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Optimizing Symmetry in Open Field Designs

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Abstract

This paper discusses the increasing problems of channel crosstalk and insertion loss drop outs. We discuss many potential causes of drop outs, and focus on one source related to crosstalk. We show that this crosstalk is at its maximum at ½ the electrical wavelength of the channel.

Through a series of experiments based on full wave electromagnetic simulations, we demonstrate that such crosstalk and related insertion loss resonances are highly dependent upon conductor shape and position.

We demonstrate a novel approach for positioning an array of conductors which leads to improved crosstalk cancellation and minimal insertion loss resonances. This approach leads to higher useful bandwidth, greater signal density and signal assignment flexibility.

Authors Biographies

Gary Biddle received his BS in Physics from University of Florida 1976 and MS in Physics from Penn State University 1991. His work experience includes high frequency VNA and EMI measurements, along with nearly 20 years of simulating PCB and interconnect structures. He has published several articles and holds several patents.

Julian Ferry earned a BSEE with an emphasis in RF and microwave engineering from Penn State University, University Park, PA. He has more than 28 years of experience in the high speed interconnect industry, focusing on product design and development, test and simulation, and team management. Julian has authored over 30 articles and papers and has been granted around 20 U.S. and international patents related to products for improved Signal Integrity and EMC performance.

Introduction

Crosstalk and insertion loss resonances in the interconnect path are a growing concern for high speed system designers.

It's well known that crosstalk usually increases as base data rate increases and as signal switching times decrease. However, crosstalk issues are also exacerbated by other recent system trends.

The desire for smaller devices and a move to multiple signal lines combine to increase interconnect signal density. This is troublesome since crosstalk tends to increase as a function of distance squared.

Also of concern is the increasing use of digital and analog signal processing. While such processing minimizes other signal integrity problems, such as reflections and attenuation, signal processing is less effective at mitigating problems caused by crosstalk. Thus crosstalk often becomes the first cause of interconnect noncompliance.

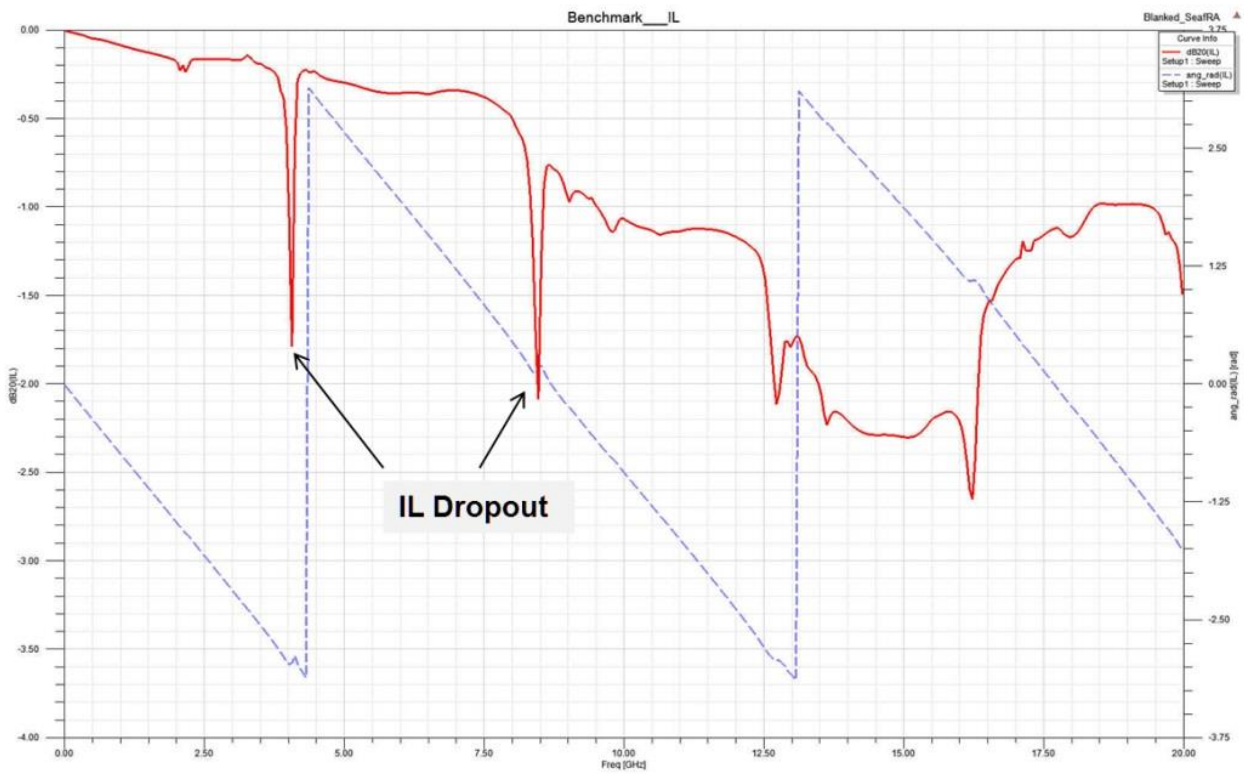
A more recent signal integrity concern is insertion loss resonances or drop outs. While such anomalies have always existed, they usually occurred at frequencies beyond those of concern in most systems. However, as clock speeds increase, they can become a problem, especially if they occur at the fundamental frequency. Drop outs might also impact digital signal processing since certain mathematical assumptions may be violated.

In this paper, we first explore some well-known causes of insertion loss resonances. We then focus on resonances caused by crosstalk or coupled noise. We show that by minimizing crosstalk, we can also reduce certain insertion loss resonances. Traditional techniques for reducing crosstalk add cost and complexity, and often decrease signal density. We investigate another approach: using symmetrical orientation and spacing of conductors to minimize both crosstalk and resonances.

Through experimentation using full wave electromagnetic simulations, we analyze and quantify various causes of crosstalk and resonances in typical multi-conductor arrangements. Our initial experiments are carried out on general conductor geometries and arrangements commonly found in connectors, PCBs and semiconductor packaging. We follow with an example of an open pin field connector. Such connectors are particularly prone to resonance and crosstalk problems. We conclude by presenting data for a new connector design concept with minimal conductor count, high density, and crosstalk and resonance performance allowing use to 40-50 Gbps.

Insertion Loss Resonances

Resonances in insertion loss or attenuation curves have been with us for a very long time, so many of their causes are well understood. They are generally considered to be deviations from the "ideal" or expected shape of the curve. They are sometimes referred to as "suck outs", "drop outs", or "notches". The effects of the drop outs also appear as anomalies in the shape of the insertion loss phase angle curve.



A quick search of signal integrity literature will provide many discussions of the causes and effects of such drop outs, from basic introductory level training to current bleeding edge research papers. [Reference 1]

The most common and well understood cause is multiple impedance mismatches within a channel or at the channel's boundaries. Such mismatches cause maximum resonances when the discontinuities occur at multiples of 1/4 of the electrical length of the channel. These are often referred to as "quarter wavelength resonances". They can be analyzed readily using transmission line theory.

In the examples we analyze, such mismatches can occur within a connector or package, within the PCB, and/or between the various devices in any combination.

The well-known issue of via stub resonances can be characterized as a wavelength dependent impedance mismatch. As signal speeds increase, small stubs within a connector or IC package, such as retention or processing features, can cause similar problems.

Sometimes severe resonances can appear as a result of multiple impedance discontinuities spaced repeatedly along the channel path. This is common in some cable structures, but can also occur in PCBs due to evenly spaced interconnection points along a bus, or sometimes even by glass weave effects. This phenomenon is often referred to as "structural return loss".

Other resonances are caused by relatively well known and understood phenomena such as radiation (covered by antenna theory) and crosstalk (covered by multiline transmission line theory). But as we work our way through a system, minimizing each known source as we go, we sometimes encounter resonances which can't be explained by the above phenomena.

We can sometimes use other frames of reference, and associated math, to characterize and mitigate these problems. Some typical approaches are to describe and analyze the problems as parallel plate resonances, cavity resonances, transverse or horizontal propagation modes, common mode resonances, or more generally, non-TEM mode resonances. While the naming conventions are somewhat ambiguous, the common defining factor is that whatever the causes, they are not well defined by traditional empirical solutions.

Therefore, to fully characterize and analyze these problems, it's best to use full wave 3D electromagnetic simulations. With a proper simulation, we are assured that any and all phenomena mentioned above will be captured in our analysis.

The Impact of Electrical Length

Most of these phenomena have a direct relationship to the electrical length of the channel. They typically become an important consideration when the signal path is long in relation to the dominant frequency content of the signal.

