

DesignCon 2009

EMI from SerDes Differential Pairs

Philippe Sochoux, Cisco Systems, Inc.
psochoux@cisco.com

Morris Hsu, Cisco Systems, Inc.
moshu@cisco.com

Alpesh Bhobe, Cisco Systems, Inc.
abhobe@cisco.com

Jinghan Yu, Cisco Systems, Inc.
jinyu@cisco.com

Abstract

SerDes differential pairs operating in the multi-GHz range are replacing slower source synchronous interfaces in many high-end digital applications. Ideal differential pair signaling can provide common mode noise rejection and overall reduction in EMI. However on a real PCB true differential signaling is difficult to achieve. Different layout techniques such as bends, layer transitions, routing over antipads, etc., create unbalances within the differential pair. At Gbps operating speeds or GHz clock frequencies, small layout imperfections such as bends or skew cause impedance mismatch and can create undesired local modes and common mode current that contribute to EMI. Comprehensive and detailed EMI layout rules for routing high-speed SerDes differential pairs are quasi non-existent. As a result, there is a strong need to create a new set of layout rules to better control the EMI of interfaces running at GHz frequencies. In this paper, using a full wave EM numerical tool, we investigate the EMI caused by various layout imperfections, and discuss a methodology that will help EMC engineers compare and contrast additional layout imperfections to develop their own EMC layout guidelines for SerDes differential pairs.

Author Biographies

Philippe Sochoux received his B.S. and M.S. degrees in Electrical Engineering from Marquette University, Milwaukee WI in 1990 and in 1994, respectively. He joined Cisco Systems in 1998 and worked as an EMC and a Signal Integrity Engineer on the Cat6K family of Switches. Since 2001 he has managed CAD, Signal Integrity and EMC Design groups within Cisco Systems. He is currently managing the EMC Design and Test groups in Central Engineering. Prior to joining Cisco, he was a Regulatory Engineer at U.S. Robotics/3COM in Chicago, IL.

Morris Hsu

Morris Hsu is an undergraduate student in Electrical Engineering at University of California, Los Angeles. He joined EMC Design groups within Cisco Systems as an intern in 2008. He will receive his B.S. in 2009 and plans on pursuing M.S. degree in Electrical Engineering.

Alpesh U. Bhobe was born in India. He received his B.E. degree in Electrical and Telecommunication Engineering from the University of Bombay in 1996 and Ph.D. in Electrical Engineering from the University of Colorado at Boulder, Colorado in 2003. He was a Post-Doc at NIST in Boulder, Colorado. While at the University of Colorado and at NIST his research interest included the development of FDTD and FEM code for EM and Microwave applications. Currently, he is working as a Hardware Engineer at Cisco Systems, San Jose, CA where he is working on EMC design. Prior to joining Cisco, he was working as a Hardware Engineer at NVIDIA Corp. in Santa Clara, CA.

Jinghan Yu received his B.S. in Control Science and Engineering from Zhejiang University, China in 1998 and M.S. degree in Electrical Engineering from Louisiana State University, LA in 2001. He has been an EMC design engineer in Cisco Systems,

Inc. supporting Cisco's GSBU and CSIBU for Catalyst 4000 series and Sypixx products since 2004. Before joining Cisco, he was an EMC engineer at Andiamo Systems, Inc.

Section I

Introduction

SerDes differential pairs are replacing source synchronous interfaces in many high end digital applications. Differential pair signaling operating in the GHz range (XAUI, XFI, etc) will soon be the signaling protocol of choice between backplane and linecards, between ASICs themselves, between ASICs and their memories, and between ASICs and front-end transceivers such as SFP+ and CFP.

Ideal differential signaling offers common mode noise rejection as well as reduced EMI levels. However, true differential signaling is difficult to achieve on practical PCB's. At GHz frequencies, small layout imperfections, such as mitered 90 degree bends or via transitions, cause unbalance within the differential pair. Such layout imperfections may generate undesired common mode currents which may contribute to EMI. Since a SerDes differential pair may have a multitude of small layout imperfections, and there could easily be dozens or even hundreds of differential pairs in a PCB (and several PCBs in a chassis), the aggregate extra EMI emission generated by these imperfections in a system may decrease radiated emission compliance margins or cause non-compliance. Hence these multi-GHz SerDes interfaces with harmonics that can extend up to 40 GHz need to be carefully routed to control system level EMI.

From a practical point of view, routing differential pairs with some degree of layout imperfection is unavoidable. Increased number of ASIC's, higher board densities and ever more aggressive cost reductions will force routing with some imperfections. Most of these small layout imperfections can very well be accepted by the Signal Integrity community since signal enhancing mechanisms such as Adaptive Decision Feedback Equalization (DFE) and Pre-emphasis exist. However the EMC engineers may not be able to neglect these layout imperfections since they can increase EMI and they must compensate elsewhere in the system if these new EMI levels become unacceptable.

As a result, the new routing rules must minimize EMI emission from SerDes differential pairs without over-constraining the routing. Currently, comprehensive and detailed EMI layout rules for routing high-speed SerDes differential pairs are quasi non-existent. EMC engineers rely mostly on old design rules that were designed for common clock or source synchronous interfaces operating in the MHz range. Some examples of these rules are: avoid routing across a moat, always reference a trace to a ground plane, provide a continuous return ground return path, etc. Although these rules are still applicable, there is a need to complement these rules with a new set of rules designed for interfaces running at GHz frequencies.

EMI emission from mismatches in high-speed differential signal and traces and cables has been investigated in [1]. The authors investigated the common mode current

generated due to delay skew and asymmetries in transmitter rise and fall times. The computed common mode voltage is used to predict the EMI performance of the high-speed signals and cables. Radiation from transmission line interconnects had received attention in the past [2 - 4]. Radiation characteristics due to acute bend in a microstrip transmission line were analyzed and compared with the experimental results in [5]. The Radiation Loss from a bent transmission line is studied using Method of Moment (MoM) in [6]. It was found that the transmission line with a right angled bend had the least radiation when compared to other type of bends.

In this paper we study the radiation caused by several layout imperfections in a high-speed differential line. The numerical investigation is carried out using Microwave StudioTM, a Time-Domain full wave EM solver developed by CSTTM. A 100 ohm differential line was modeled with a stackup as shown in Fig 1. For all cases with individual imperfections in this paper, the total length of the differential pair was kept constant at 4000 mils. In order to capture the radiation from the transmission line the open boundary condition was used in our simulation and we simulated from 1 to 40 GHz. Our analyses were performed by calculating the total radiated power (TRP) from the structure. The default Gaussian pulse was used in our simulations. The total radiated power was normalized to the input source to ensure equal input energy in the simulated frequency range of 1 – 40 GHz. Since the total length is kept constant in every case (4000 mils), and the input power is always the same, it is possible to compare the layout imperfections according to how much EMI they contribute at specific frequencies. We selected 10.3, 12.5 and 20.3 GHz since these are harmonics of frequently used SerDes data rates.

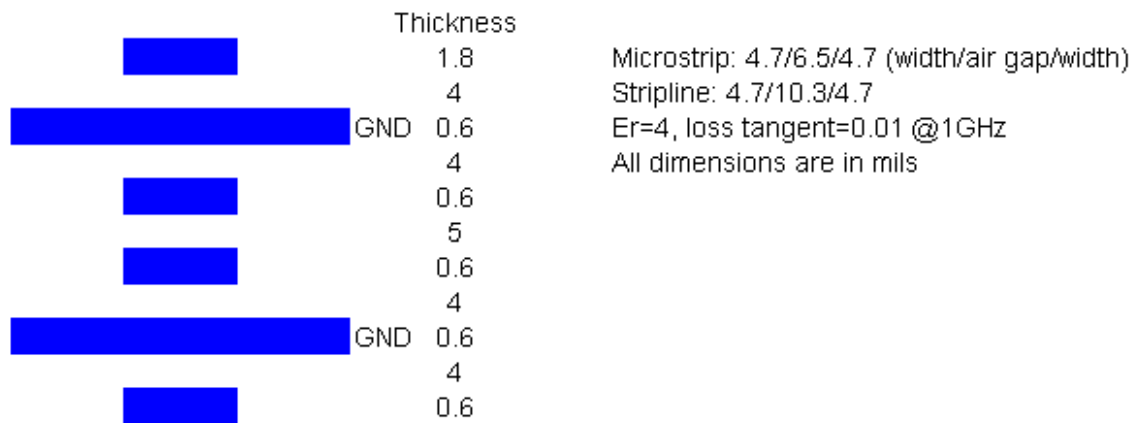


Figure 1 Physical dimensions

We relied extensively on scripting to automate our work. MATLABTM is capable of interfacing and controlling Microwave StudioTM's Visual Basic Application macro language through ActiveX and Component Object Models. Thus, MATLABTM scripts were employed to automate the simulations and to generate the plots. First, Microwave StudioTM models were parameterized with global variables for all physical dimensions, such as the width and the thickness of the differential pair. Then, MATLABTM scripts controlled Microwave StudioTM to run a series of simulations with different parameter values pre-programmed to the script. After each simulation, the script read the

Microwave Studio™ formatted results and extracted the information on the radiation pattern. Finally, different post-processing MATLAB™ scripts were used to read the data and to produce the plots. With the scripts, simulation results were stored after each simulation automatically, thus simulations could be run incessantly and reduced the simulation time.

