Proximity Effects Between Striplines and Vias
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Abstract—This paper presents initial results on spurious trace–via interactions, i.e. the coupling between striplines and vias that are routed in close proximity in printed circuit boards. It is shown that the primary interaction is mediated by a capacitive coupling. Moreover, antipads of signal vias act as discontinuities in the return current path of striplines. The relevance of this effect is increased by layer misregistration in fabricated PCB laminates. For differential traces, imbalances in antipad to trace overlap margin lead to imbalances in the differential pairs, resulting in mode conversion and degradation of differential noise margins. Finally, crosstalk between striplines on different signal layers, even widely separated ones, can be mediated through capacitive coupling to and from signal vias.

Keywords—via trace coupling, via array cross-talk

I. INTRODUCTION

In many printed circuit board (PCB) layout situations, traces are routed in close proximity to vias – e.g. for the escape routing of a dense via array. For this reason, it should be known what kind of electromagnetic interaction will take place between traces and vias, and how this interaction will impact the integrity of the routed signals. For practical design purposes, several questions are of particular interest: How close can a trace be routed to vias without a detrimental impact on signal integrity? What are the effects that can occur, and how does their strength depend on the number of vias? And what configurations are likely to be problematical?

Based on the geometry of the problem, which is shown in Fig. 1(a) for single-ended traces and in Fig. 1(b) for differential traces, two main effects can be expected. First, a coupling of local fields will take place between striplines and adjacent vias. Second, antipads in the reference planes will be seen as discontinuities by the stripline modes [1], changing the local characteristic impedance and leading to reflections. In principle, the antipads can allow direct field coupling between striplines on adjacent cavities, without primary intervention of the via [2]. Furthermore, in the differential case, imbalances in the antipad overlap with the stripline pair will lead to mode conversion and asymmetrical coupling of noise into the stripline. So far, studies on the interaction between traces and vias have focused on the impact of guard vias, i.e. rows of vias stitching the ground (reference) planes together, which are often used to shield traces from each other – see e.g. [3]-[7]. In [3]-[5], it is shown in a package context that if traces are placed too close to a guard via fence, the vias can increase the coupling rather than reducing it. To the author’s knowledge, no works exist which specifically study the interaction between signal vias and traces, which may be attributed to two reasons:

First, in contrast to the coupling between (parallel) traces, which is a two-dimensional problem that can be handled with analytical formulas [8] or efficient 2-dimensional numerical approaches as described in [9]-[10], and the coupling between via segments, which is a cylindrical wave problem [11], via-trace coupling is an effect which is more difficult to analyze due to its intrinsic 3-dimensional geometry. Second, the effects of via-trace coupling may not have been significant for typical geometries and data rates used in the past. However, even if these effects can be neglected for current ground rules, the impact of future geometrical scaling and increasing data rates needs to be investigated. This is also important in the context of via modelling approaches such as physics-based models [12]-[14] or multiple scattering methods [11], [15]-[16]. These approaches typically include traces with a modal decomposition approach [17], neglecting near-field coupling between vias and traces.

The goal of this paper is to study the effects that may appear in case of small separations between striplines and vias. The paper consists of two parts: in Section II, full-wave simulations for simple geometries are used to analyze the effects and their dependency on the via-trace separation. In Section III, measurements on realistic test cases are used to evaluate the relevance of the effects for signal integrity, indicating possible directions for further studies.
II. QUANTIFICATION OF PROXIMITY EFFECTS USING FULL WAVE SIMULATIONS

In this section, the effects outlined in the introduction are studied for simple configurations. The analysis is based on full-wave simulations, which facilitates investigating the impact of certain parameters on the magnitude of these interactions.

