S-Parameter-Based Delay Calculations in Low-Cost Module

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***Abstract*— High-speed single-ended and differential busses in low-cost modules are usually specified to have certain delay matching requirements. While 3D electromagnetic (EM) solvers and system simulation tools are readily available, rapid design cycles can prevent a full system-level analysis during every iteration. Therefore a theoretical approach to delay calculations and timing estimation is proposed by directly using S-parameters obtained from the 3D EM solver. This reduces the design cycle time significantly. Using this approach, a 2 metal-layer (2ML) design is compared to 4ML design. Practical issues in precise delay matching are demonstrated and clarified.**

Keywords*— *Signal Integrity, Differential Pair, Interconnect, Delay matching, RLC, S-parameters, 3D electromagnetic solver.

I. Introduction

Low-cost high-performance modules containing an IO bus with differential pairs is a common design challenge. Usually, electrical design constraints are imposed to match the intra-pair delay within a differential pair to within a small amount such as 1ps (for example), and to match the pair-to-pair delays to within a typically larger amount such as 5ps (for example). This corresponds roughly to length match within-pair to about 25um, and between pairs to about 1mm. Length matching is typically achieved through various meanders, accordions and hooks, a task which can get highly complicated in limited routing space in a small package. These features tend to increase effects of crosstalk and makes it difficult to select the optimum design choice that can be used for length matching.

There is the traditional method of match based on length or delays as calculated in the constraint manager of the layout tool. But a difficulty in layout is that the formulations behind the layout tool delay approximations may at times not agree with more rigorous 3D EM simulations. Even trying to use pure length matching there can be issues such as the approximate length being measured from the center of large via and BGA pads, not the beginning of the trace at the periphery of the pad or considering the pad loading effects.

Even when we are not considering crosstalk-induced delay changes, there is not always a clear choice in how to match delays within pair and between pairs. Effects of return loss and discontinuities on the delay are also complex and can cause shifts of the timing edges. A special challenge in low-cost 2ML designs is that there are worse impedance discontinuities and more crosstalk between the lines than in 4ML where more solid ground planes can usually be used.

II. Theoretical Foundations

A fast method is needed to efficiently evaluate the quality of the signal routing to ensure better delay matching after each design iteration. This paper presents an approach based on pure S-parameters to estimate quiet, even and odd switching mode delays of a design. Differential pairs are modeled as two oppositely switching signals and a complete mixed-mode S-parameter transformation is used. A 3D EM solver is used for the most confidence in simulation accuracy.

All of the available analysis methods rely on a fair number of approximations and assumptions. Even when using wideband models in full system-level transient simulations, we need to decide on many options such as deciding what topology, source and load impedances to use, as well as what source qualities such as risetime and bit patterns to use, all of which will affect the result. And these concerns arise before crosstalk is even considered. So using the direct S-parameter calculations provides as viable an approach as any.

The conventions for quiet, even and odd switching used in this paper are shown in Fig. 1. In the presence of differential pairs, it is necessary to enforce that the signals within a pair switch in opposite directions at all times. In this work it was chosen to implement 1.That the differential pairs must always switch oppositely, and 2. That the switching direction of a pair is by definition the switching direction of the P leg of the pair.

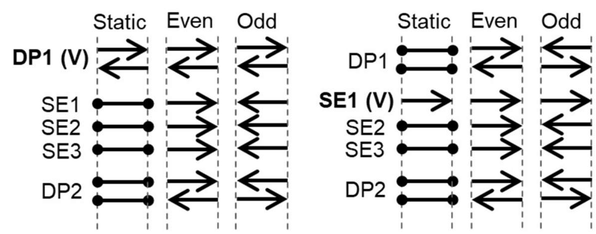

Fig. 1. Definition of even and odd modes for differential-pair (DP) victims [left] and single-ended (SE) victims (V) [right].