In section II we compare the radiation from a simple straight differential line using three different commercial tools. In section III we present the different differential layout imperfections we studied

1. Different types of bends and arcs
2. Adjacent differential pairs
3. Intra-Layer Skew
4. Unbalanced padstack
5. A differential pair over anti-pads

Section II

Confidence Check

In this section we study the Total Radiated Power for a simple 100 ohm differential line of length 500 mils using three different 3-D full-wave numerical EM tools: CST™ Microwave Studio™, Ansoft™ HFSS™ and CST™'s MicroStripes™. The physical dimensions and the electrical parameters used in our simulations are listed in Drawing 1 (we used a microstrip differential pair for the confidence check). The purpose of this study is to crosscheck the simulation setup. These tools use different numerical analysis techniques, Finite Integral Time Domain (FITD), Finite Element Method (FEM), and Transmission Line Matrix (TLM), respectively. The input powers in to the ports for each tool were kept constant to 1 W. The total radiated power v/s frequency is plotted in Figure 2. . The results obtained from the CST tools correlate within 3 dB of each other for the frequency range of 1 – 40 GHz.

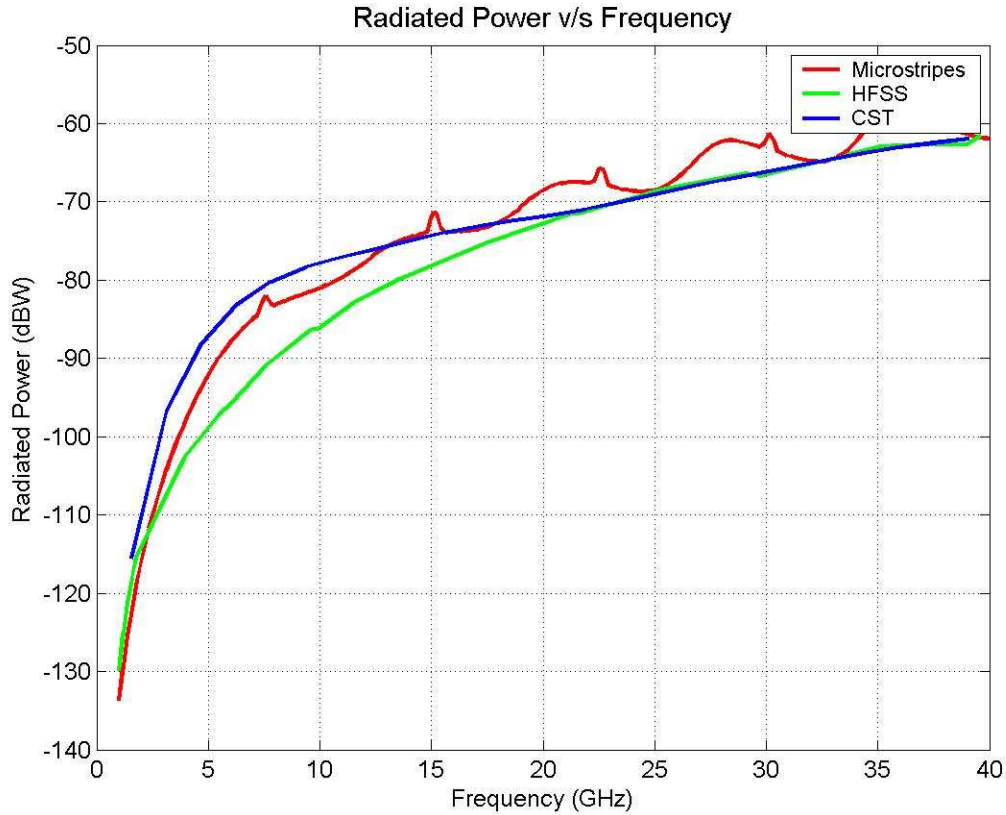


Figure 2 . Total Radiated Power v/s Frequency for a straight 4 inch 100 Ω Differential Line calculated using CST MicrostripesTM, Ansoft HFSSTM and CST Microwave StudioTM

Section III

Studies of Layout Imperfections

The effects of bends

In this section we study the relative increase in TRP caused by various types of bends like 45, 90 degree and arcs as shown in Figure 3. It is safe to say that a “90 degree” turn as shown in Fig 3a is seldom used and as a result it is neglected in this study. The outer corner of the “pseudo-mitered 90 degree” bend (Fig. 3b) is mitered (forming two successive 45 degree bends), while the inner segment is not (some CAD tools may report a small 45 degree inner segment but for all practical purposes a 90 degree angle is formed). In the “mitered 90 deg” bend case (Fig. 3c) both the inner and the outer corners are mitered. Finally, it is also possible to use an arc to create a 90 degree bend (Fig. 3d).

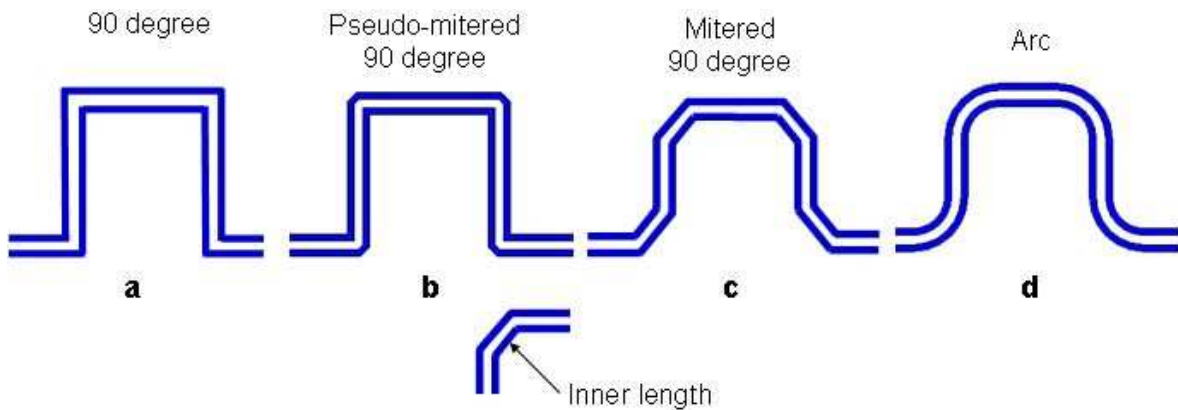


Figure 3. Various types of bends in a loop configuration: (a) 90 degree bend, (b) Pseudo-mitered 90 degree bend, (c) Mitered 90 degree bend and (d) 90 deg arc bend

In this section we study a special case of bend transmission line in which the differential pairs sidestep an obstacle on the PCB using two successive and opposite bends as shown in Fig 4. The length difference between the positive and negative line of the differential pair is zero since the two opposite turns cancel any skew. The sidestep transmission line is composed of 5 segments a to e, see Fig. 4. We varied the length of the two equal segments b & d from 10 mils to 690 mils. Since the overall length of the transmission line and also the vertical distance between sections a & e were kept constant, the length of the segment varied from 985.86 mils to 15 mils. The two 45 degree bend model consisted of sections b and d of length 707.1 mils with length of segment c equal to zero.