A. Coupling Between Single Via and Stripline

For the case of a stripline running in close proximity to a signal via, local field coupling between the two structures can be expected. To study the nature and magnitude of the coupling, simulations with commercial full-wave solvers have been carried out for the simple setup shown in Fig. 2. For the simulation, a 200 mil x 200 mil portion of a single cavity is taken into account. An absorbing boundary condition is used, so that the results are not affected by reflections from the edges of the cavity. The via is placed at the center of the cavity and the stripline is transversely located at a distance $d$ (edge to edge) from the via. The via is coaxially extended, so that waveguide ports can be placed at the ends of the via (ports 1 and 2). Additional waveguide ports are placed at the ends of the stripline (ports 3 and 4). The via ports are de-embedded so that the reference planes lie in the upper and lower ground plane, respectively. Detailed values for all geometry parameters can be found in Fig. 2(d).

The scattering parameters obtained from the full wave simulation are used in Fig. 3(a) to calculate the response at port 3 due to a Gaussian pulse at port 1. As expected, some part of the signal is coupled from the via to the trace, and the amount of coupling depends on the distance $d$ between trace and via. The reflected step response at port 1 in Fig. 3(b) illustrates that the coupling is of a capacitive nature. This result agrees with physical intuition, since coupling provided by the electric field should exist for small distances between trace and via, while no inductive coupling should exist due to the orthogonality of the two conductors. Electric field plots for a via without a stripline in Fig. 4(a) and for a via with a stripline in close proximity (via to trace separation $d = 5$ mil) in Fig. 4(b) show how the electric field distribution around the via is disturbed by the trace, with capacitive coupling occurring due to electric field lines from the via ending on the trace.

The simulated S-parameters for the via-trace coupling in Fig. 5(a) show how the coupling increases with decreasing via-trace separation $d$. Values for the coupling capacitance have been extracted from the full-wave results based on a simple equivalent circuit model. In the equivalent circuit, a lumped capacitance is placed between the center of the stripline and the via. The stripline is represented by two striplines of half length, assuming that the coupling is a local effect. The via is approximated as a short circuit, which simplifies the analysis and can be justified by the small magnitude of the via barrel impedance. The capacitance values in Fig. 5(b) have been extracted for two different relative permittivities $\varepsilon_r = 3.5$ and $\varepsilon_r = 4.3$ of the dielectric substrate, with the trace widths adjusted for 50 $\Omega$ characteristic impedance and all other parameters as listed in Fig. 2(d). An empirical formula can be derived for the curves shown in Fig. 5(b) as described in [18]:

![Image](https://via-trace-coupling-figure.png)
\[ C_{\text{coupl}}(d) = A \cdot \ln(B / d), \]

with the via to trace separation \( d \) and the constants \( A \) and \( B \) depending on other geometry and material parameters. For the curves shown, we obtain \( A_1 = 17.0 \) fF and \( B_1 = 14.0 \) mil for \( \varepsilon_r \) and \( A_2 = 14.2 \) fF and \( B_2 = 13.9 \) mil for \( \varepsilon_r \). Additional curves in Fig. 5(b) show the static capacitance between trace and via obtained from a commercial tool. The curves are close to each other for \( 1 \text{ mil} < d < 10 \text{ mil} \), indicating that the static capacitance is a reasonable approximation to describe the coupling effect.

B. Effect of a Single Via Segment on Stripline Transmission

Vias in close proximity to a stripline can represent a discontinuity for the signal propagating along the stripline. The impact of a via segment (terminated with 50 Ω against the reference planes on top and bottom of the cavity) on the transmission along a stripline in close proximity is shown in Fig. 6 (a). Fig. 6(b) compares the impact of different discontinuities. The detrimental impact of the ground via on the stripline transmission is smaller than the impact of the signal via. This can be explained by the effect of the antipad around the signal via, which leads to additional field lines ending on the via barrel (increasing the capacitive coupling), and in itself represents an additional discontinuity for signal propagation along the stripline. A simulation with the antipad only (simulated is the structure shown in Fig. 2 without the via barrel) leads to almost the same result as the simulation with signal via, indicating that the stripline transmission is affected more by the return path discontinuity caused by the antipad than by the capacitive coupling to the via itself.

