids from all input ports are assumed to add in phase yielding the maximum possible crosstalk.

Note that port 2 has the maximum crosstalk and that this crosstalk exceeds the 5% maximum allowed. This seems reasonable because the port 2 line has two immediately adjacent aggressor lines while the other lines have only one adjacent line. Since the maximum crosstalk is indicated on port 2, instead of

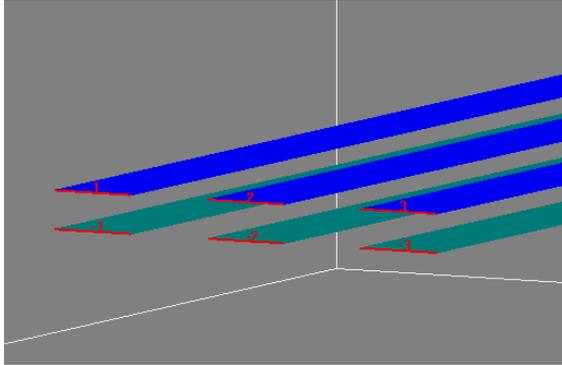


Figure 10. A redesign of the previous circuit so that each line becomes a differential pair. This can be viewed as each line now has its own private ground plane for return current. The Z-axis (vertical) dimension is exaggerated.

S	T	U
Final Step		
Calculate Max Crosstalk		
Click Here		
Calculate Crosstalk		
Port	Cross-Talk	
1	0.11%	
2	0.16%	
3	0.11%	
4	0.03%	
5	0.05%	
6	0.03%	

Figure 11. The use of differential pairs almost completely eliminates cross-talk.

port 5, we also see that the reverse crosstalk is worse than the forward crosstalk for this circuit.

Redesign Time

Figure 10 shows a redesign of this simple circuit. Now, we are using differential ports. The signal line for port 1 is labeled “1”, while the ground line is

labeled port “-1”. Sometimes a differential pair will have the return current line side-by-side with the signal line, this is also known as “co-planar”. In this case, the return line is directly underneath the signal line. This can also be viewed as each signal line has its own private microstrip ground plane.

The idea is to confine the fields of each signal line to as small a volume as possible. If very little field extends over to the adjacent line, the crosstalk will be small. Analyzing this circuit and loading the results into the spreadsheet, as before, yields the results shown in Figure 11. We see the crosstalk is now almost completely gone. Analysis time for each of these circuits so far discussed is well under 1 second per frequency.

Validation

This section compares published crosstalk measurements with results derived using this approach.

The published results [1] are for a single pair of coupled lines on silicon. The lines are each 1 micron wide, 1.2 microns thick, with a 1 micron separation. Because the thickness of the lines is on the order of the gap between the lines, two levels of infinitely thin metal were used to model the actual thick metal. One level was placed at the bottom of the actual thick metal, the other was placed at the top of the actual thick metal. This extra model complexity is needed only with closely spaced lines. If a single layer model were used, coupling capacitance would be underestimated by a few percent. Single layer models are sufficient when the gap is greater than about twice the metal thickness.

The lines are 8000 microns long on 300 microns thick silicon with dielectric constant of 11.9. The lines were measured using an HP5412T with 100 mV pulse amplitude and 40 pS risetime connected to a Cascade Microtech GSG probe station.

Measurements of the probe pads indicate a shunt capacitance of 0.58 pF. This was added to the electromagnetic analysis by changing the port terminations (Parameters->Ports). Alternatively, the probe pads could have been included in the analysis.

The silicon doping concentration is 1×10^{15} P-type, corresponding to a bulk conductivity of 7.6 S/m [2]. There is a 0.8 micron layer of silicon dioxide,

dielectric constant 3.9, between the metal and the silicon.

Worst case spectrum amplitudes were assumed to follow $1/N$ starting at 0.2 GHz and going to 3 GHz with even harmonic amplitudes set to zero.

The test pattern geometry consists of two coupled lines with the input on one line at one end and the output on the other line at the other end. The unterminated line ends are left open. The measured crosstalk waveform is shown in Figure 12 along with the waveform calculated in [1]. The waveform calculated in [1] required the use of measured transmission line capacitance values in order to simulate the crosstalk.