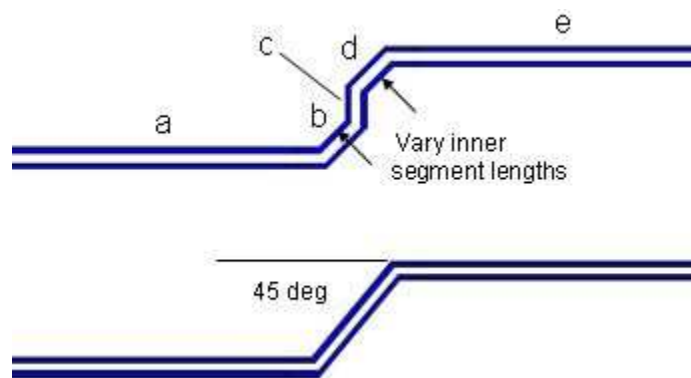
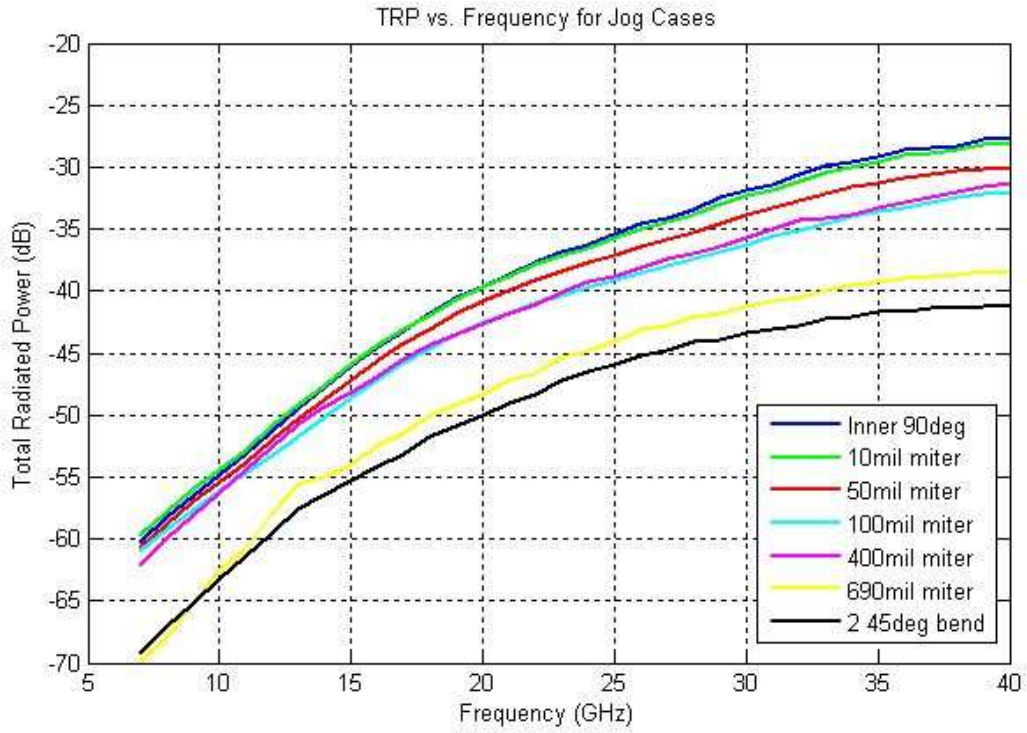
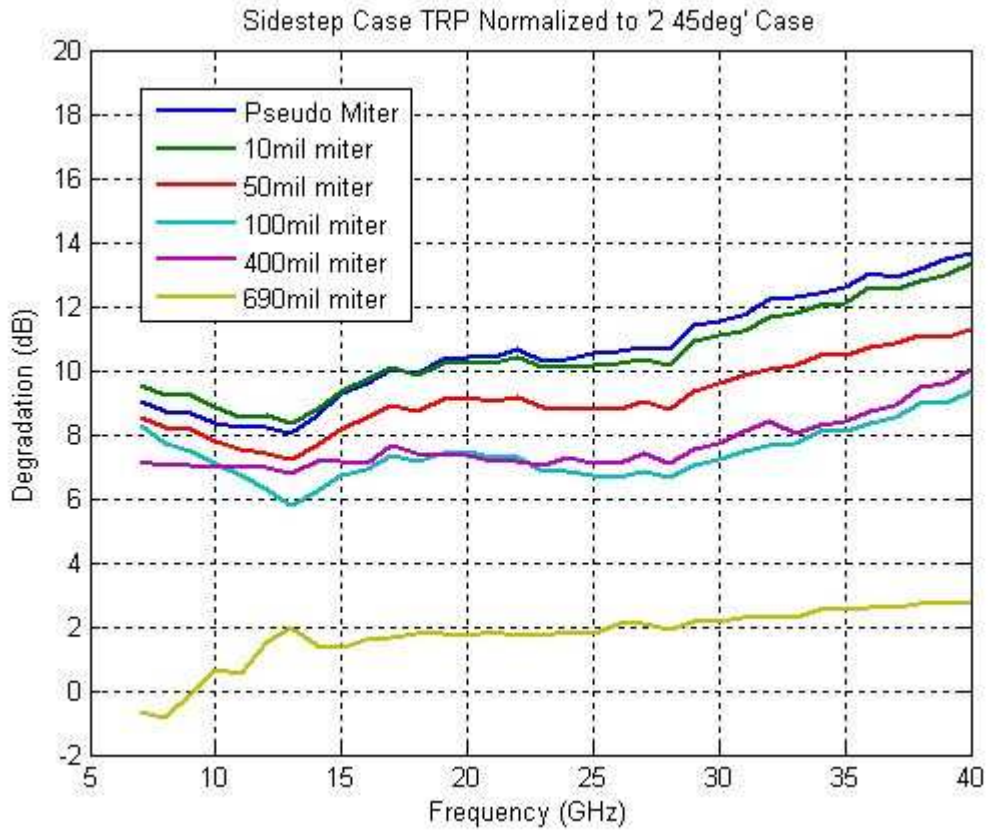


Figure 4: Various sidesteps cases



(a)



(b)

Figure 5. (a) TRP for various mitered side stepped bends, (b) TRP normalized to the 'two 45 deg' case

The total radiated power for the various side step cases are plotted in Fig. 5a. The TRP normalized to the 'two 45 deg' case is shown in Fig 5b. The two plots show that the case with the two 45 degree bends has much lower TRP than the case with the two mitered 90 degree bends. The difference is about 8 dB at 10.3 GHz and 10 dB at 20 GHz. As we increase the mitered length from 10 mils to 100 mils the TRP decreases. As the electrical length increased of segment b and d there is less coupling between the discontinuities caused due to the 4 bends resulting in reduction of the total radiated power. At 690 mil segment c is electrically very small causing less radiation compared to other cases.

In many cases a differential pair has to be routed around an obstacle (such as a capacitor for example) on the PCB. We refer to such a differential pair as a "Jogging Differential Pair". In this part we investigate the benefits of removing as many bends as possible from a differential pair either by relocating the obstacle or by planning ahead to avoid bends for example. In the next study we compare four 45 degree bends to a straight line as shown in Fig 6. The 45 degree bends was previously shown to be the case with the lowest amount of TRP compared to mitered 90 degree bends. In both cases the overall length is still 4000 mils. The total radiated power (Figure 7) of the straight line is 6 dB and 14 dB lower at 10 and 20 GHz respectively compared to the jog case.