C. Effect of Multiple Vias on Stripline Transmission

The configuration of a single stripline passing a single via segment, while insightful for the study of the basic behavior, will rarely be encountered in real designs. A more realistic scenario is shown in Fig. 7(a): a differential stripline (consisting of two traces) is routed between two rows of vias, as would be the case for routing through a via array. The vias may be either signal or ground vias, however, based on the results in the previous subsection it can be assumed that the worst-case scenario would be one where all vias are signal vias. Out of the many cases to study, only one is shown in this subsection: the impact of a misalignment of the traces between the vias is studied for the setup in Fig. 7(a). Each via row consists of 15 signal vias, with a via pitch of 40 mil along the row and 35 mil between the rows. The traces are either centered between the rows, or have a specified offset from the center (leading to different via-trace separations and antipad overlaps). In all cases, the trace width is 3.8 mil, and the trace separation is 4 mil (edge to edge). The trace length is 0.8 inch. All other parameters are identical to the ones specified in Fig. 2(d). The differential mode insertion loss for the centered case (via-trace separation 6.8 mil) does not show a significant deviation from the nominal case (stripline without via rows). With increasing offset, more deviation can be observed. The results demonstrate that even in the presence of multiple vias, a significant degradation of the stripline transmission will only occur in case of an antipad overlap.

![Fig. 5.](image-url) (a) Results from a commercial FEM code describing the coupling between trace port and via port for the structure shown in Fig. 2. (b) Extracted capacitance values (‘x’) with fitted curves compared to the static capacitance values obtained with a commercial 3-D parasitic extraction tool.

![Fig. 6.](image-url) (a) Impact of a signal via segment (terminated with 50 Ω against the reference planes on top and bottom of the cavity) depending on the via to trace separation \( d \). (b) Comparison between stripline transmission disturbed by a ground via (smallest impact), a signal via, or by an antipad only (without via) for a via to trace separation \( d = 1 \text{ mil} \).
III. MEASUREMENTS

To validate the findings obtained from full-wave simulations in the previous section, a printed circuit board (PCB) with several test structures has been fabricated. While the full-wave simulations allowed a broader variation of parameters, the simulation results are based on some simplifications such as the assumption of a homogeneous substrate and the restriction to a single cavity. In this section, it will be studied how far the observed effects can be reproduced with measurements on the real PCB.

A. Stripline with a Single Via

The first test structures aim at an experimental study of coupling effects indicated by the results in Sections II.A and II.B. The general setup of these structures is shown in Fig. 8(a): a stripline on signal layer L6 is routed in close proximity to a single signal via. For the measurements, recessed probe launches [19]-[20] have been prepared at the ends of the stripline, while the signal via was probed directly on the top pad, using a flooded GND plane. The different test sites are isolated from each other by cages constructed from double rows of ground vias. A cross section of signal via and stripline is shown in Fig. 8(b). In the different test sites, two parameters have been varied: the stripline to via separation \( d \) and the antipad radius \( r_a \) (Fig. 2a). Fig. 9(a) shows the impact of the signal via on the transmission along the stripline for via-to-trace separations from \( d = 25 \text{ mil} \) down to \( d = 10 \text{ mil} \), which was the smallest separation permitted by the PCB design rules. The results indicate that the separation is not small enough to show an impact, which is in line with the simulation results shown in

![Fig. 7](image)

Fig. 7. (a) Top view of the simulated differential stripline with rows of 15 signal vias at each side (PMC boundary condition in the antipads). The offset for the shown structure is 4 mil from the centered case. (b) Comparison of the differential mode insertion loss obtained with a commercial FEM tool for different offsets. A significant deviation from the nominal case exists for the case with 4 mil offset, for which a large trace-antipad overlap exists.