Many resonances begin to appear when the channel length approaches 1/2 the wavelength of the signal for purely sinusoidal signals. However, the issue becomes less clear with typical pulse-based signaling schemes, since the sinusoidal frequency content is often unclear. To understand the impact of resonances and crosstalk on final system performance, a secondary simulation in a circuit simulation type tool may be required.

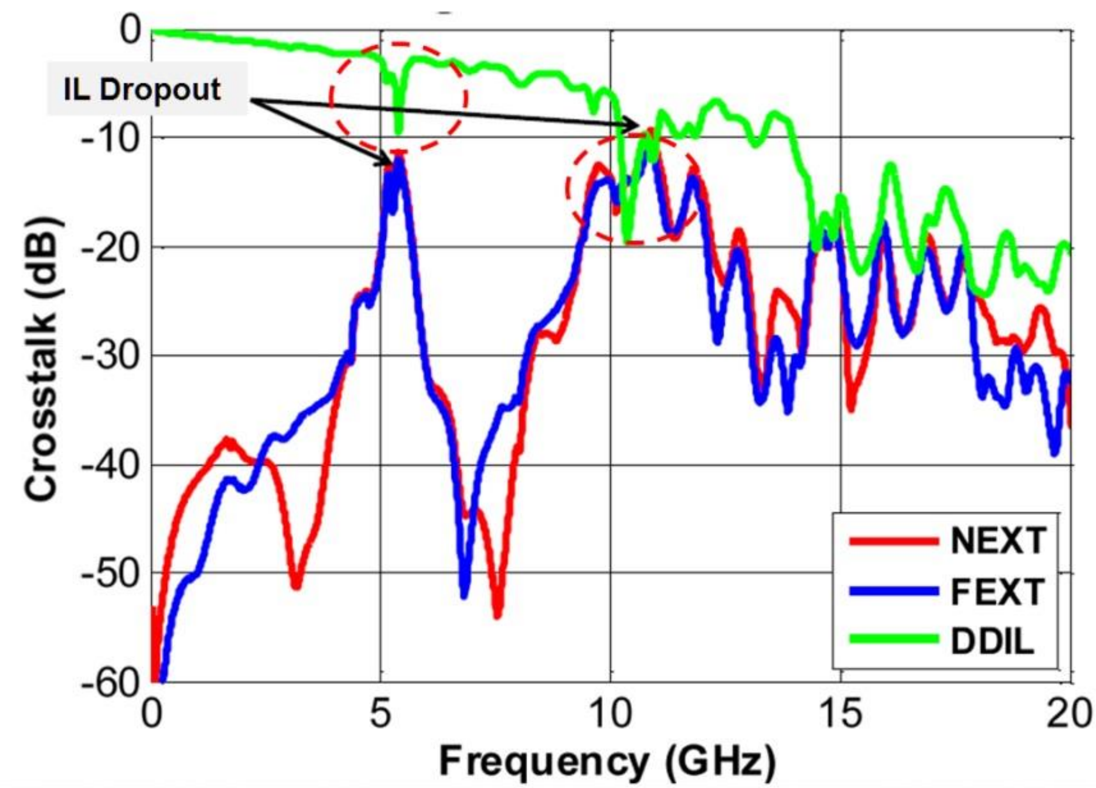
The type and severity of problems potentially caused by insertion loss drop outs are currently subject to some debate. Most analog equalization schemes can compensate for losses described by a well behaved curve, but they cannot compensate for an unexpected drop out. It's also possible that drop out might violate certain mathematical assumptions upon which more complex digital signal processing schemes are based.

The depth of a notch may appear disturbing when examining the performance of a connector in isolation, yet in a typical application, the drop will be much less severe. Such resonances are often damped by losses elsewhere in the system, such as in PCB traces.

Nonetheless, engineering prudence encourages avoiding such resonances if possible and practical. This is especially true if they occur near a frequency in which significant signal content is concentrated. While negative effects might not appear in the drive channel (i.e., the one experiencing the drop out), or in other channels nearby, we must keep in mind that the lost energy “went somewhere”. It’s possible it could cause problems elsewhere in the system, such as EMI issues, which may not become apparent until final system testing.

In-depth Analysis of Crosstalk

While investigating these issues, we found that some of the more insidious resonances are caused by a form of crosstalk. Below are overlaid plots of crosstalk and insertion loss for a common commercially available connector. We can see that the crosstalk peaks at the first insertion loss drop out, just above 5 GHz. This happens again a bit above 10 GHz.



If we can reduce this crosstalk, we can “kill two birds with one stone”. Not only do we increase channel bandwidth by minimizing potential crosstalk problems, but we greatly reduce or even eliminate the insertion loss resonances.

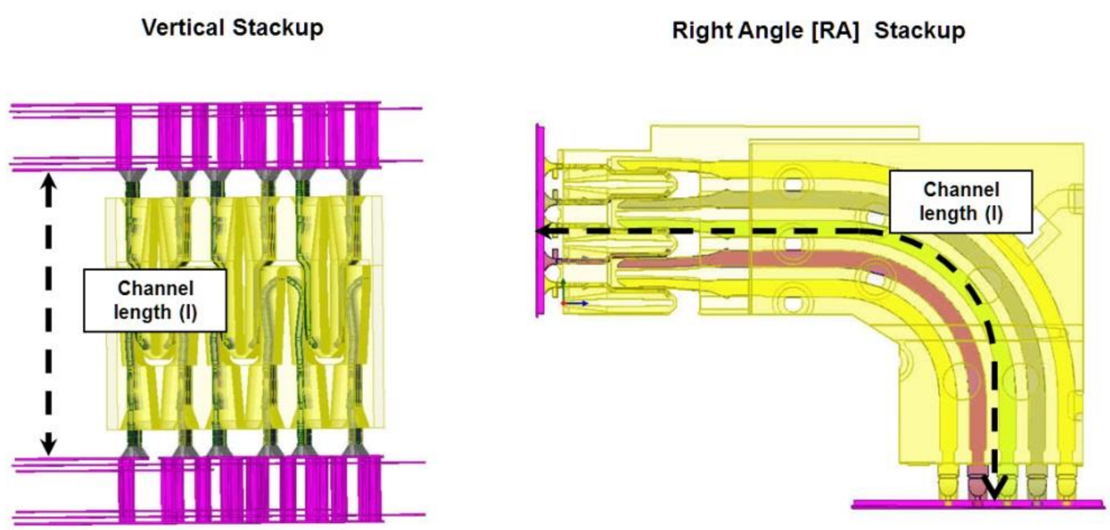
In this paper, we define crosstalk or coupled noise as any undesirable signal generated from energy within the system itself, as opposed to external (sometimes referred to as “alien”) coupled noise. However, many techniques used to mitigate problems with internal noise will also reduce problems arising from external noise, and can also lead to improvement in EMI emissions.

We will focus on differential signaling, since it is most prevalent at today's highest data rates. But to get an in-depth understanding of the issues at play, we break the coupling down into its individual components, examining both electric and magnetic coupling. Electric coupling can sometimes be minimized by using shields and/or low dielectric constant materials. However, magnetic coupling can be much more difficult to control.

Establishing Crosstalk Peaks with Transmission Line Theory

A set of conductors arranged in an array, as in a typical open pin field connector or multiple PCB traces, will have natural resonance modes which are directly related to the channel path length.

For analyzing a connector, we can define the channel length as follows:



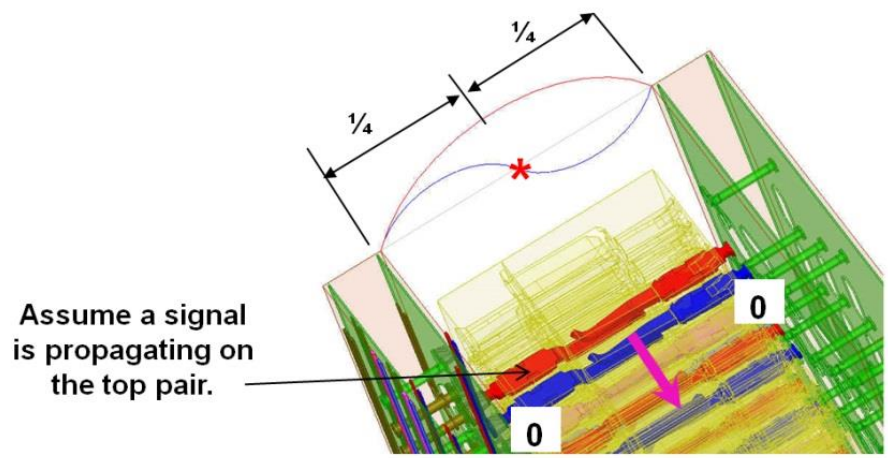
The portions in pink represent the boundary of the PCBs to which the connector is attached. For the most straightforward analysis, this boundary will be a ground plane.