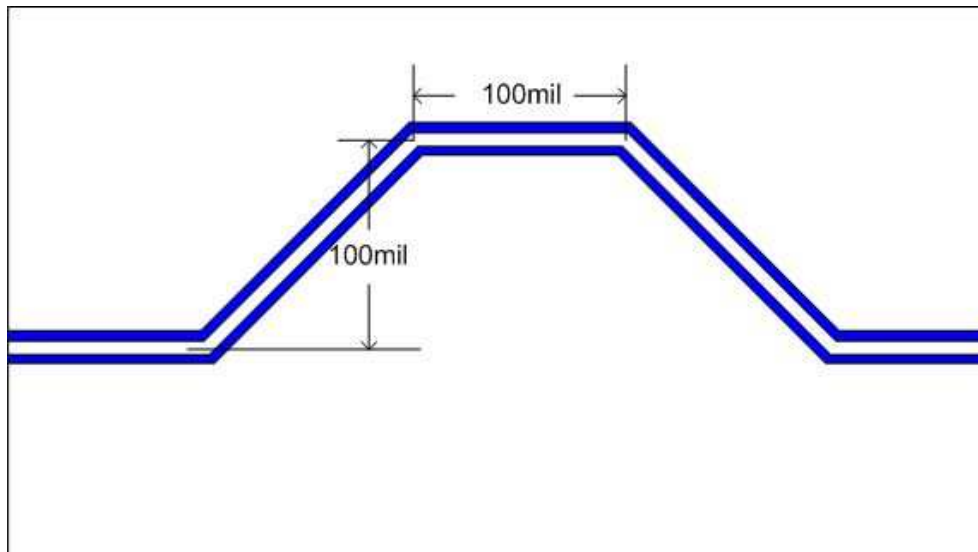


Figure 6: A differential transmission line with four 45 degree bends

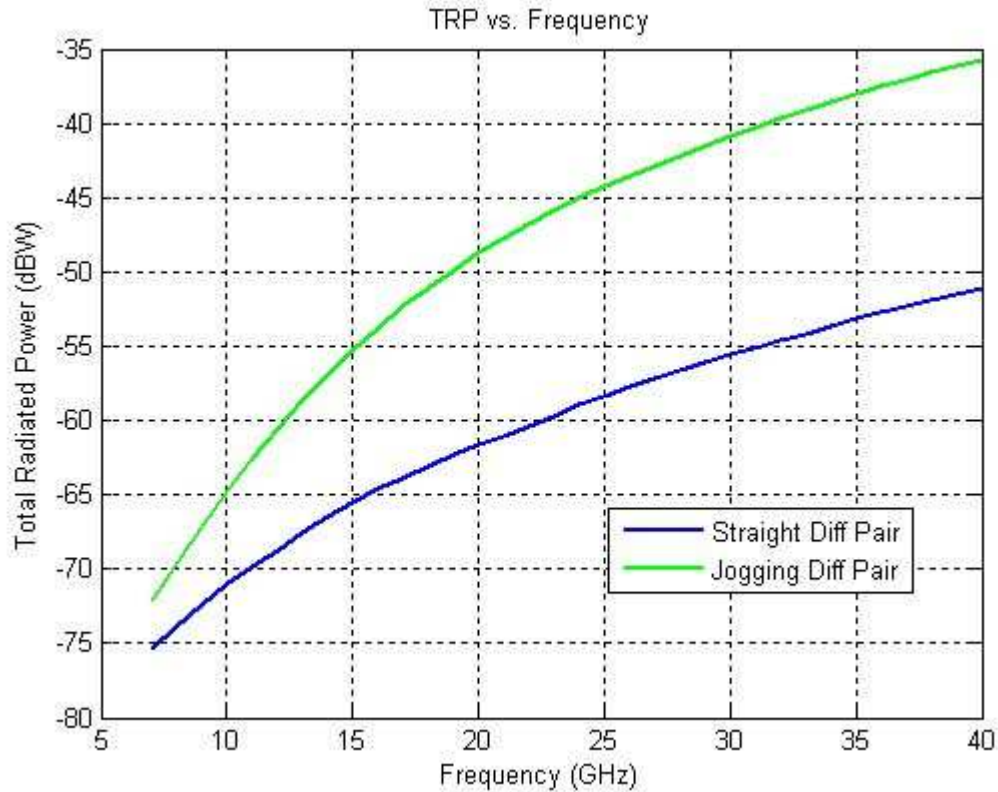


Figure 7: TRP of a straight line and a four 45 deg bend transmission line

Finally, we investigate the effects of replacing a mitered 90 degree bend (Figure 3c) with its corresponding arc radius (Figure 3d). The relationship can be described as follows: if the inner segment length is x , then the radius of the center of inner trace is $x/(2*\tan(\pi/8))=1.207x$, so a 15mil miter segment length converts to a 18.1mil radius. In all cases the jog is composed of four turns (overall skew is still zero). The TRP for the mitered as well as the bend cases are plotted in Figure 8. Figure 9 shows the TRP of the mitered cases normalized to their corresponding arc cases. For example, the results from the 20 mils case with the arc are subtracted from the results from the mitered case with 20 mils. The results show a modest improvement of using arcs over mitered 90 degree bends.

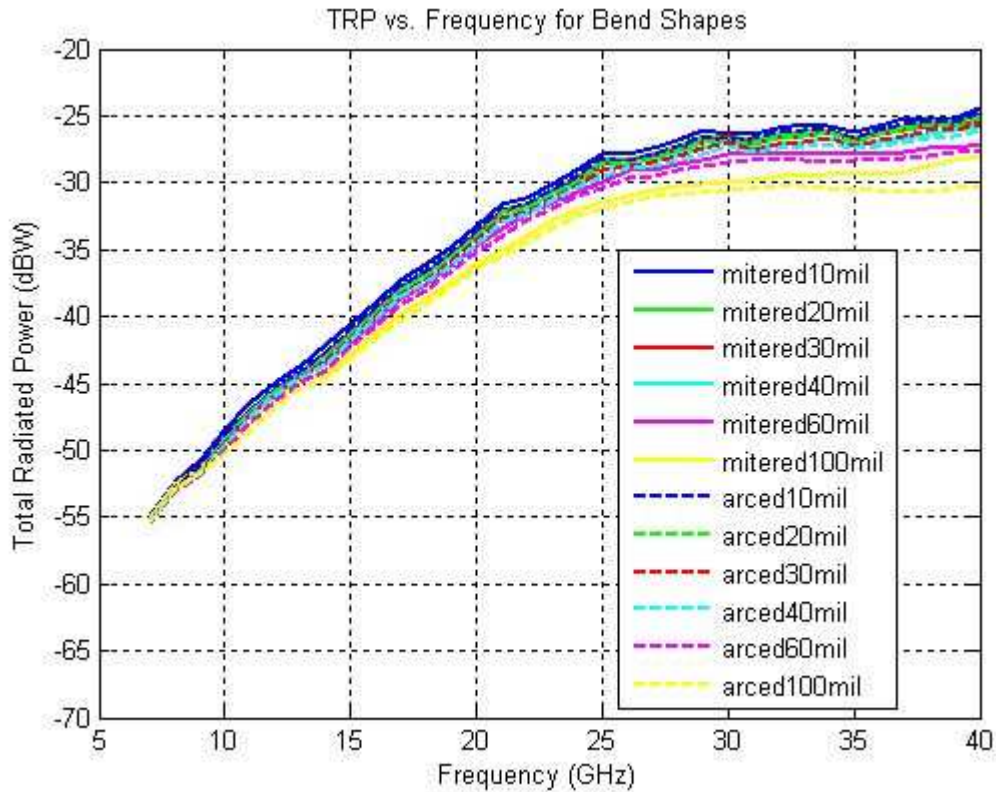


Figure 8: Total radiated power of mitered and the arc bends

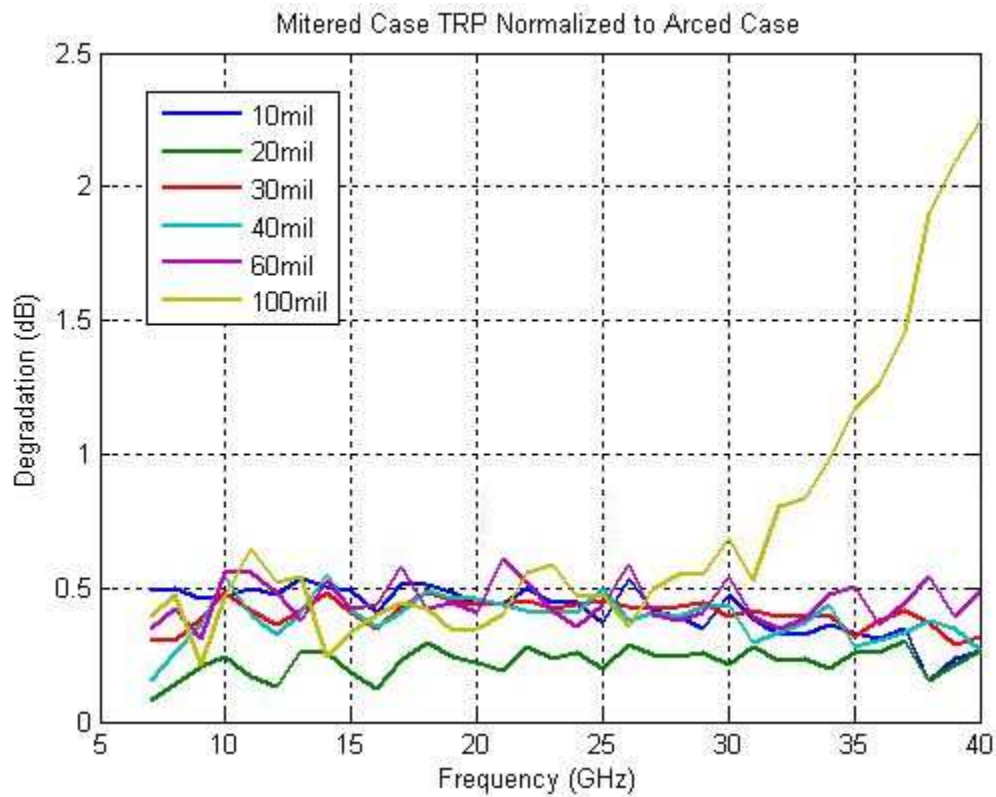


Figure 9: Total radiated power of mitered bends normalized to the corresponding arc and bends

The influence of an adjacent parallel differential pair

In this section we investigate the radiation caused by the proximity of adjacent differential transmission lines. We routed two parallel differential pairs, one active and the other passive, and simulated the two pairs at various distances from one another (air gap measurements), as shown in Fig. 10. The distance between the differential pairs was varied from 15 to 60 mils. Fig. 11 shows the relative increase in TRP at various separations normalized to the case where the passive pair is non-existent. In other words, any value above 0 dB shows the degradation in TRP with respect to the ideal case. When the spacing was 60 mils away the TRP change is insignificant. However, the TRP increases by up to 4 dB at 10.3 GHz, by almost 2 dB at 12.5 GHz, and by 1 dB at 20.6 GHz as the gap between the two pairs decreases to 15 mils. At frequencies above 25 GHz, the increase in TRP is not noticeable.

