USING AN ELECTROMAGNETIC SIMULATION TOOL FOR DEMONSTRATIONS IN A COURSE ON ELECTRONICS PACKAGING

Harry Kroger*, Jiayuan Fang#, and Yuzhe Chen+

* **Department of Electrical Engineering, State University of New York at Binghamton**
# **Department of Electrical Engineering, University of California at Santa Cruz**
+ **Sigrity, Inc., San Jose, California**

ABSTRACT

This paper presents the experience of using an electromagnetic simulation tool, SPEED97, in a course at the University of Maryland, Baltimore County. SPEED97 is a versatile electrical simulation tool for the analysis and design of electronic packages including chip carriers, multi-chip modules and printed circuit boards. SPEED97 integrates circuit and transmission line simulations with a fast, special-purpose electromagnetic field solver that computes electromagnetic interactions within electronic packages. With SPEED97, the simulation of 3D electromagnetic fields in multiple power and ground planes is orders of magnitude faster than conventional algorithms. The speed and accuracy of these simulations make it an ideal instructional tool in the classroom. The reflections of signals from a variety of terminations on transmission lines are readily set up for study. SPEED97 also offers illuminating demonstrations of the behavior of coupled transmission lines that can assist students in understanding forward and reverse crosstalks. The behavior of the voltage waves between conducting planes can be viewed in striking animations. The effectiveness of placing decoupling capacitors is demonstrated by simple "what-if" experiments to converge to optimal placement. The presentation of the paper also includes illustrations of several of these demonstrations with live computer display.

INTRODUCTION: COURSE DESCRIPTION

The Computer Science and Electrical Engineering Department of the University of Maryland, Baltimore County (UMBC) offered a graduate level course in electronics packaging during the fall semester in 1998. One of the authors (HK) taught this course and also had several times previously taught essentially the same course at the State University of New York (SUNY) at Binghamton. But the availability of a fast, accurate electromagnetic simulation tool for classroom demonstrations permitted an extensive revision of the course at UMBC.

Slightly more than half of the course concerned the electrical engineering aspects of packaging. This covered a review of the basics of transmission lines and a brief discussion of superconducting transmission lines. (Superconducting lines provide an alternative look at the basics rather than a practical and useful example of interconnections.) Cross talk was discussed in detail. CMOS circuits used as drivers and receivers were described. Signal integrity and the low frequency treatment of "delta-I" noise were carefully discussed. The introduction of Sigrity's SPEED97 electromagnetic simulation program helped to provide a review of transmission line basics early in the course, but its use concentrated on cross talk and signal integrity issues, especially the exact treatment of what is termed "delta-I" noise at low frequencies. The basic features of the SPEED97 approach to simulation have been described by Chen et al (1995). Experimental confirmation of the predictions of the program have been achieved in many experiments, beginning with Rosser et al (1996).

The remainder of the course covered topics in routing, thermal management, description of typical boards and packages, packaging materials, measurement and consequences of thermally induced strain, packaging of optical components, and manufacturing processes. This wide range of topics required less intensive discussion. One goal of this latter part of the course was to help electrical engineering students respect the knowledge and contributions of other fields. Basics were emphasized. This included, for example, how thermal contact resistance is measured and how thermal expansion is measured.

In earlier versions the course made extensive use of colleagues' research at SUNY Binghamton. Advanced issues in signal integrity were introduced using computer simulations in Professor Fang's laboratory. The availability of the SPEED97 program compensated in part for not being able to bring the UMBC students to Fang's laboratory.

BASIC TRANSMISSION LINE PROPERTIES

Following a description of packaging trends and providing actual examples of modern board and package structures, the course introduced a review of electromagnetic wave propagation and transmission lines. This review was vital for some students who lack a thorough background in these fields.