Coupling between two parallel conductors that define a transmission line is frequency dependent. Potentials induced on nearby conductors are similarly frequency dependent. Thus coupling is therefore dependent upon signal wavelength.

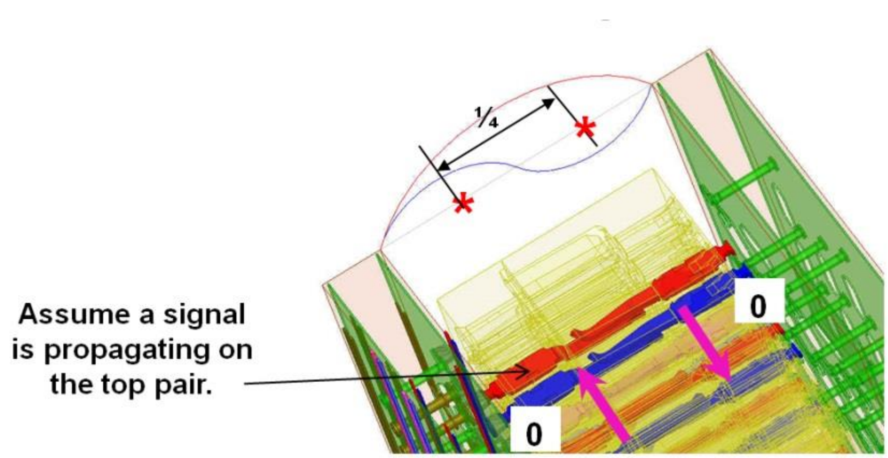
This frequency dependence can be visualized with the example of a directional coupler. In such designs, maximum energy transfer occurs when the electrical lengths of the lines are equal to phase points of 90 degrees, or at one half the signal's wavelength. A very thorough analysis of this type of structure can be found in Samtec's Golden Standard Reference paper series. [Reference 2]

Such an analysis can be extended to multi conductor arrays. [Reference 3]

In the connector channel below, the red and the blue lines represent the first and second resonant frequencies or the half and quarter wavelengths. The pink arrow represents the area of greatest E-field coupling from the aggressor pair to the victim pair. At the half wave length resonance point, the maximum EMF (electromagnetic field) will occur in the center along the length of the victim pair, with EMFs distributed equally along the entire channel length. Assuming a perfect impedance match, at either end of the line, the energy goes to zero by definition of the boundary conditions.



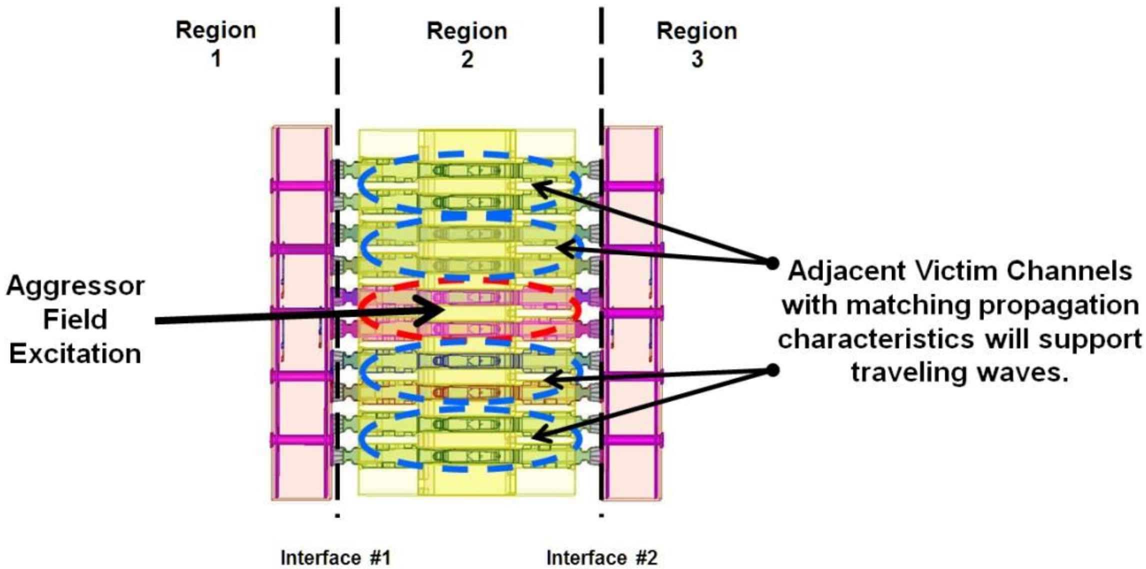
At the quarter wavelength frequency, the induced EMFs will be of lesser magnitude. They will eventually move to zero in the middle of the pair. This corresponds to the point indicated by the asterisk.



In further analyzing the quarter wavelength resonant condition, we see that the polarity of the signal is different in each segment. Therefore, the induced EMFs will occur in opposite directions (see pink arrows). This leads to some cancellation of energy coupled between the two pairs.

As we move into higher multiple resonance points (1/8, 1/16 wavelength, etc.), we observe even more cancellation along the length of the conductors. Thus, we find that maximum coupling occurs at the ½ wavelength frequency.

This problem can be compounded in a large array of equally spaced conductors. The induced EMFs can, in certain conditions, begin to add constructively. This can have the effect of turning the array into an efficient transmission line that allows energy to propagate horizontally or transversely across the array. Because off the cancelling effect at shorter wavelengths discussed earlier, this effect will be maximized at half wavelength frequencies as well.

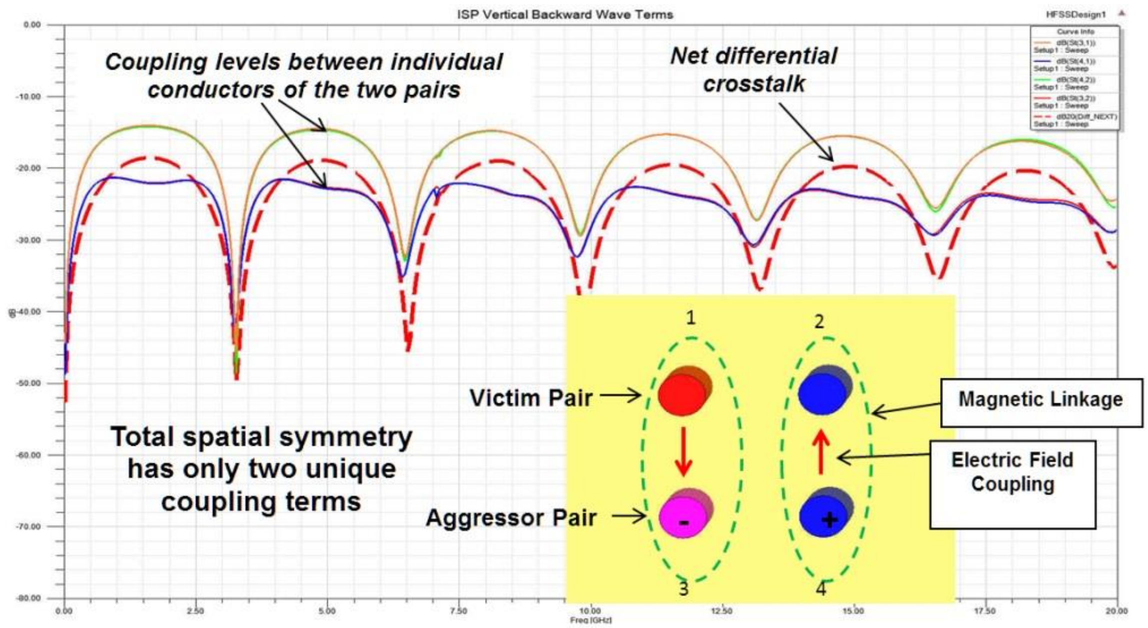


Minimizing Crosstalk

Some traditional approaches to reduce crosstalk are to increase spacing between pairs, and/or add shields or grounds. Increasing the spacing almost always works; however, it comes with the penalty of decreased signal density. Shields and grounds also have a density penalty. And once we reach the half wavelength frequency, as discussed earlier, they can lose their effectiveness. In fact, in some cases, for example if the resonance is a cavity type, the shields can actually exacerbate the problems.

We have found that by creative use of conductor shape and orientation, we can achieve significant crosstalk reduction across a wide bandwidth, including at the ½ wavelength resonance frequency. Simultaneously, many insertion loss drop outs can be eliminated.

To develop a basic understanding of the phenomena that lead to crosstalk, we begin by analyzing all potential coupling situations between the four individual conductors of two differential pairs.