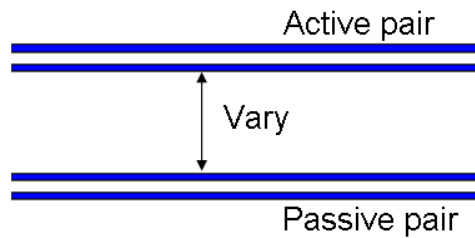


Figure 10: Adjacent differential pair

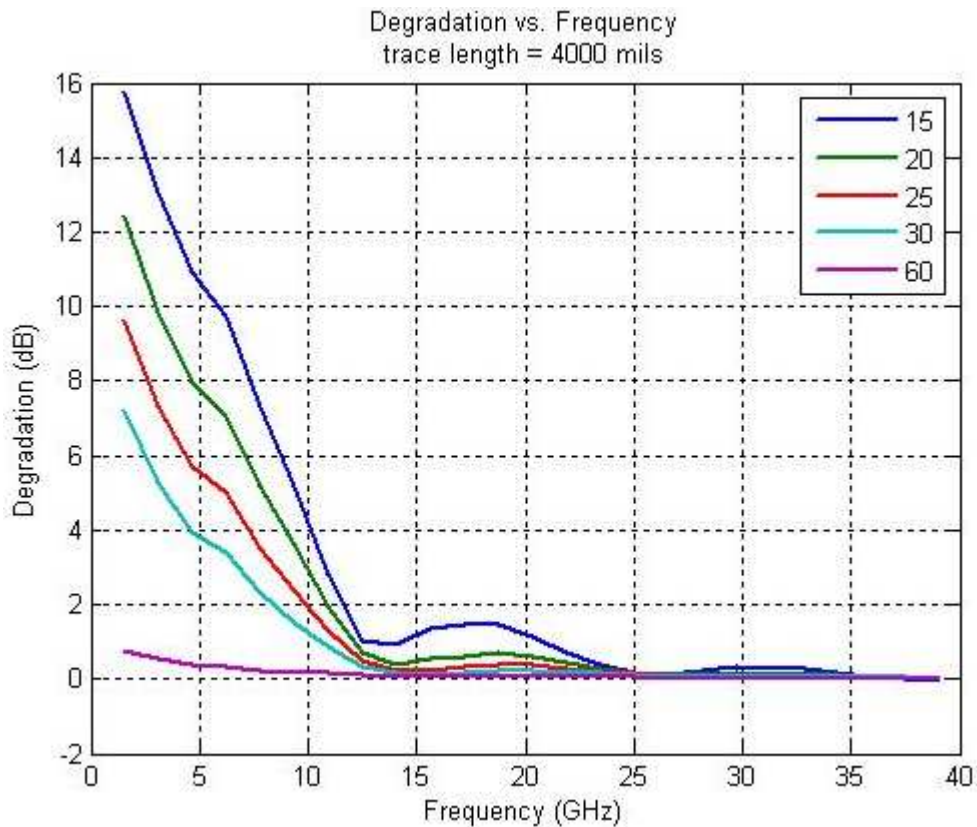


Figure 11: TRP Results for the adjacent differential pair case

The influence of two adjacent parallel differential pairs

In this section we study the effect on TRP when two passive differential pairs are routed in parallel on either side of an active differential pair, as shown in Fig. 12. The distance **a** between the top passive-active pair is kept constant and the distance **b** between the bottom active-passive pair is varied from 15 to 60 mil. Fig. 13-15 show the normalized radiated power for $a = 15, 25$ and 60 mil respectively. Each figure is normalized to the baseline case in which the passive pairs are non-existent, and as a result any value above 0 dB shows degradation in TRP.

From the plots we can see that when the distances between active-passive pairs are equal (i.e 15, 25 or 60 mils) on either side, the TRP does not increase noticeably across all frequency ranges. In all three cases shown, the TRP is high at low frequencies and decreases as the frequency increases noticeably below 25 GHz when the passive differential pairs surrounding the active differential pair are routed asymmetrically.

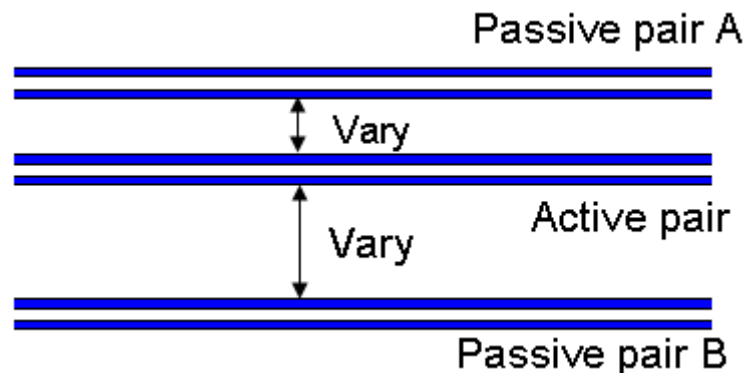


Figure 12: Two adjacent parallel differential pairs

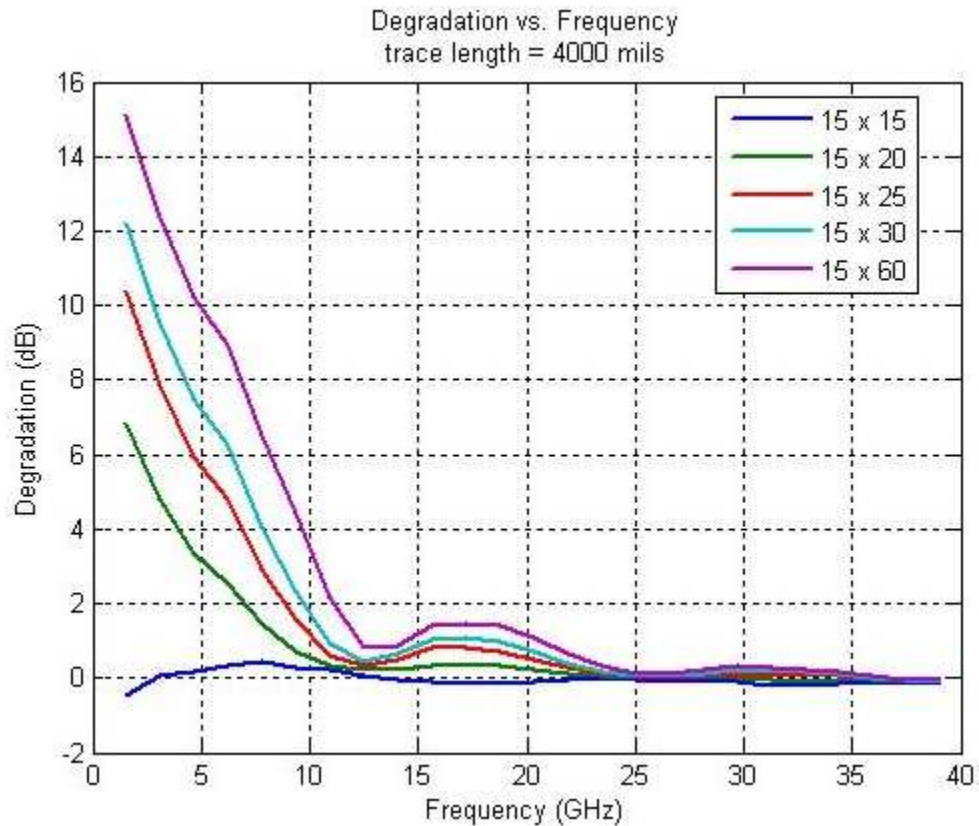


Figure 13: TRP for two passive lines on either side of an active line (a=15mil)