Also indicated in Figure 12 is the absolute maximum possible crosstalk for this circuit calculated based strictly on the geometry of the circuit using electromagnetic analysis and the technique described in this paper. Note that for this simple circuit, the

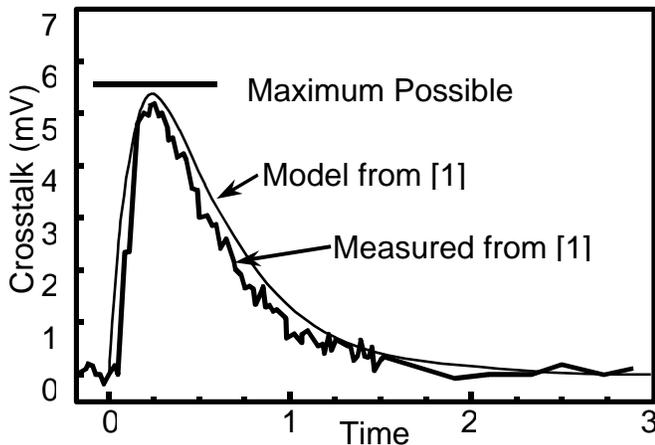


Figure 12. Calculated maximum possible crosstalk is 5.6 mV compared to 5.3 mV measured.

absolute maximum crosstalk (5.6 mV) is very nearly achieved in practice (5.3 mV measured).

During an initial analysis, maximum crosstalk was calculated to be only 2.1 mV. There was no passivation layer in this first analysis. After some numerical experimentation, it was determined that adding a passivation layer 1.2 microns thick with a dielectric constant of 3.9 increased crosstalk to 5.6 mV, almost identical to measurements. A communication with the authors of [1] verified that such a passivation layer with very nearly those parameters indeed existed but was not mentioned in

the paper. Lesson learned: the passivation layer can substantially increase crosstalk.

Large Circuit Analysis

Figures 13 and 14 show a cross-over junction between two 32 bit busses. This is a 128 port circuit with 64 input ports. Analysis time is 7.6 minutes per frequency on a 400 MHz Pentium. The EM analysis even includes all couplings to and from the vias. There are $128 \times 128 = 16,384$ complex (magnitude and angle) numbers to read in at each frequency. The spreadsheet requires about one minute to read the data for all five frequencies.

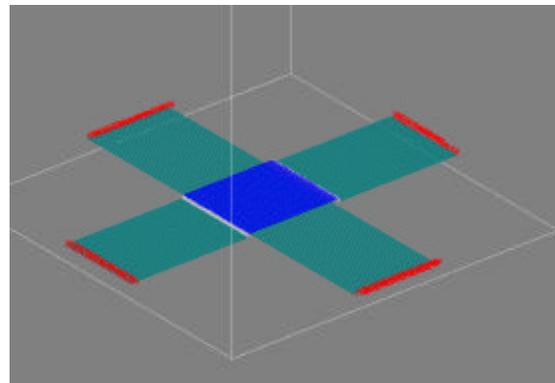


Figure 13. Two 32-bit busses crossing over each other yield a complex 128 port circuit.

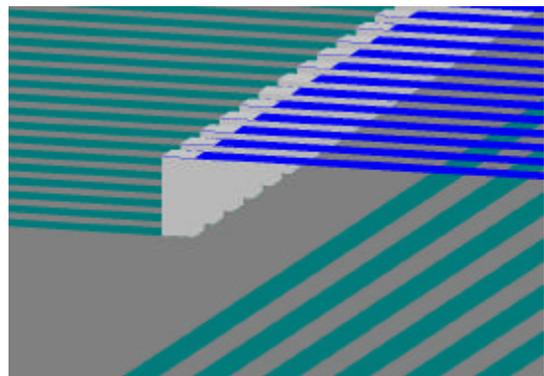


Figure 14. Close-up of the cross-over region of the 32-bit bus cross-over circuit. The Z-axis (vertical) is exaggerated.

When performing the third step for this circuit, be sure to specify the first 64 ports as input ports. This is easily done by selecting the first 3 input port entries (1, 2, and 3 in Figure 6). Then click and drag down on the small square at the lower right corner of the selection box.

When performing the fifth step, we encounter a surprise. No connections are found, see Figure 15. Note that the Vout/Vin column starting at port 65 indicates only about 0.79 Volts output for 1 volt input. This is a hint that this bus design is going to have problems. To allow the spreadsheet to find the connections, go to the fourth step and change the Connection Threshold to 0.7. Repeat the fifth step and all connections are now found.

The output of the final step is shown in Figure 16. The crosstalk for this bus design is large and will likely result in the failure of any system which uses it.