Variations of the circuit displayed in Figure 1 were used extensively. The weakly coupled lines are 23 cm long and separated by 0.5 cm. Dielectric layers are set at a thickness of 0.5 mm and a relative dielectric constant of 4.0. The thickness of the trace and plane metal layers was set to be 36 microns with a conductivity of 5.8×10^7 S/m, the conductivity of copper at room temperature. The widths of the lines were chosen to yield a characteristic impedance of 50Ω. SPEED97 calculates the characteristic impedance of lines using the method of moments, so it is a simple iterative process to quickly choose line widths to nearly equal any desired characteristic impedance value.

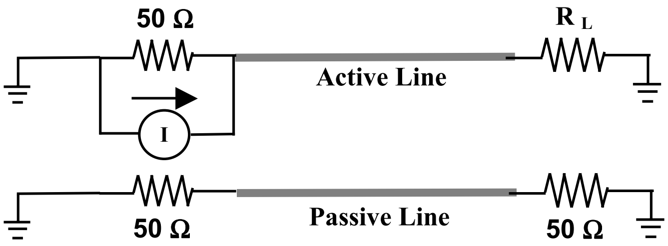

Figure 1. Equivalent circuit extensively used in demonstrations for class. Both active and passive lines had characteristic impedances of approximately 50Ω. For most demonstrations the load resistor was chosen to be 50Ω.

The SPEED97 program served as a summation of this part of the course. It was especially convenient to use, because of the simple structure of the SPEED97 program made it possible to often modify the original program within less than a minute. Instead of a purposeful match in impedance to the transmission line, a lower or higher resistance termination (or a complex impedance) could be introduced quickly. Students often took this brief interval of time between their suggestions and the time to modify the program and the few seconds it took to rerun the program to verbally predict what the result would be. This experience turned out to be an effective learning tool.

Some simulations that illustrate the basic properties of transmission lines are presented in Figures 2-4. All these Figures are reproduced from the SPEED97 program, but in reduced size and without the color that is useful when using the program. For this series of experiments the lines were modeled as microstrip structures.

It has been our experience that it is useful to use both step functions and pulses to introduce cross talk. Students appreciate the decomposition of a pulse into a positive and negative step functions. Comparison between Figures 2 and 3 serves this purpose. An advantage of using a fast simulation tool in class is that students can immediately request to review the previous or an earlier example.

The behavior of transmission lines with mismatched terminations is illustrated in Figure 4. Students usually can predict what the results of most simulations will be, so seeing the evolution of their expectations is a useful reinforcement of their knowledge. The obvious results of reflections from higher or lower resistance terminations than the characteristic impedance of lines are illustrated in Figure 4a. There are also effects on the passive lines. Figure 4b illustrates that the pulse reflected from the 60Ω termination on the active line generates a "forward cross talk" that is received by the near end termination on the passive line. Other mismatches were explored in class, including resistances less then the characteristic impedance, complex impedance mismatches, as well as mismatches on both the passive and active lines.

STRIP LINE CIRCUITS AND VIAS

SPEED97 can also address problems involving strip line structures, for which metal strips are embedded in a homogeneous medium.

There can be significant differences in how signals are applied to or extracted from strip line structures: Are the signals to a strip line applied symmetrically from above and below (which will not cause radial modes between the conductor planes to be excited)? Or are the strip lines excited from only one side of the surrounding conducting planes which may excite parallel plate mode fields?

Vias which carry currents between conducting planes will excite radial modes between these conducting planes. These radial modes will affect other vias and therefore this type of interaction has extremely important significance for signal integrity. Resonances determined by the lateral dimensions of the circuit board can be especially disruptive. (Fang et al, 1998).

If the strip lines are driven from within the same layer or by symmetrical connections from both the upper and lower level conducting planes, than no forward cross talk is observed because this is now a homogeneous configuration. The simulations confirm this so long as via coupling is not involved. The only signals detected on the far end of the passive line are reflections from the near end cross talk from an imperfectly matched termination as shown in Figure 5.