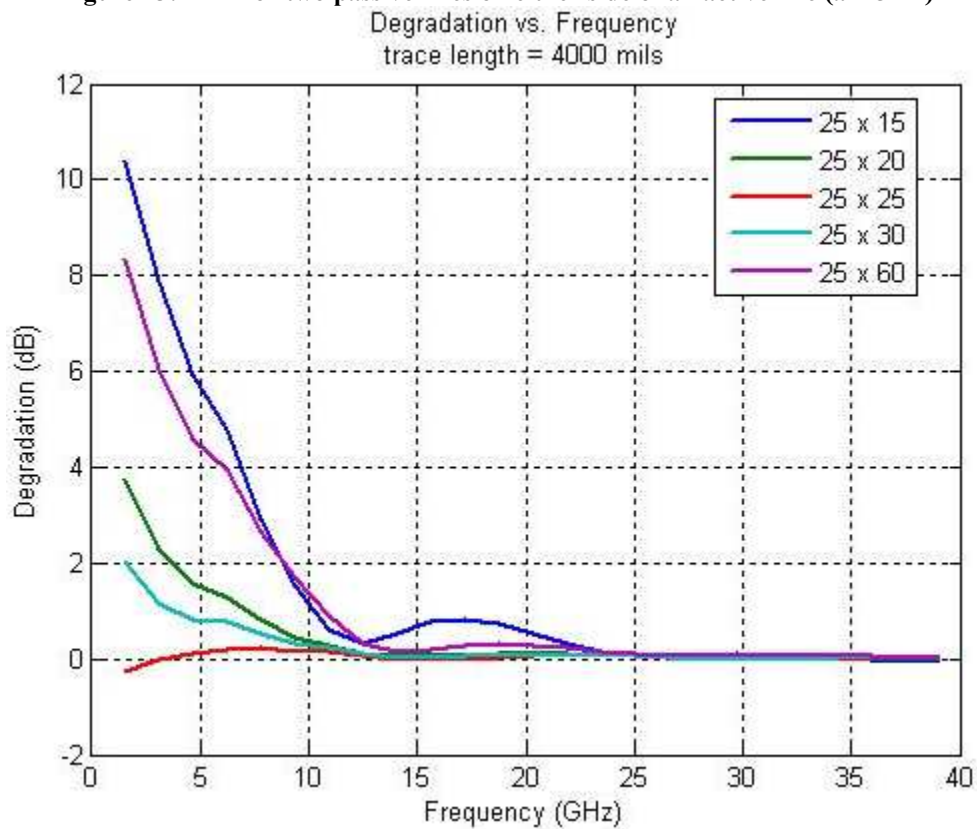


Figure 14: TRP for two passive lines on either side of an active line (a=25mil)

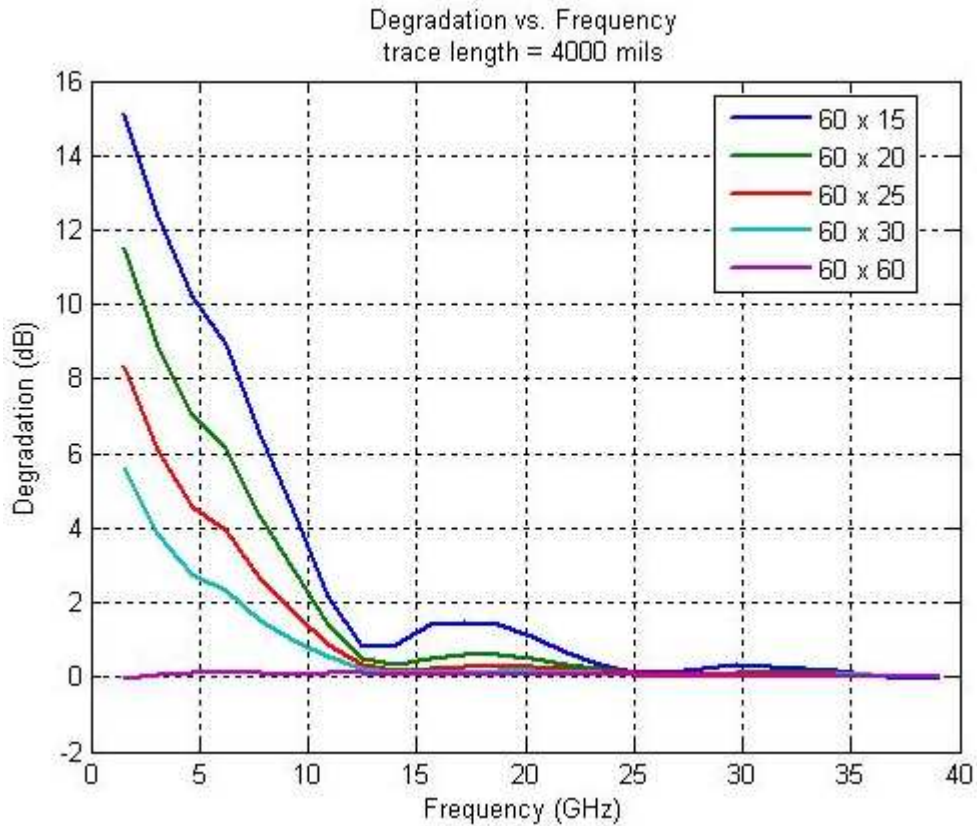


Figure 15: TRP for two passive lines on either side of an active line (a=60mil)

Loopback

The effects of a loopback as shown in Fig. 16 are studied in this section. A loopback can be used for length matching several differential pairs. The overall length for all the models was kept constant at 4000 mils. In the first part of the study length L was kept constant and the spacing S was varied from 15 to 60 mils. In the second part the dimension S was kept constant and L was varied from 500 to 1500 mils. The increase in spacing S did not change the total radiated power as depicted in Fig. 17. Additionally, when the length L of the loopback (or protrusion) was increased while keeping all other parameters constant, the TRP increased noticeably at frequencies below 30 GHz. These observations follow the same general trend described in the “Influence of an adjacent differential pair” case. The proximity of an adjacent differential pair creates an imbalance and causes the TRP to increase.