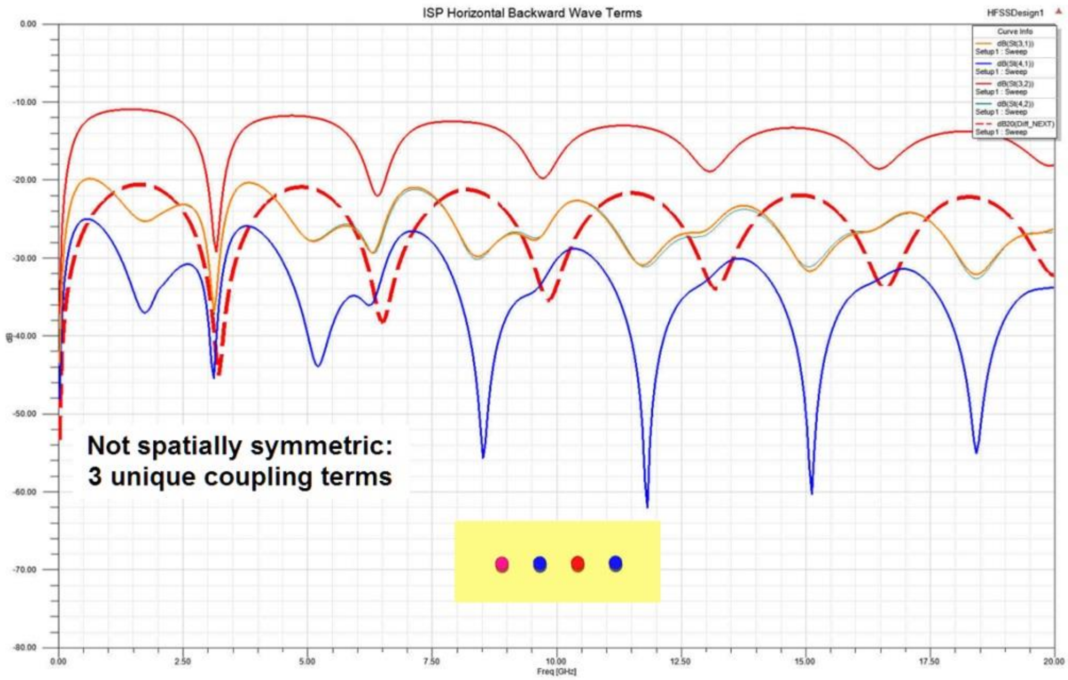
The vertical axis is in dB of loss or isolation. The plots represent the amount of coupling that occurs between two conductors at the various frequency points across the horizontal axis. The four dots at the bottom of the plot represent the cross section view of four conductors. The conductors are driven as differential pairs. The two on the top are a pair, and the two on the bottom are another pair. We've numbered them 1, 2, 3, and 4, starting with 1 on the top left, proceeding clockwise. 1 and 2 are defined as a differential pair, and 3 and 4 as another differential pair.

The solid plots on the graph represent the amount of coupling between various conductors. Per the key in the upper right, the first plot (orange) is the amount of coupling between conductor 1 and conductor 3. The second plot (blue) is the amount of coupling between conductor 1 and conductor 4. Note that 1 and 4 are farther apart than 1 and 3, so the amount of coupling is less.

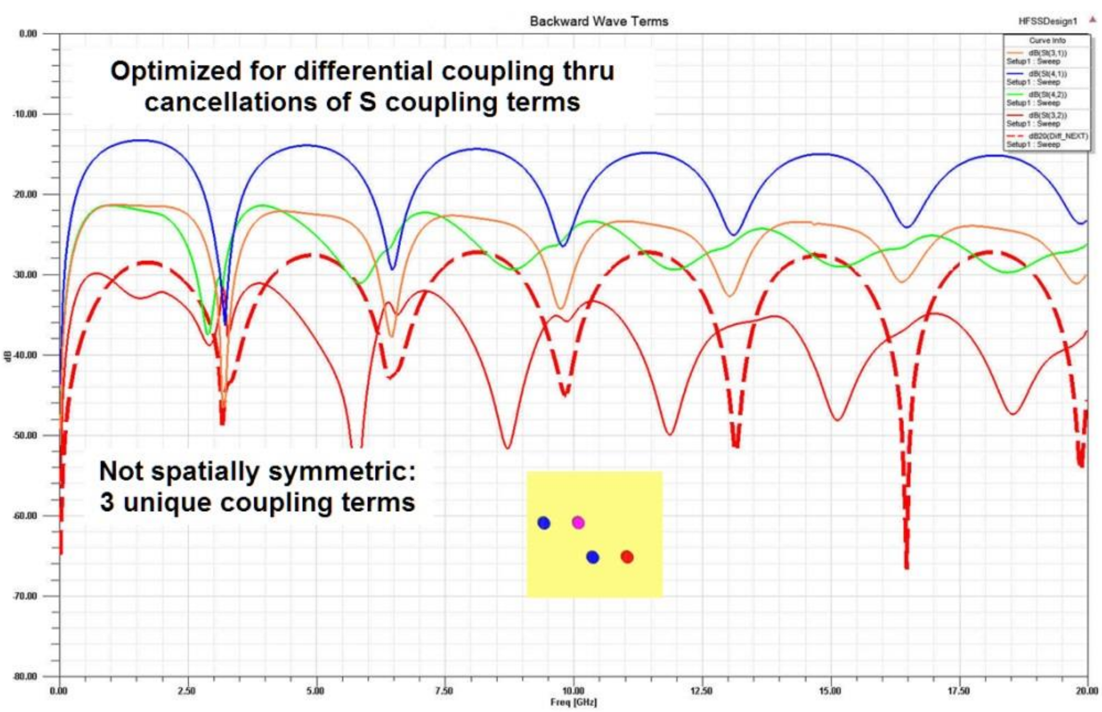
The next plot is solid red, which is coupling between conductors 2 and 3. Since these are the same distance apart as conductors 1 and 4, their coupling is identical. The next plot, green, is the amount of coupling between conductors 2 and 4. Since their spacing is identical to that of 1 and 3, the amount of coupling is the same, so the traces overlap. Because of the spatial symmetry, we find only two unique coupling terms.

The dashed red line shows what happens when one pair is driven differentially, and the other receives differentially. This is in effect the net differential crosstalk between the two pairs. It is the algebraic sum of the four solid plots above.

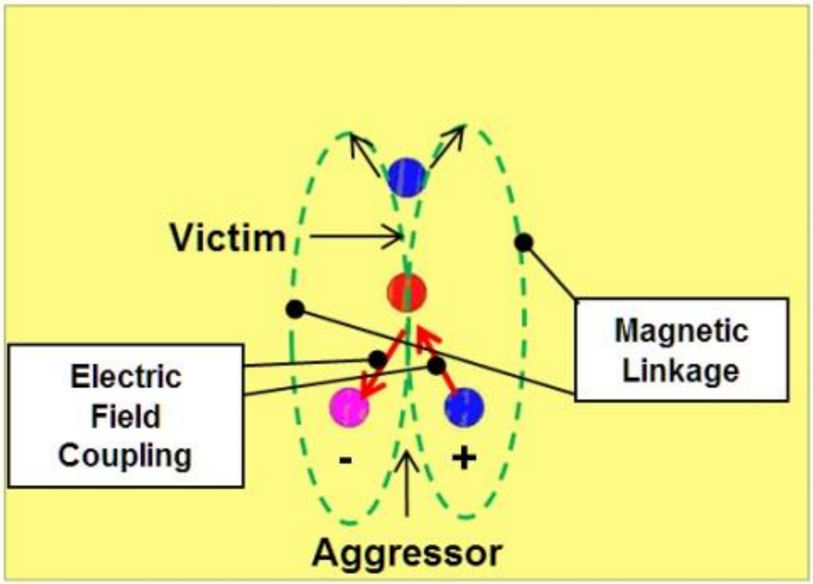
We performed a similar analysis on several common conductor arrangements. An even planar distribution yields three distinct coupling terms as shown below. The color and labeling conventions are the same as above. Note that a vertical arrangement would behave similarly.