Simulations for the case where the lines are driven asymmetrically are presented in Figure 6. The effect of vias is substantial. The via effect on cross talk has been carefully investigated by Zhao and Fang (1997).

Excitation of the electromagnetic waves that propagate between the conducting planes greatly changes the amount and qualitative appearance of cross talk. Comparing Figures 5 and 6b, we can see that the near end cross talk on the passive line has increased by a factor of 50. The far end cross talk has increased from essential zero to be comparable to the increased near end cross talk. The coupling to

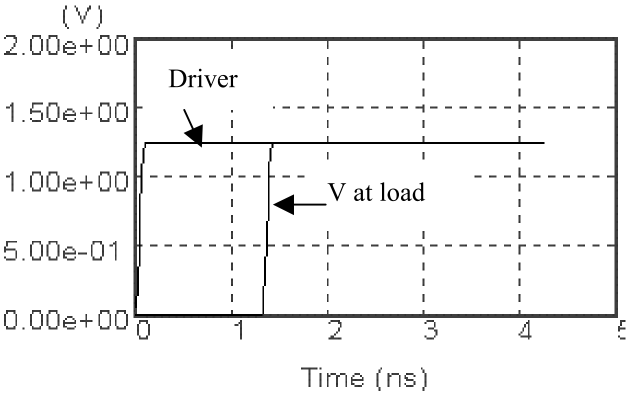

Figure 2a. Transmitted and received step voltage signals for active line in microstrip circuit. Load impedance is 50Ω.

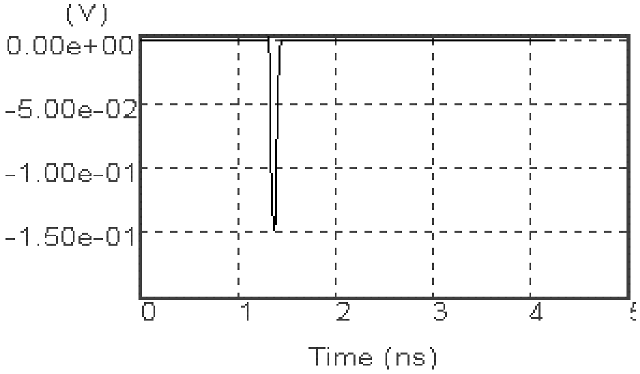

Figure 2b. Far end cross talk on passive line for step voltage microstrip circuit. Load impedance is 50Ω.

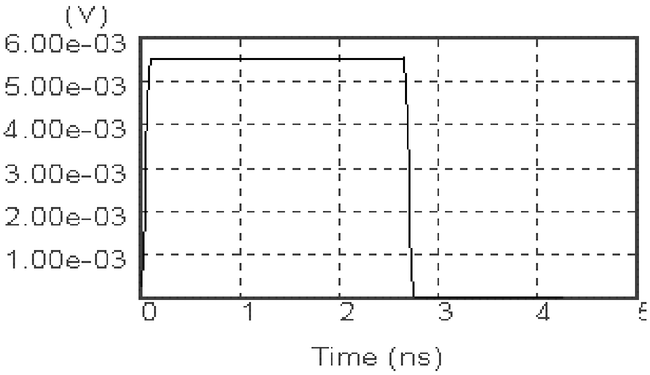

Figure 2c. Near end cross talk for step voltage on microstrip line. Load impedance is 50Ω.

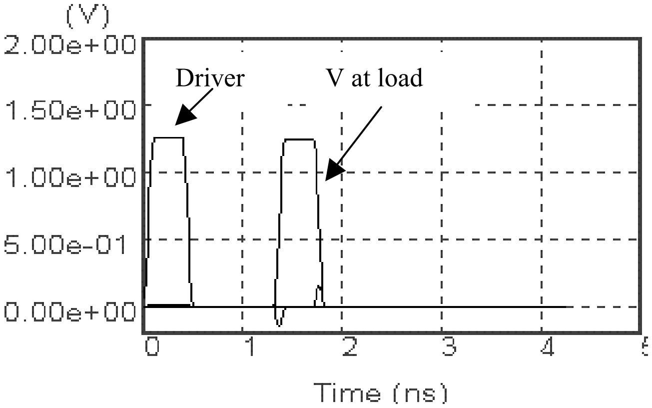

Figure 3a. Transmitted and received pulse signals on active microstrip line. Load impedance is 50Ω.