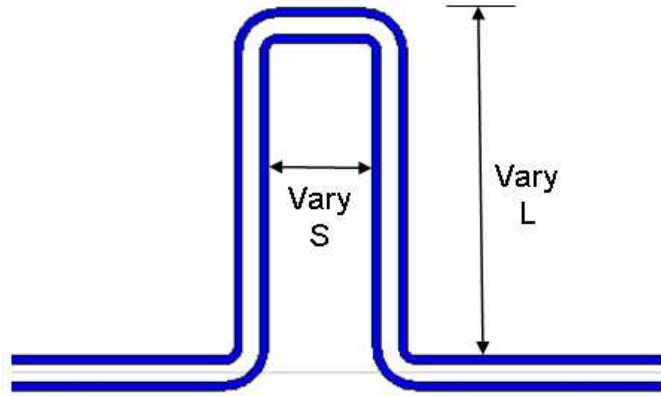


Figure 16 Loopback

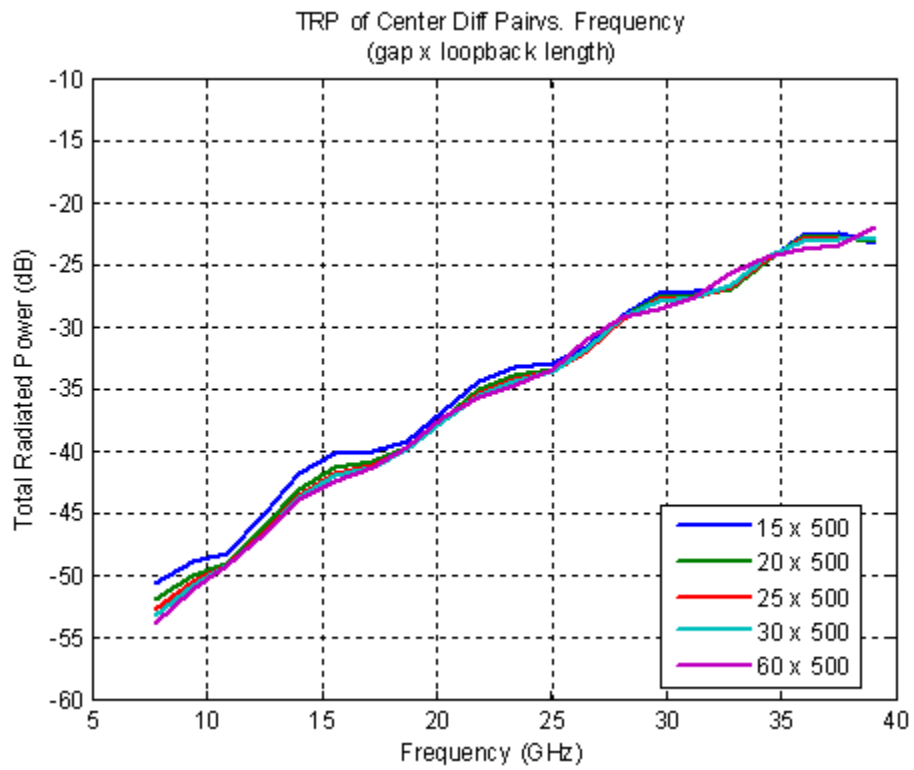


Figure 17: Total Radiated Power for the loopback case with L constant at 500 mil

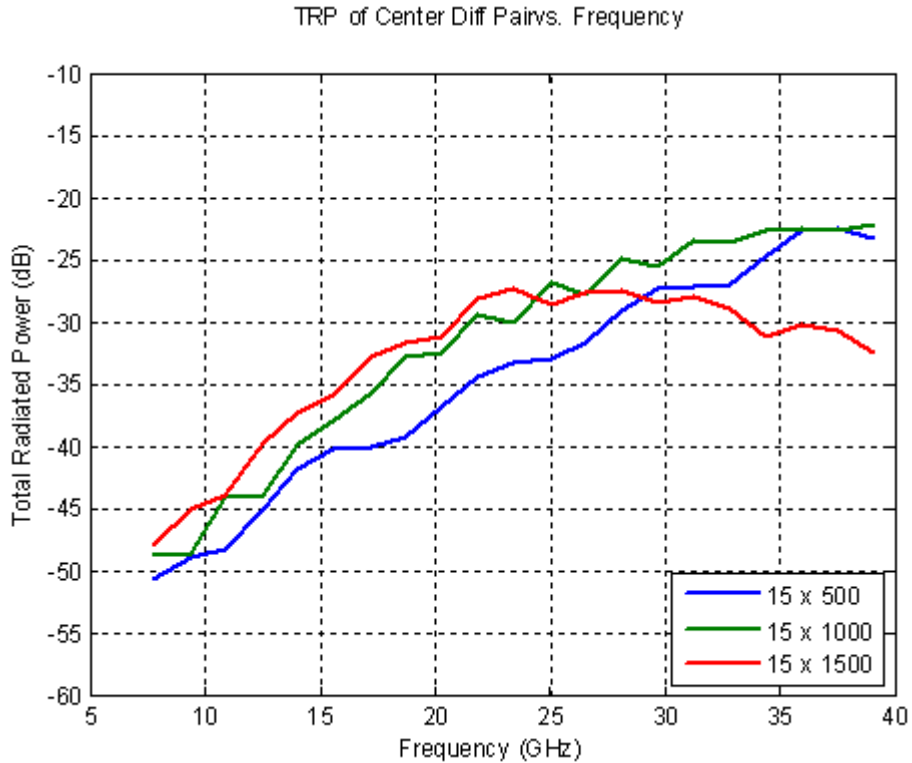


Figure 18: Total Radiated Power for the loopback case with S constant at 15 mil

The effect of intra-layer skew

Differential pairs are usually routed with the minimum amount of overall skew as allowed by the CAD tool. However it is possible to have unnoticed intra-layer skew. In the example shown on Fig. 19, the intra layer skew is (a-b). These two via transitions can excite parallel plate modes between the ground planes which could lead to increased EMI. In the case shown here we studied a differential pair that straddles a ground plane, where the ground plane is hidden from view for clarity. Fig. 20 shows the increase in TRP relative to the case where the intra layer skew is (a-b) = 0. Note that the overall skew is always 0. The TRP increases noticeably as the offset (intra-layer skew) is increased. The increase is more prominent in the lower frequency range (8-25 GHz). Above 15 GHz, there is no longer a clear trend above 15 GHz. However, the TRP increases in all cases when the offset is not 0.

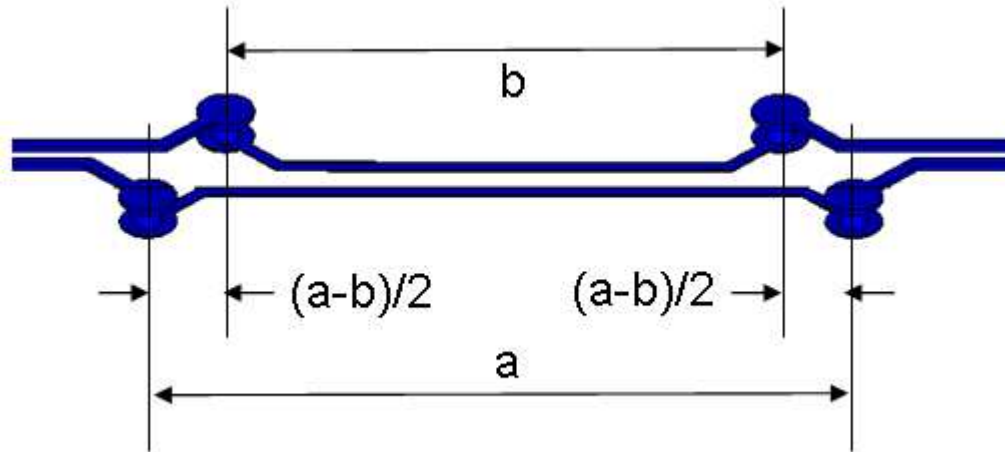


Figure 19: Differential Transmission Line with Intra layer skew

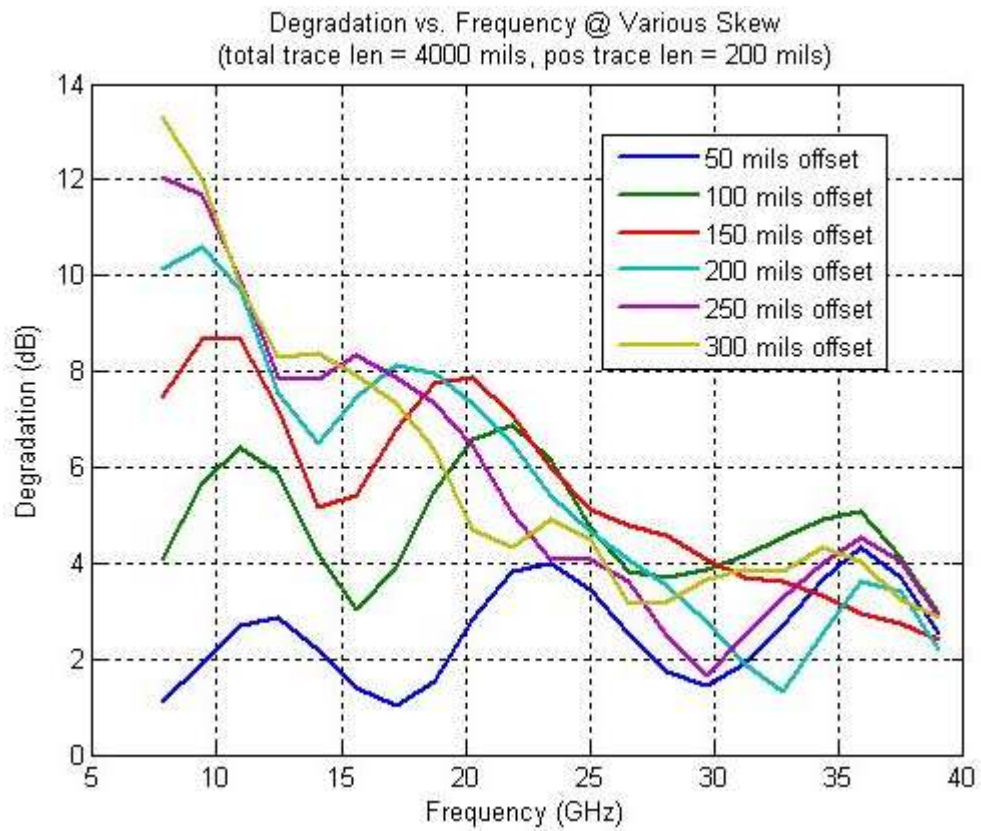


Figure 20: Results for intra layer skew

An unbalanced padstack

Occasionally the padstacks on differential pairs become unbalanced as shown in Fig 21, where an exaggerated case is shown for clarity. Layout tools don't necessarily flag this mistake and it is difficult to notice it while reviewing the layout. We simulated with various combinations of via padstacks. The via padstacks are VIA19RD8 (8/19/30), VIA25RD10 (10/25/36) and VIA40RD20 (20/40/49) where via/pad/antipad diameters in mils are listed between parentheses. The results shown in Fig. 22 are normalized to the VIA19RD8 X VIA19RD8 case, and as such the graph shows the degradation in TRP with respect to that baseline case. The TRP increases significantly when there is a large via mismatch, and the TRP increases by about 1 dB when the mismatch is relatively smaller (VIA19RD8 x VIA25RD10)