Depending on routing pattern and specific adjacency in the module, even and odd switching modes in this definition may not always correspond to the worst-case switching condition electromagnetically. This is demonstrated later, in Section IV Fig. 7. It can also be pointed out that due to non-homogeneity in materials and non-uniformity aspects, the differential delay is usually lower than the single-ended delay of each leg taken one at a time, which is in turn shorter than the delay of the pair signals switched in even mode. Also, ideal differential pair termination requires three elements (T- or Pi-network) to fully terminate both even and odd modes. Due to the heavy non-uniformity as well as asymmetry and imperfect matching, differences would result for each termination scheme especially due to relatively high propensity for mode conversion. If these differences alone are measured in the multiple picoseconds, then indeed a specification to match within pair or between pairs to better than that certain number of picoseconds may be theoretically impossible to achieve. This paper assumes a single parallel termination for each leg of the pair.

It is also necessary to decide how to terminate static nets, whether to use the system impedance, their own self-Zo, or even to open or short one or both ends. For S-parameter based work it is easiest to assume non-switching lines are terminated in the system Zo, usually 50 ohms. When LC matrices were used to make similar calculations there are also nuances to multiple ways in which the L or C matrix may be assuming other lines are opened, shorted, or terminated, and great care is needed to sort it out correctly. There are also issues in

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formulas to extract LC at the needed frequency to represent high-speed edge delay, and often a less-accurate hybrid solver is used.

To provide a fast way to use a full 3D solver and avoid LC extraction, the pure S-Parameter based delay calculation method is described comprehending both crosstalk and differential pairs-aware. A convenient arrangement of the S-matrix is defined in Fig. 2. Typically in a package we have a die-side, and a board-side. For N lines, the left side (choose die-side) are numbered 1 to M, while the right side (choose board side) are numbered M+1 to 2N, and in the same net-order.

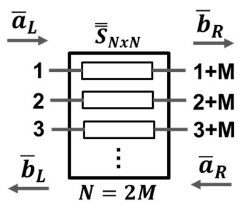

Fig. 2. Assumption for the S-Parameters port ordering for convenient book-keeping purposes where number of lines=M and number of ports=N=2M.

We have for the above S-matrix split into quadrants for routes having left- and right-side ports and placed into a Zo system environment, the matrix equation,

$$\begin{bmatrix} \bar{\boldsymbol{b}}_L \\ \bar{\boldsymbol{b}}_R \end{bmatrix} = \begin{bmatrix} \bar{\bar{\boldsymbol{S}}}_A & \bar{\bar{\boldsymbol{S}}}_B \\ \bar{\bar{\boldsymbol{S}}}_C & \bar{\bar{\boldsymbol{S}}}_D \end{bmatrix} \begin{bmatrix} \bar{\boldsymbol{a}}_L \\ \bar{\boldsymbol{a}}_R \end{bmatrix} \quad (1)$$

where **a** are the forward-travelling pseudo-waves and the **b** are the reverse travelling (reflected) waves. For purpose of simple delay analysis, we assume propagation from left to right in a matched system so that the **a**-waves on the right side are all zero and the **a**-waves on left side are only due to the forward injection from the source since the left-side **b**-waves get fully absorbed back into the matched source. The right-side **b**-waves are only due to the transmission through the block since there are no **a**-waves to reflect and add on that side. Then the matrix equation for the right-side b-waves in terms of the left-side **a**-waves is reduced-to and given by,

$$\bar{\boldsymbol{b}}_R = \bar{\bar{\boldsymbol{S}}}_C \bar{\boldsymbol{a}}_L \, . \quad (2)$$

The differential pairs aspect needs to be accounted where the N leg gets injected the polar opposite signal as the P leg. This is accomplished by letting a_N=-a_P for all differential pairs. The victim signal under consideration can be a differential pair or a single-ended line. To impose even mode aggression then the $a_{aggressor}$=a_{victim}, while for odd mode aggression the $a_{aggressor}$=-a_{victim}, keeping in mind the rule for differential pairs. All this book-keeping can get fairly complex and is handled using advanced scripting and matrix transforms.

To determine the delay in time we use the phase-delay from the victim line when perturbed by the aggressor lines (if switching) and the opposite leg if it is a differential pair. In the case of the N-leg computation, the polarity of all other nets is simply reversed as compared to when treating P as the victim. Generally one will find that if the P-leg is delayed in time then the N-leg will be advanced in time, but not always by the same amount. Ideally the P is changed in one direction by the same amount the N is changed in the opposite direction such that the differential delay as found by the crossing point is unchanged. The mismatch between the P and N skew is a measure of asymmetric aggression and relative quality detriment. The adverse effect of skewed P and N in terms of waveform distortion such as shelfing is not considered here. Only the cross-point delay change introduced is considered, although the actual mixed-mode transformation can be used to get the true differential delay of a pair.