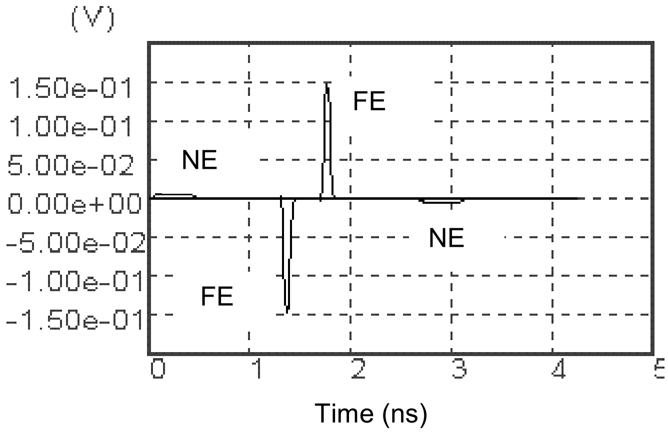

Figure 3b. Signals received at ends of passive microstrip line. Load impedance on active line is 50Ω.

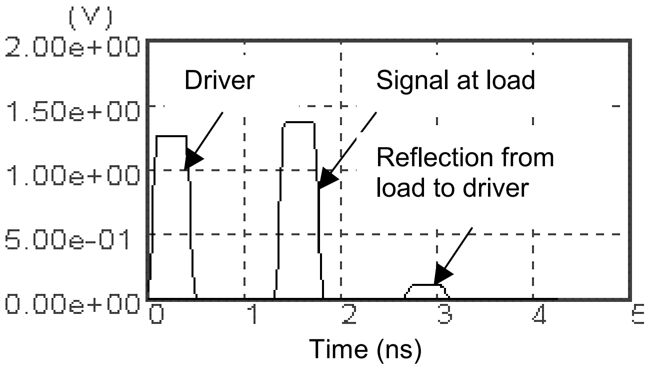

Figure 4a. Transmitted and received pulses on active line with load resistance on active line equal to 60Ω.

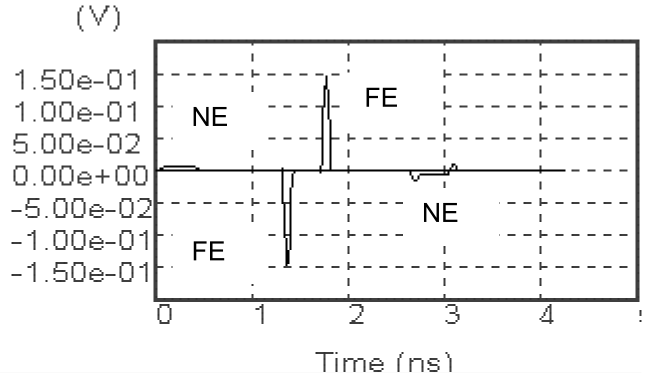

Figure 4b. Signals received on passive line with load resistance on active line equal to 60Ω.

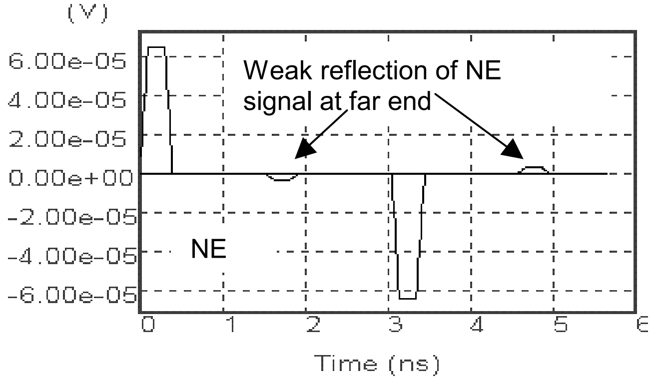

Fig 5. Signals received on passive line of coupled strip line pair. Note absence of large forward cross talk.