We also examined an offset configuration, as below. It also has three coupling factors

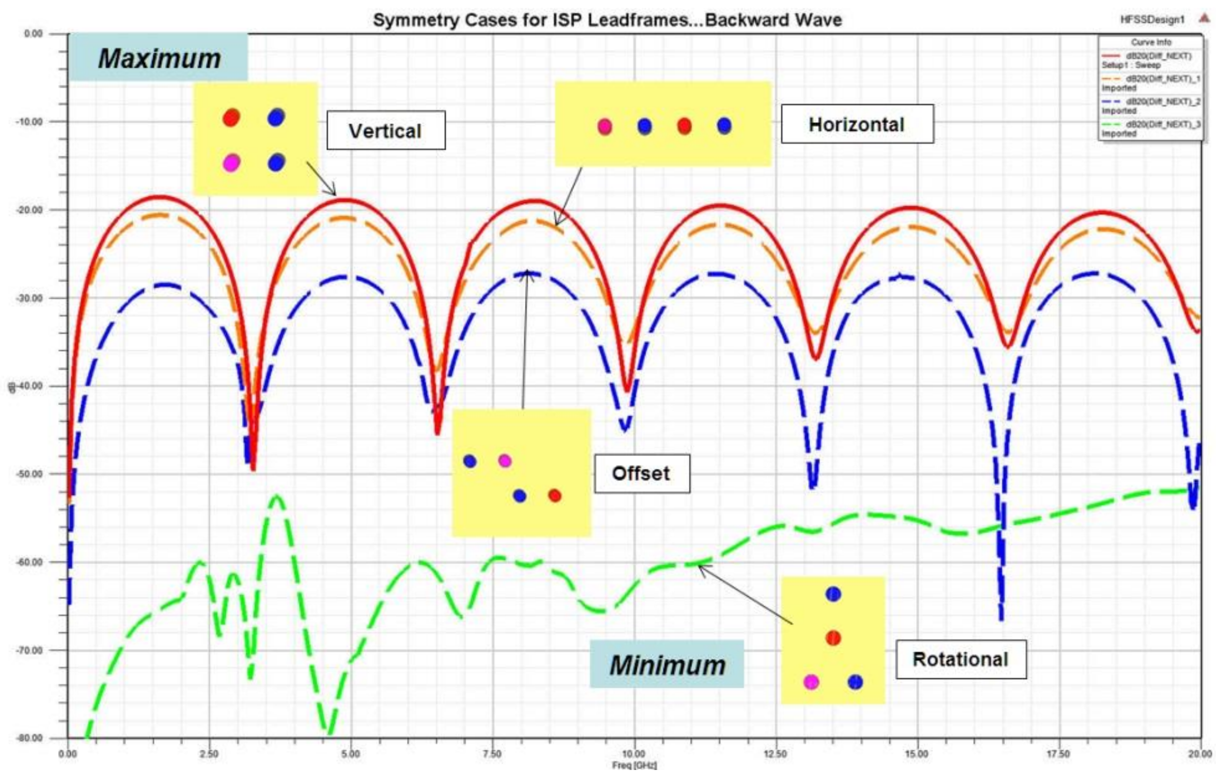


Through careful analysis, it is observed that different geometric arrangements offer different levels of field cancellation and the greater the cancellation, the lower the crosstalk. This insight leads to an optimal geometric spacing solution shown below.



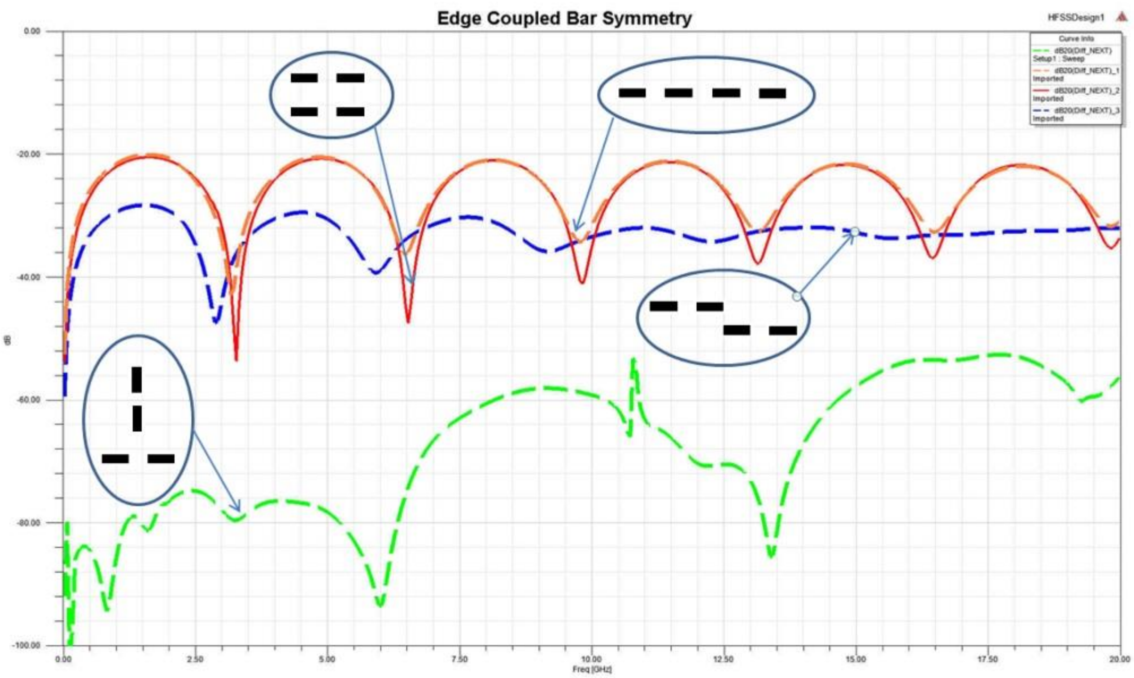
This arrangement also has only two coupling terms, like the first case we analyzed, so it can also be considered to have perfect symmetry. However with this rotated arrangement, both the magnetic and electric couplings perfectly cancel out. So while the perfect symmetry leads to maximum possible coupling in the first case, the rotational symmetry provides the minimum possible coupling.

The net sum crosstalk for each of the four arrangements is plotted on one graph below. This plot clearly shows the low level of crosstalk inherent to the rotated case.



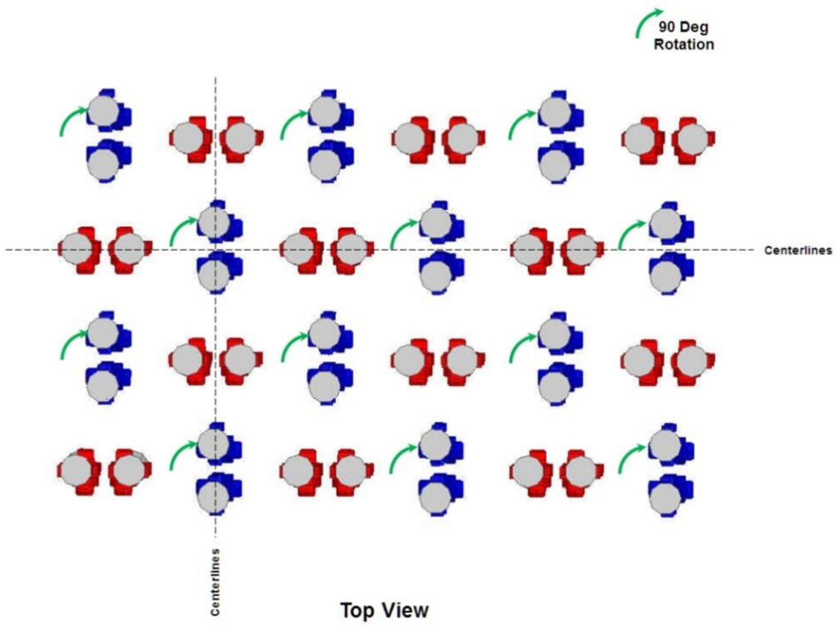
Designing a Real World Solution

While circular conductors produce the best case scenario, they are not practical to fabricate in the real world. Therefore, we also performed this analysis using rectangular cross sections. The net results are presented below. While the levels are slightly different, the rotational complementary symmetry again shows the minimum coupling arrangement. Note a slight perturbation in the crosstalk has appeared near the half wavelength frequency.

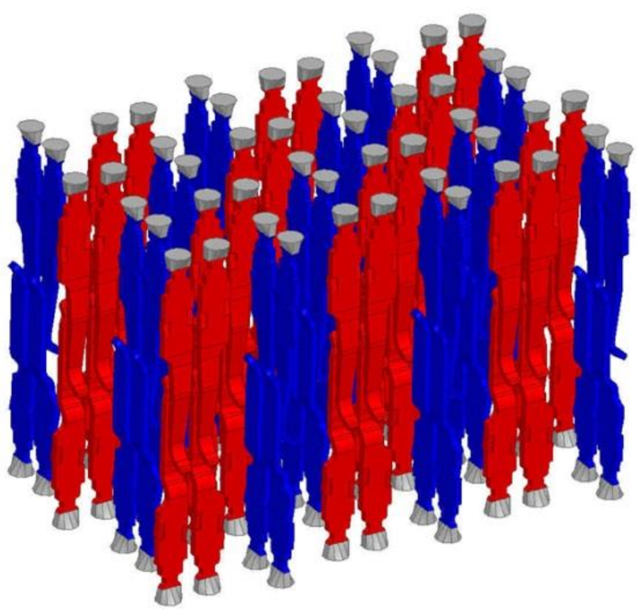


Implementing a rotational configuration in a real world connector system requires many further compromises from the rectangular cross section case. But an initial concept shows excellent potential for very low crosstalk and resonance free insertion loss to beyond 30 GHz for a 7 mm tall design.