![Fig. 8](image)

Fig. 8. (a) Test structures with a single signal via and a single trace routed on signal layer L6. A ground via cage is used to shield the test structure against other elements on the PCB. (b) Cross section of a via with a trace routed on L6 in close proximity to the via. The via diameter may be larger than suggested by the picture (via is not cut at the exact center). (c) Stackup of the complete test board as measured from a cross section. Dimensions shown are in mils.

![Fig. 9](image)

Fig. 9. Measured S-parameters for different via-to-trace separations and antipad radii. (a) Transmission along the stripline. (b) Coupling between
In contrast to the simulation results, however, the measurement results show an offset between the nominal stripline (without via) and cases with a signal via for \( d = 10 \) mil the antipad radius is increased from 15 mil to 25 mil, so that a large overlap between trace and antipad exists. The impact of the increased antipad radius can also be seen in the reflection (not shown), which is significantly increased due to the discontinuity in the return current path of the stripline caused by the antipad overlap. For the coupling (Fig. 9(c)), it can be seen how the coupling increases with decreasing separation between via and trace, and further increases for an increasing antipad radius (which increases the capacitance between stripline and via).

To further analyze the impact of vias in close proximity on the stripline transmission, several striplines with adjacent via rows – similar to the case analyzed in Section II.C – have been designed for the test vehicle. The complete setup is shown in Fig. 10(a). The complete setup is shown in Fig. 10(a). Of the two via rows running on each side of the stripline, the inner row consists either of alternating signal and ground vias or signal vias only. The measurements have been carried out using SMA demountable connectors, and an SOLT calibration HP85052D cal kit was used for the SOLT calibration. The impact of the connectors and feed lines has been removed by de-embedding up to the boundary indicated in Fig. 10(a). Measurements have been carried out for centered traces and for traces designed with +/- 2 mil offsets. These are all nominal design targets, and the actual PCB panel will differ due to layer registration and
drilling offsets. Cross sections of a solder sample in Fig. 10(c) show the positions of the traces relative to reference planes and antipads. These cross-sections may not show the worst case overlap between traces on L6 and L8 since it is not certain if the full diameter of the antipads was cross-sectioned. For the case with 2 mil offset, a top view of traces and vias is shown in Fig. 10(d), with measured dimensions specified in Fig. 10(e). The differential mode insertion loss (Fig. 11(a)) and common mode insertion loss (Fig. 11(b)) both show the detrimental effect of a trace offset, which is strongest if the via rows consist of signal vias only. Resonant notches due to the periodic via rows appear at different frequencies for differential and common mode insertion loss. The frequency of the notches also depends on the via pattern (alternating signal / ground versus signal vias only), and the notches are more pronounced in the case of signal vias only. In Fig. 11(c), the conversion between differential and common mode is shown. The plot shows the high sensitivity of the mode conversion to layer registration. A small offset of a few mils can increase the mode conversion by more than 20 dB. Furthermore, even the (presumably small) deviations between the +2 mil and -2 mil cases which exist in the real structure lead to a considerable difference in the mode conversion.

IV. CONCLUSION

For vias in close proximity to striplines, two effects have been observed and experimentally verified: capacitive coupling between via barrels and traces, and a degradation of stripline transmission due to the discontinuity caused by the antipads of the vias. Both effects are comparatively weak for typical via-trace separations (> 10 mil). Even for smaller separations, the impact of a single via will be negligible from a signal integrity point of view. However, in the case of a periodic arrangement of a larger number of signal vias, the observed magnitude of effects increases. For the signal transmission, the impact of antipad overlap seems to be stronger than the impact of the capacitive coupling to the via. In most cases, the minimum separation between via and trace will therefore be determined by the antipad radius. In the case of differential transmission, asymmetric antipad overlap will result in additional mode conversion, which will increase the sensitivity to layer misregistration for striplines routed close to antipads and may require additional layout margins or tighter specifications on layer registration. Cases may exist where the capacitive coupling is the limiting factor for the placement of traces and vias, since it can provide crosstalk even between distant signal layers.

REFERENCES