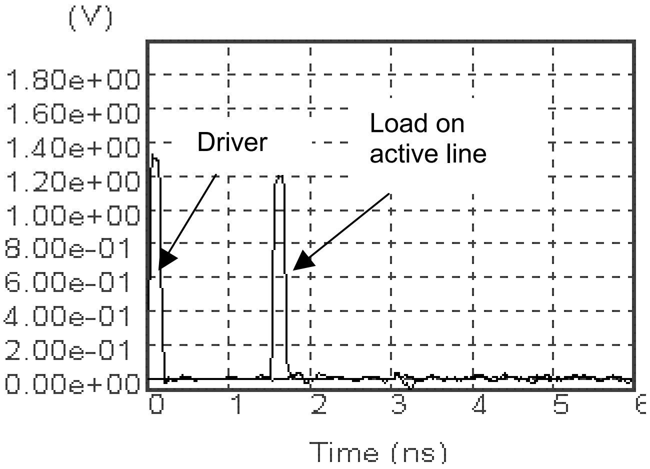

Figure 6a. Transmitted and received pulses on active line of asymmetrically driven strip lines.

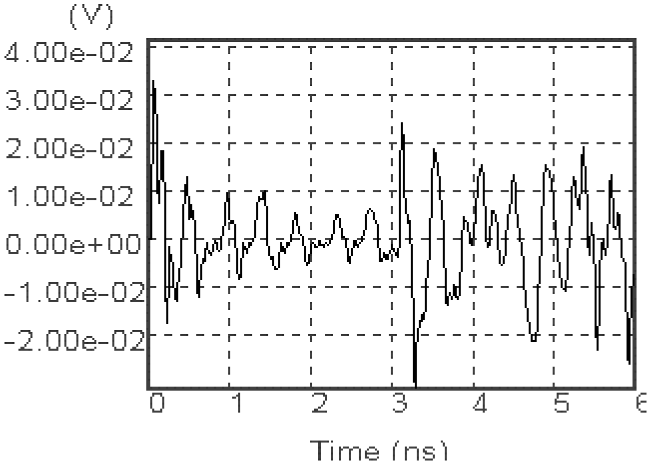

Figure 6b. Signal received at near end of passive line of asymmetrically driven strip line.

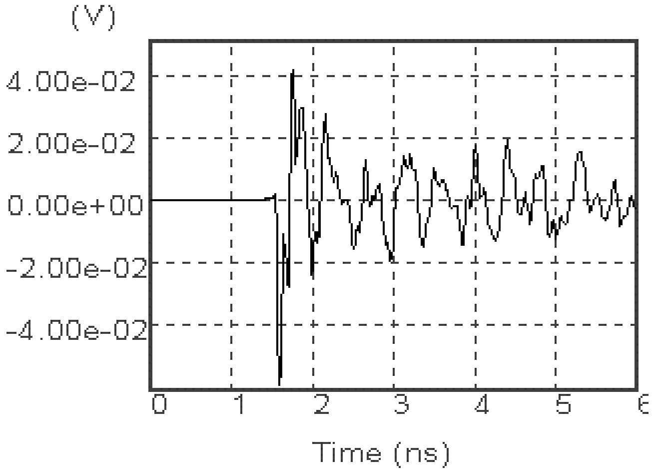

Figure 6c. Signal received at far end of passive line of asymmetrically driven strip line.