The phase delay in presence of aggression and in pairs the effect of opposite leg is found from the victim row of Eq. 2 under all the prior stated assumptions and conditions. Taking an example for four lines, then M=4, N=8. Assume that lines 1 and 2 form a pair and lines 3 and 4 form another pair. Then for odd aggression to the first line as victim we have,

$$\boldsymbol{b_5} = \boldsymbol{S_{51}a_1} + \boldsymbol{S_{52}a_2} + \boldsymbol{S_{53}a_3} + \boldsymbol{S_{54}a_4} \, . \quad (3)$$

where a_2=-a_1, a_3=-a_1, a_4=a_1, thus,

$$\boldsymbol{b_5} = (\boldsymbol{S_{51}} - \boldsymbol{S_{52}} - \boldsymbol{S_{53}} + \boldsymbol{S_{54}})\boldsymbol{a_1} \equiv \boldsymbol{T a_1} \, . \quad (4)$$

Finally, the phase delay of the victim of interest under aggression from other lines and its other leg, if a differential pair, is obtained at a chosen frequency from the unwrapped phase ϕ of **T** (in degrees),

$$\boldsymbol{D} = \frac{-\boldsymbol{phase(T)}}{\boldsymbol{360f}} \, . \quad (5)$$

III. Layouts for comparison

In order to test out the formulations and identify limits of applicability, two layouts were examined. Comparison to SPICE simulations under a set of assumptions is carried out in later installment. The two layouts are for a section of a MIPI block having ten differential pairs. A very dense design is selected where matching is also needed between pairs such there is a very tight "Medusa" or "brain"-shaped routing with a lot of crosstalk, discontinuities, asymmetries and undesired effects like extensive route over split in plane. Signals do atrocious things like route over power instead of ground, or over wrong BGA ball of other net. Two different layouts are examined: 2ML coreless (Fig. 3) vs. 4ML 1-2-1 (Fig. 4.) The size of die and package, relative positioning, ball pitch and routing paths are kept almost same for both packages, yielding a good apple-to-apple compare of 2ML versus 4ML.

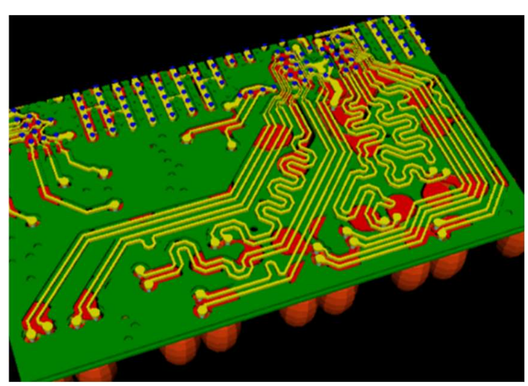

Fig. 3. 3D view of the 2ML module. Lines and meanders must maneuver within tight areas and end up traveling over power patches, splits in GND plane, and right over BGA pads of other signals.

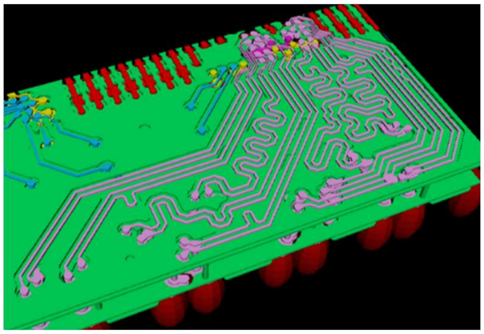

Fig. 4. 3D view of the 4ML module. Lines and meanders must still maneuver within tight areas but are placed over a largely solid ground plane.

Note that the 2ML module suffers from traces routing over the wrong reference net, splits in GND, and directly over BGA pads of other nets. Yet the 2ML is a coreless technology with only two thin 50um layers in the Z-direction. The 4ML allows a solid M2 GND plane under the microstrips. However, the 4ML is thicker and suffers from large plated-though-holes in a thick 200um core, and limited shielding vias in the Z-direction. Therefore it is not always easy to say which will be "better", the 2ML or the 4ML. In fact, "better" itself may be exceedingly difficult to define given the inevitability of mixed results (some better, some worse).