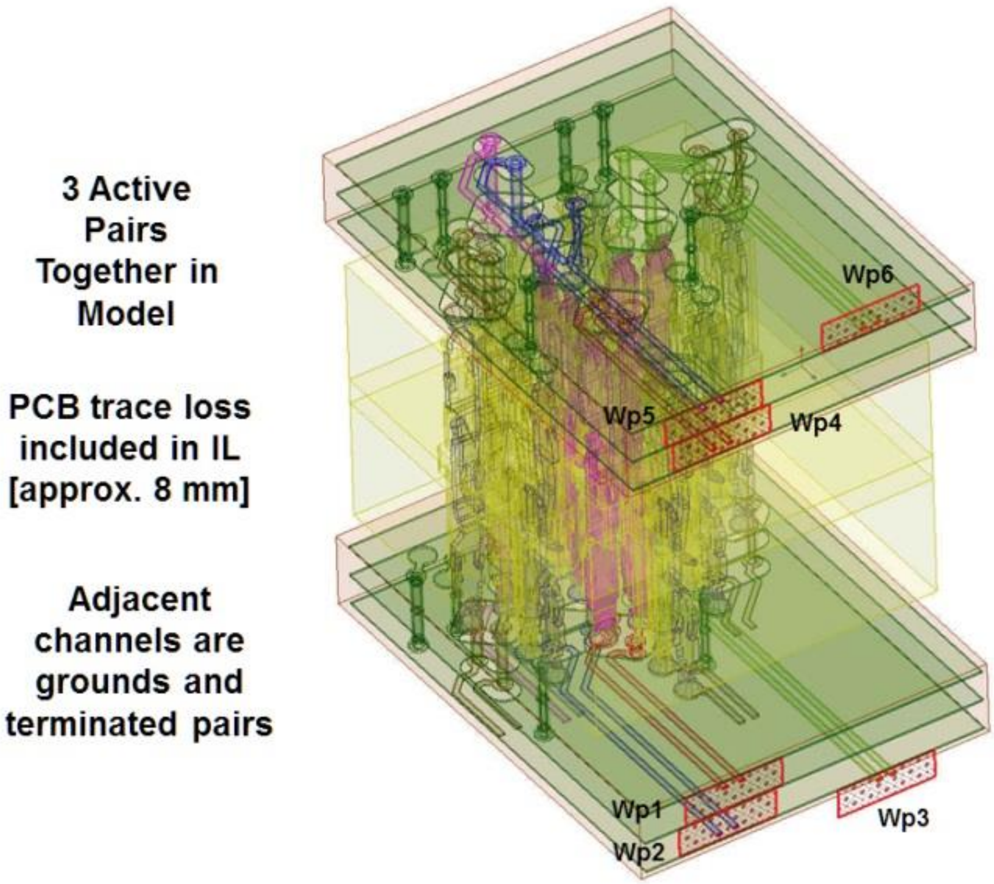
Below is a view of an optimal arrangement of terminals. The gray circles represent solder balls on the end of the terminals, and the thicker, slightly off balance rectangles are retention features that anchor the terminals in a plastic housing. The terminals within a pair are edge coupled, as above.



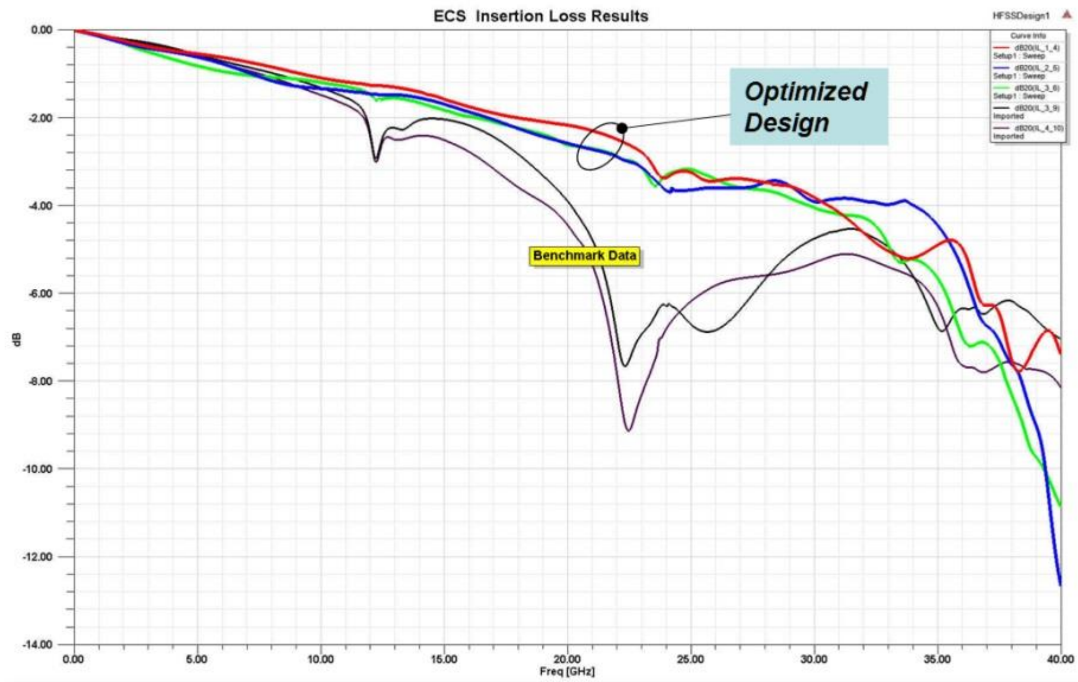
This 3D view shows the terminal's features from an angle.

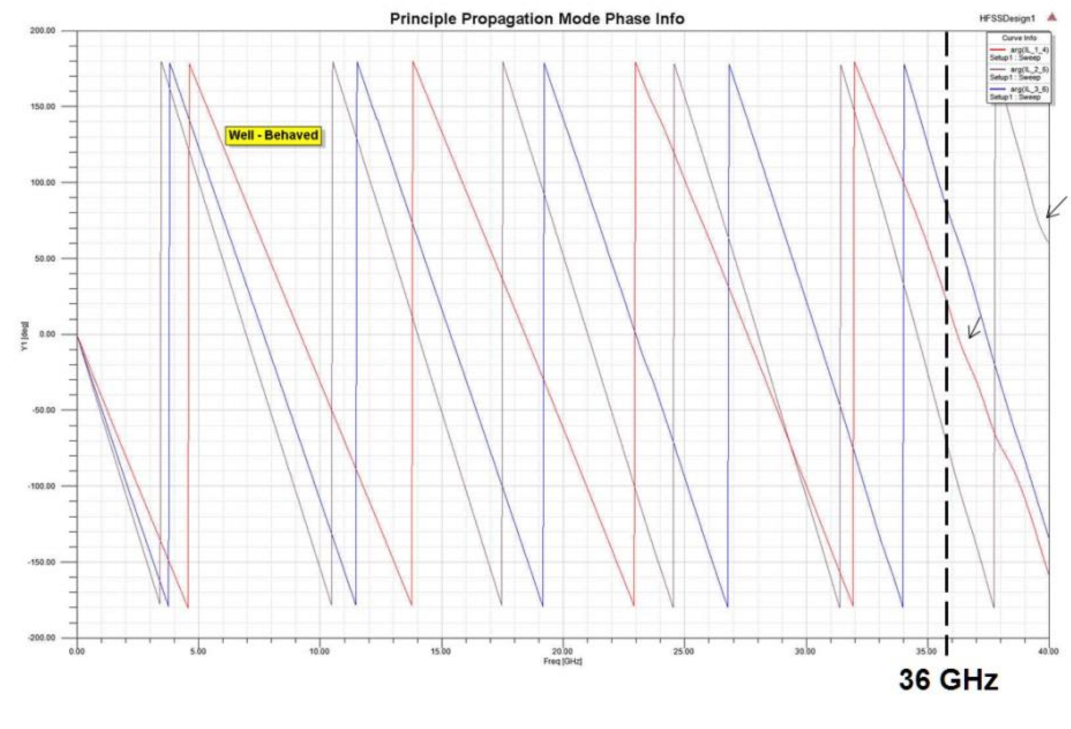


While reducing the crosstalk eliminates one source of insertion loss resonances, as mentioned earlier, resonances can still appear unexpectedly due to other causes. To analyze any potential resonances generated by effects occurring elsewhere in the channel, such as skew or cavity resonances, we performed several simulations of this connector concept which included typical PCB structures.