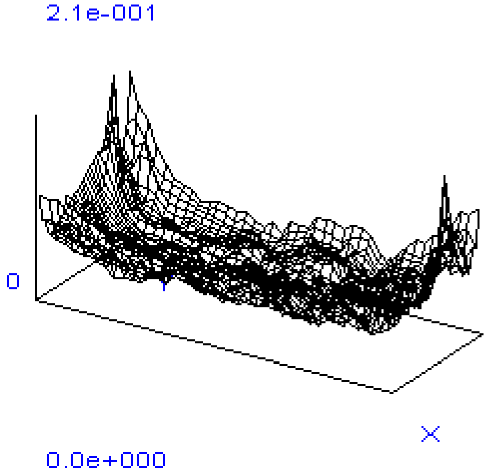

Figure 6d. Peak voltage observed during simulation run between conducting planes.

the radial electromagnetic modes and their reaction back on the lines and vias has added more cross talk and disturbed the signal integrity to a much greater extent than has the direct mutual coupling along the traces themselves. Figure 6d presents the maximum voltage between the conducting planes recorded at each mesh site during the simulation. The driver is near the left hand edge of the circuit board and the load is near the right hand edge.

SIMULATING DIFFERENTIAL DRIVERS

It is possible to simulate coupled lines which have drivers on both lines. This is illustrated in Figure 7 and we assume that the two pulse drivers have opposite polarity. We will simulate only two cases for relative delay between the pulses: either complete overlap in time or having the second pulse start as soon as the first one ends, although the SPEED97 program will permit arbitrary relative delays. In these simulation experiments the trapezoidal pulse was chosen to have rise and fall times of 50 ps and a length of 100 ps. Thus when a delay was assumed to be 200 ps to precisely avoid overlap. We assume that the excitation is asymmetrical with respect to the conducting planes that lie above and below the coupled strip lines and therefore the radial modes of the conducting planes will be excited.

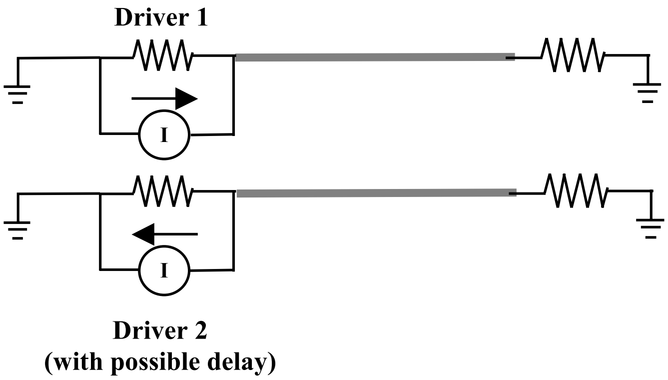

Figure 7. Double driver circuits used to simulate results in Figures 8 – 10.

Figures 8 and 9 show the transmitted and received waveforms. It is not evident from these illustrations that the zero delay case presents much quieter signals at both the near and far ends, because SPEED97 normalizes waveforms relative to their highest value. Additional curves could have shown this, but there is a more direct way. SPEED97 can perform statistical summaries of simulations. In particular, it can plot the number of mesh locations that have attained particular values of voltage between two metal planes during the simulation. Figure 10 presents the results for the overlapping and non-overlap simulations. With complete overlap, it is clear that the noise generated by the electromagnetic waves propagating between conductor planes is substantially reduced. The value of differential driving is confirmed by these simulations.

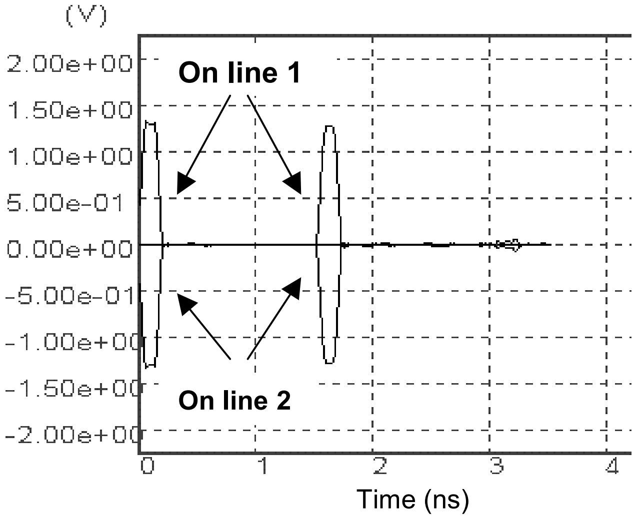

Figure 8. Transmitted and received pulses with no delay between transmitted pulses. Asymmetric drive.