IV. Results and Discussion

The S-parameters for the two test packages were extracted using HFSS modeling. A frequency sweep from DC to 20GHz was used with suitability for transient simulation with fast edge rates with risetimes of less than 100ps. The ports are all ordered in most suitable form for either the even-odd timing analysis or mixed-mode transformation. Finally, the phase delay is calculated under quiet, full even and odd conditions.

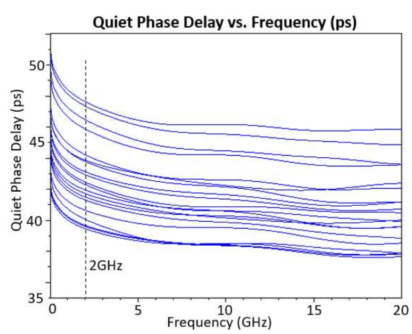

Fig. 5. Frequency-dependent phase delay for all 20 signals comprising the 10 differential pairs extracted, in-situ, each while all other signals are quiet.

As seen in Fig. 5, a suitable frequency felt to correspond to the delay that a sub-100ps edge would see, is used. In this case a balance frequency of 2GHz was selected. Since relative skew in-pair or pair-pair in differential bus was of most concern, the differences between the delays are of more interest than the total end-end value of the delay. Delays can be checked as if every signal was an independent SE signal, in quiet condition and when all other signals acting as aggressors are switching either even or odd to the victim line. While for individually well-shielded pairs with good P-N coupling, a full SE treatment would not be representative due the intentional in-pair coupling, in these layouts the space between pairs is nearly as small as the space within the pairs and little room for shielding between. This is common in modules requiring to be extremely dense.

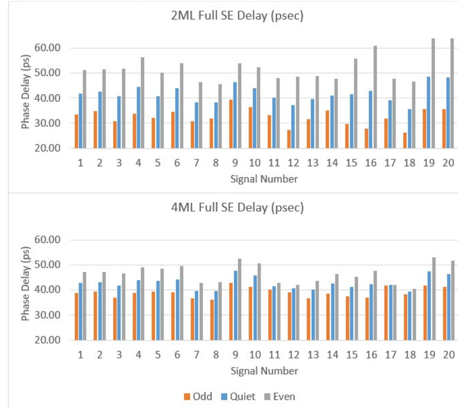

Fig. 6. 2ML vs. 4ML odd-even-quiet delay charts.

Charts comparing results for 4ML and 2ML packages are given in Fig. 6 with all signals treated as independent SE signals. The 4ML indeed shows a tighter spread due to the decreased levels of coupling. Apparently the thicker core and larger PTH vias in 4ML did not detriment performance enough to counteract the use of a full GND plane for the microstrips, when used in a single-ended sense.

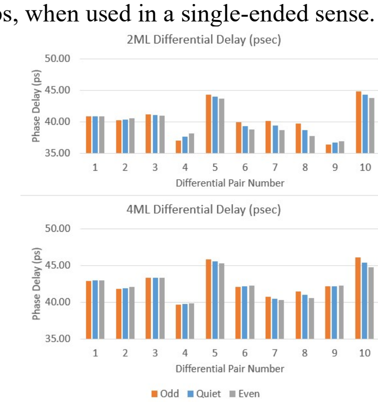

Fig. 7. Differential delays as calculated through mixed-mode transformation, under quiet, even, and odd transitioning.

Fig. 7 displays charts for differential signaling. Several observations can be made. The odd mode is now not always the one advanced in time and even most delayed. Results get mixed and also the timing impact of the crosstalk is far less, as expected, for the differential case. Also, for differential signaling, the timing impact is about the same in 2ML as in 4ML, showing that the 2ML can be adequate for the module and opening up potential of saving cost.

V. Conclusion

A strictly S-Parameter-based formulation was presented to estimate timing shift of a high speed edge in presence of heavy coupling and SSN. The method was extended to differential pairs estimates using mixed-mode transformation. A 2ML design is compared to a 4ML design showing that the 4ML was significantly better for an SE bus while the 2ML as expected fares better than 4ML in the differential case. The methods of this paper allow quantification of these statements.

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