Once the circuit geometry was captured, the entire process, including the full electromagnetic analysis, required about 45 minutes. If done in the time domain, as much as one week could have been required to develop a lumped model, validate the lumped model, run all the required analyses, and then correctly summarize the massive amount of resulting data needed to rigorously evaluate the

Fifth Step		
Find Connections to Input Ports		
Click Here Find Connections		
Port	Has Input	Vout/Vin
1	1	
2	2	
3	3	
4	4	
5	5	
6	6	
7	7	
63	63	
64	64	
65		0.79
66		0.79
67		0.79
68		0.79
69		0.79

Figure 15. The initial attempt to find connections fails. This is because only about 0.79 volts appears on each output line for 1.0 volt input. Revising the Connection Threshold in the fourth step to 0.7 volts allows the spreadsheet to correctly find all connections.

maximum possible crosstalk.

Final Step	
Calculate Max Crosstalk	
Click Here Calculate Crosstalk	
Port	Cross-Talk
1	34.15%
2	44.49%
3	46.60%
4	47.62%
5	48.10%
6	48.31%
7	48.38%
8	48.38%
9	48.34%
10	48.29%
11	48.25%

Figure 16. When signals are applied to all 64 input ports simultaneously, the maximum possible cross-talk exceeds design requirements by a substantial margin. This circuit will not work reliably with a 1 GHz clock.

Conclusion

Crosstalk can easily result in the failure of a high-speed digital system. The problem is especially acute given, for example, a 1 GHz clock means there are 1,000,000,000 chances every second for the crosstalk from all input signals to occasionally add in phase and create an operational failure. For this reason absolute maximum crosstalk should be calculated to ensure that crosstalk limits are never exceeded.

Calculating absolute maximum crosstalk using a time domain analysis is difficult because a large number of analyses are required when there is a large number of aggressor circuits. In addition, lumped models lose accuracy at high frequencies, where crosstalk is most important.

The absolute maximum crosstalk is easily calculated in the frequency domain by simply assuming all the sine waves from the spectrum of all input signals add in phase. The amplitudes of these sine waves are

determined by means of an electromagnetic analysis. There is no dependence on lumped models at all. All results are based directly on Maxwell's equations. For large circuits, the massive amount of data is easily handled with the described spreadsheet.

Once the absolute maximum crosstalk is determined, design changes can be made early in the design cycle allowing success on first fabrication to become a reality.

Acknowledgement

Detailed comments from Dr. Howard Johnson were particularly helpful in preparing this paper.

References

[1] Y. Eo, W. R. Eisenstadt, J. Y. Jeong, and O. K. Kwon, "A New On-chip Interconnect Crosstalk Model and Experimental Verification for CMOS VLSI Circuit Design," IEEE Trans. On Electron Devices, Vol. 47, No. 1, January 2000, pp. 129 – 140.

[2] Web based calculator at <http://www.solecon.com/rho2ccal.htm>, which uses equations from Thurber, Mattis, Liu, and Filliben, National Bureau of Standards Special Publication 400-64, *The Relationship Between Resistivity and Dopant Density for Phosphorus-and Boron-Doped Silicon* (May 1981), Table 10, Page 34 and Table 14, Page 40

Addendum

Following the submission of the above paper for publication, a problem was found in the spreadsheet. Version 2.0 of the crosstalk spreadsheet has been corrected. The problem concerned the definition of non-50 Ohm S-parameters. There are multiple definitions and the spread sheet used one definition and the electromagnetic analysis used another.

This problem affected only S-parameter results normalized to complex impedances. For the results presented in this paper, only the validation result, Figure 12 is affected. When using the corrected

spreadsheet, calculated crosstalk increases from 5.6 mV to 5.76 mV.

In addition, not mentioned in the body of the paper, the result of Figure 11 was calculated with all ports set to 18 Ohms in the spreadsheet.

In modifying the spreadsheet to correct for the non-50-Ohm S-parameter definition problem, the desired non-50-Ohm S-parameters are now calculated internally. Thus, only 50-Ohm S-parameters are allowed for input to the spreadsheet now. This is actually an advantage because different impedance terminations may be explored by simply changing an entry in the spreadsheet. A repeated electromagnetic analysis is not required.

I hope you find version 2.1 of the Sonnet Crosstalk Spreadsheet to be useful.

-- J. Rautio 24 January 2001