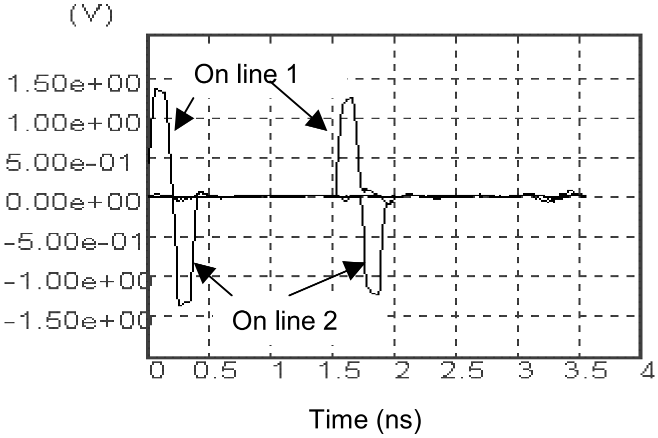

Figure 9. Transmitted and received pulses with 200ps delay between positive and negative pulses. Asymmetric drive.

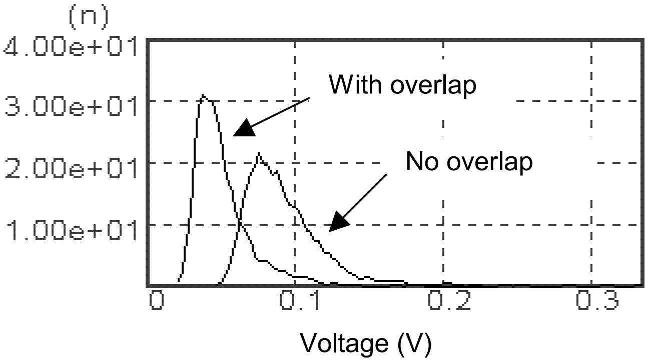

Figure 10. Number of mesh locations (n) between the conducting planes that obtained a maxim voltage during the simulation run. The zero delay clearly reduces the noise relative to the non-overlap case.

OTHER CAPABILITIES AND STUDENT INTEREST IN SPEED97

There are other important and significant capabilities of SPEED97 that is worth to mention. The Sigrity web site (http://sigrity.com) has many reprints, comments and illustrations. Two were extremely impressive to students at UMBC. The question of where to place a decoupling capacitor drew rave reviews from both students and a faculty member who attended most of the lectures. The Sigrity discussion of impedance of circuit boards as a function of frequency is also important. Rather than simply review the Sigrity discussion, the problem was set up and run in class, in part because this illustrated the capability of SPEED97 to perform fast Fourier transforms

The students also appreciated more complex demonstrations that involved intelligent guessing as to where to place several decoupling capacitors when there were several simultaneously switching current sources. Students enjoyed predicting which placement would be most efficient. Students also requested demonstrations of how the forward cross talk would change as the thickness of the dielectric above a microstrip structure was increased as the structure thereby approaches a homogeneous configuration.

More complex examples were also studied in class. One example resulted from a real world problem. This was a strip line circuit in which three lines were mutually coupled. Repetitive input pulses and coupling to radial modes resulted in extremely complex waveforms on the passive lines. By using single pulse inputs and varying terminating resistor values to affect reflections it was possible to sort out the origin of most of the features in the simulated waveforms.

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