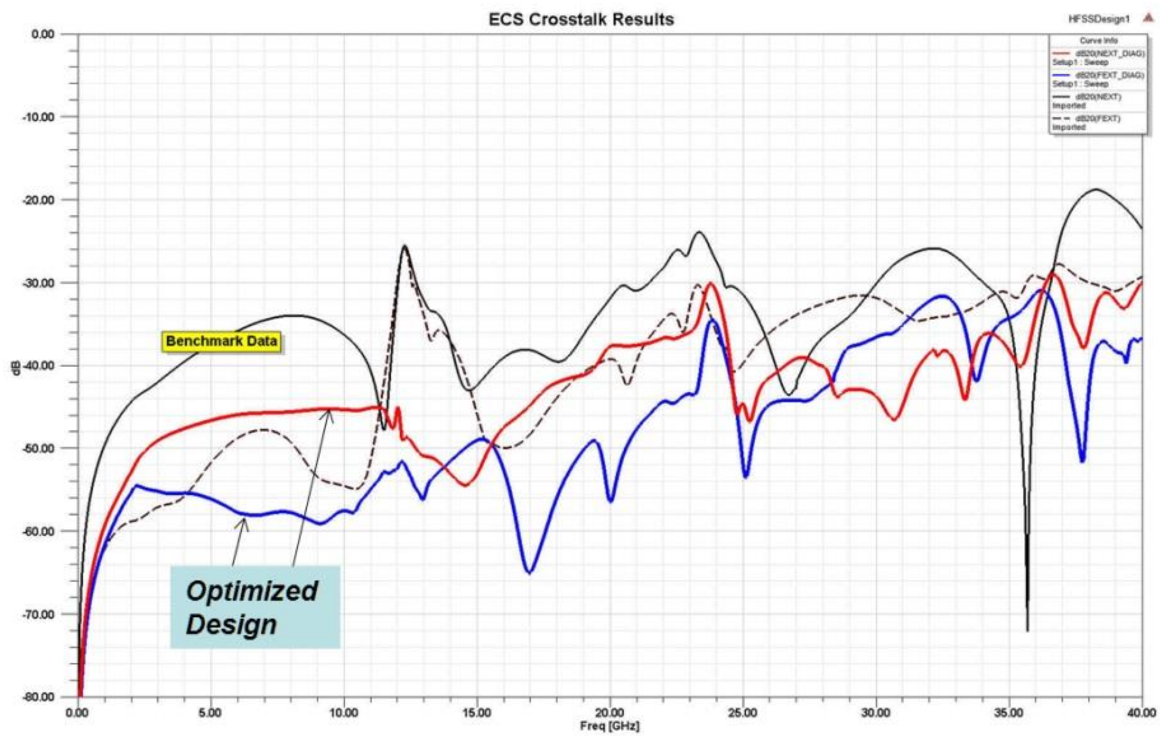


The full path insertion loss results look promising to at least 35 GHz, with only slight excursions noted in the insertion loss around 24 GHz, and no visible phase distortion until 36 GHz. Note the benchmark data included on the plot below is from an existing 7 mm height connector design.

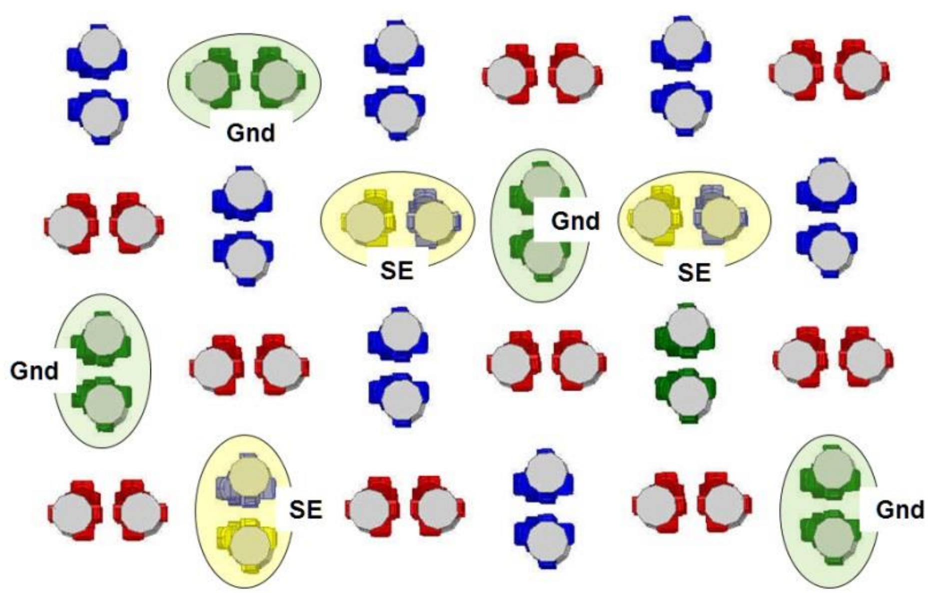




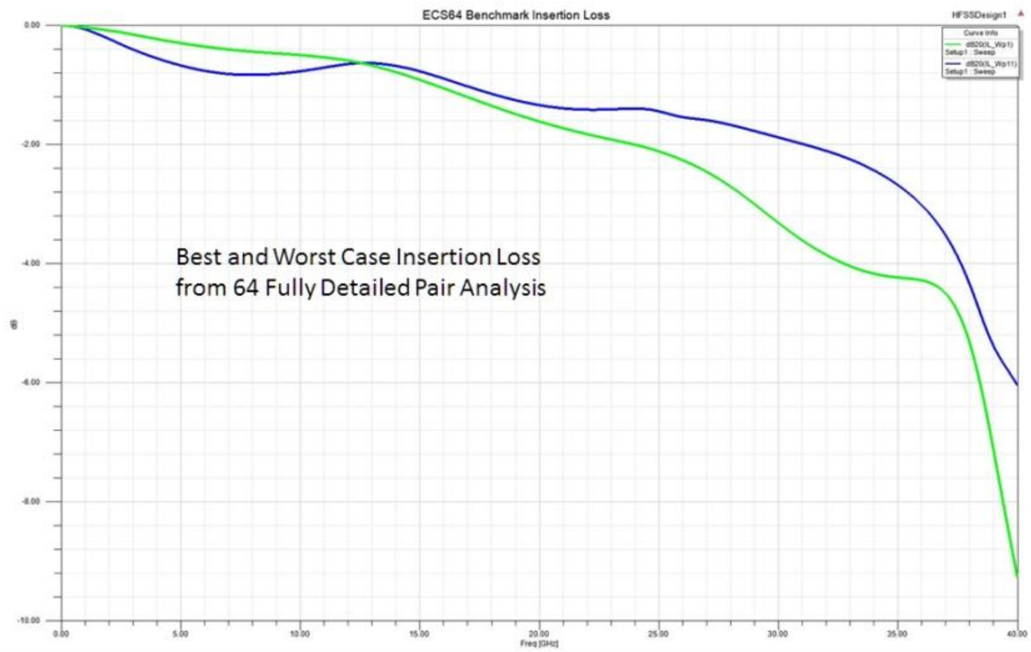
Crosstalk is also excellent, with -30 dB performance or better to the 40 GHz range.

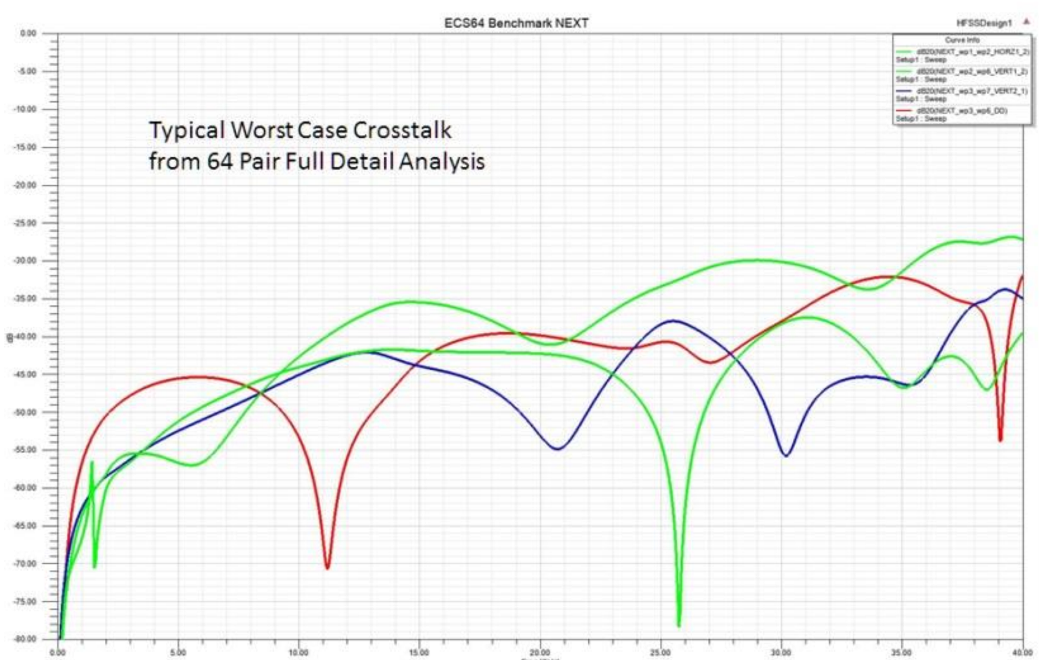


In addition to excellent differential performance, careful selection of terminal spacing allows the same design to be used successfully for lower speed single-ended signals, or as high speed ground return paths. One such signal mapping is shown below.



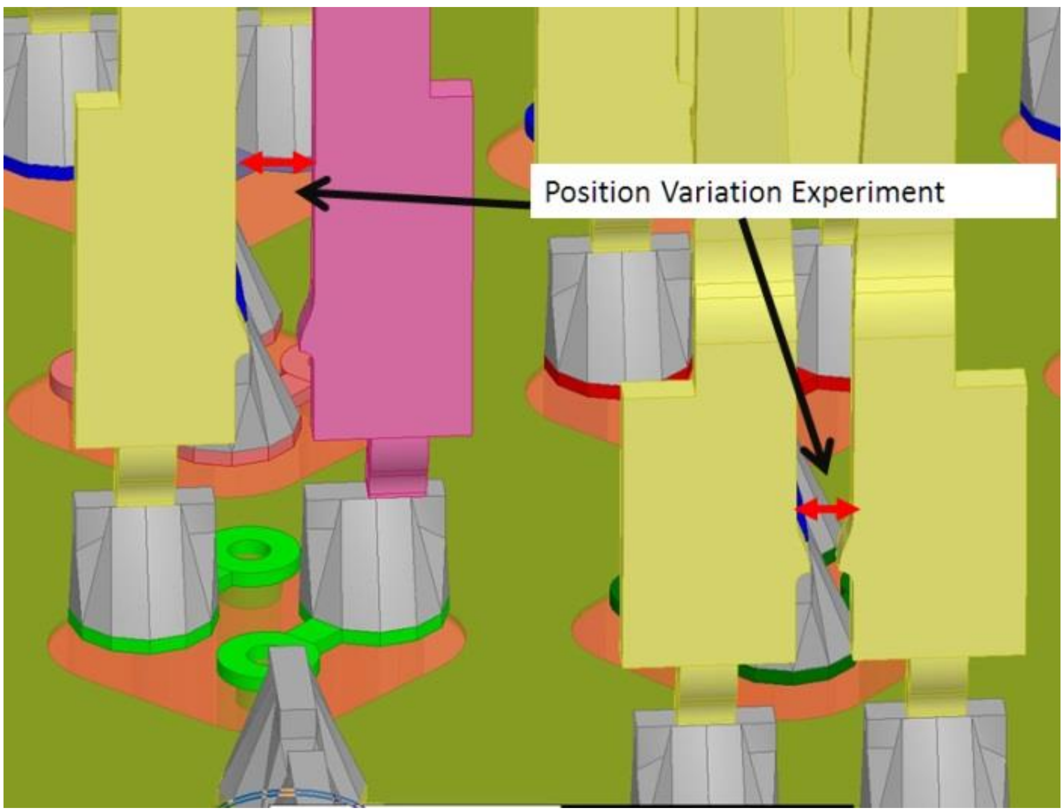
There were some concerns that an unexpected horizontal transmission mode might develop in a fully loaded array. Most of our simulations were run with 6 to 12 pairs in the array. Analysis of large arrays (32 pairs) with perfectly round or flat conductors showed no problems, we decided to run a simulation using the actual terminal design. This very large simulation showed no problems in crosstalk or insertion loss.



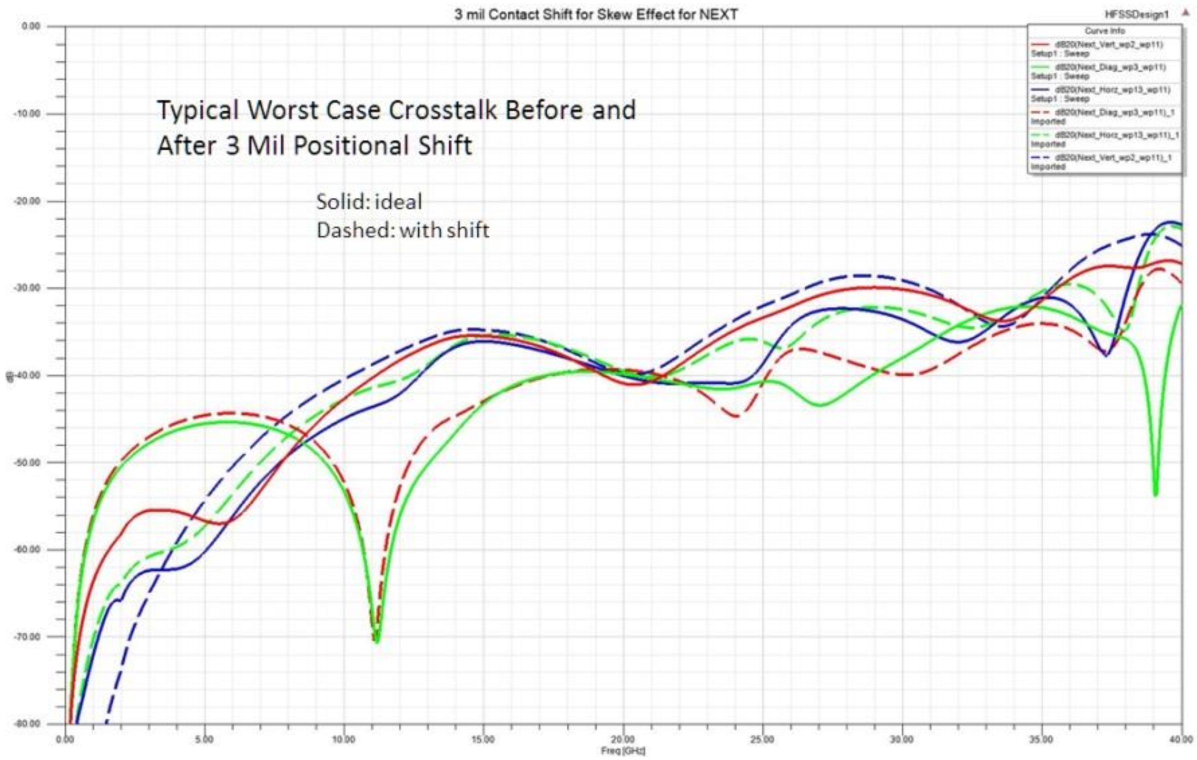


Because the crosstalk cancellation effect relies on careful placement and alignment of the connector terminals, it's possible that such a design could be more susceptible to terminal placement tolerances. To determine if this would be an issue, we performed an analysis comparing the crosstalk in several configurations involving various dislocations from ideal positioning.

It is assumed that worst case misalignment would occur along the line of the plastic retention features. We estimated a conservative worst case positional change of +/- 3 mils in a practical manufacturing environment. This shift is illustrated with the red arrows in the image below. Simulations were again run with a full detailed, 32 pair array.



Even with assumed worst case misalignment, the results were still very promising. In some cases performance degraded. In others it improved. But overall, the worst case change was not significant.



Conclusion

We have shown that there are many potential causes of suck outs in channel insertion loss. One such source is related to crosstalk. This crosstalk is at its maximum at ½ the electrical wavelength of the channel.

We demonstrated that such crosstalk and related resonances are highly dependent upon conductor shape and position. We demonstrated a novel approach for positioning and orienting an array of conductors that leads to improved crosstalk cancellation, and minimal insertion loss resonances. Such an approach leads to much greater useful bandwidth, higher signal density, and signal assignment flexibility.

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