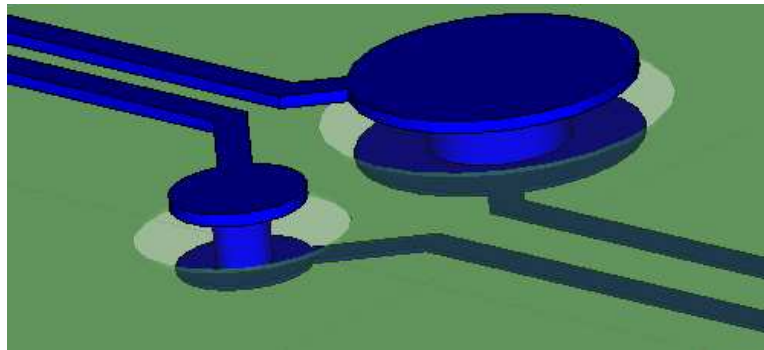


Figure 21 Unbalanced padstack

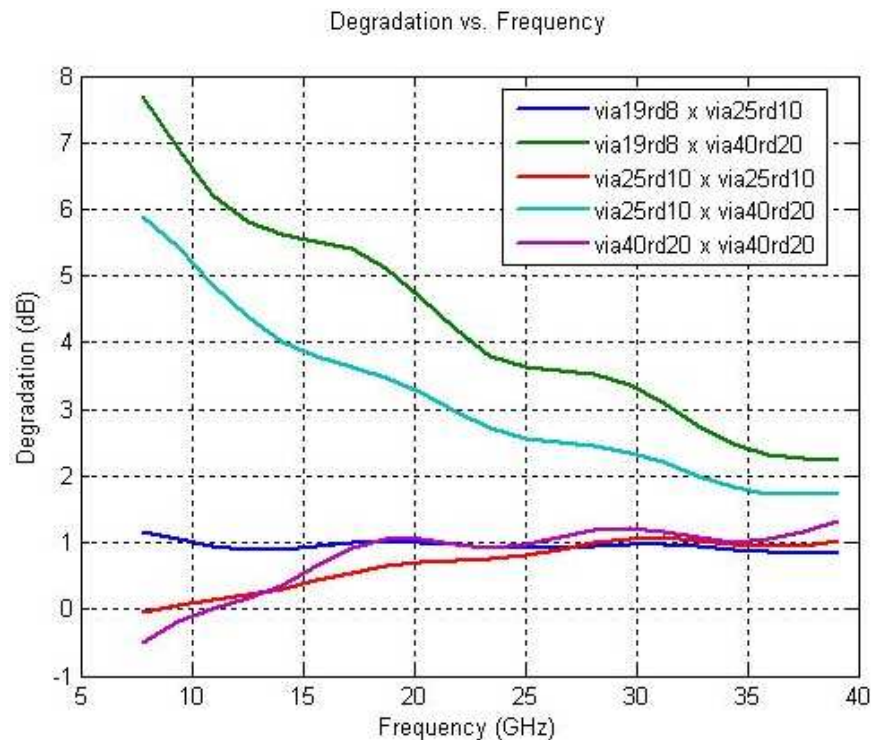


Figure 22: Results for unbalanced padstack

A differential pair over anti-pads

We simulated the effects of anti-pads on TRP as they are slid under one leg of a differential pair, as shown in Fig. 23. The anti-pad is 30 mils in diameter, and the spacing is measured between the center of the via and the edge of the trace (i.e., when the spacing is 15 mils the void of the anti-pad is touching the outer edge of the trace when viewed from above). The TRP varies by about 3dB @ 27 GHz with 10 anti-pads as shown in Fig. 24, even if the anti-pads are routed completely under one of the traces. The TRP increases by up to 7 dB above 23 GHz when the anti-pads are routed completely under one of the traces when there are 19 equally distributed anti-pads along the length of the differential pair, as shown in Fig 25.

In practice, the void of the anti-pad is slightly routed under one side of a differential pair as it skirts a via in the board, and the anti-pads will rarely be uniformly spaced as shown here. In such a case, the user will have to simulate for the TRP that is appropriate for the case at hand. It would not be practical to simulate various combinations of anti-pad sizes and via spacings in this paper. However, as a first order observation, one can say that routing one leg of a differential pair over an appreciable number of anti-pads can increase the TRP by several dBs if not more.

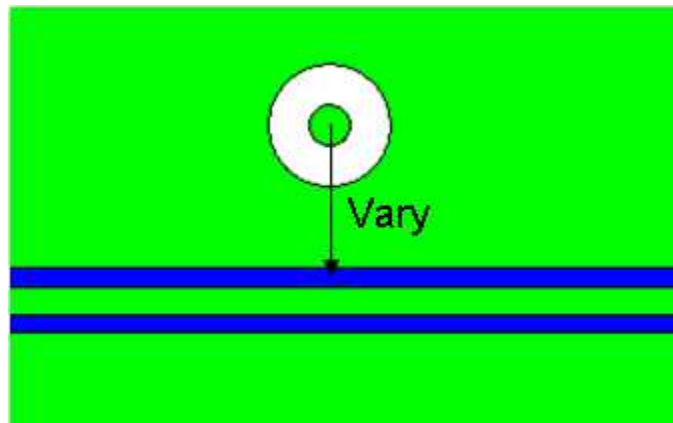


Figure 23: Anti pad under differential pair

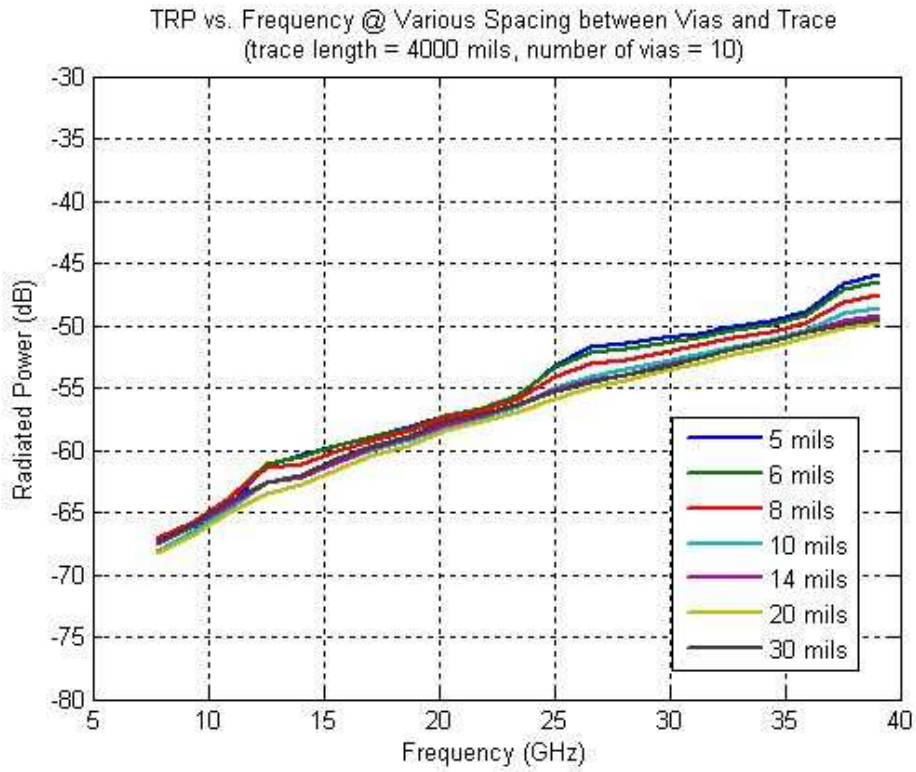


Figure 24: Results for anti pad under differential pair

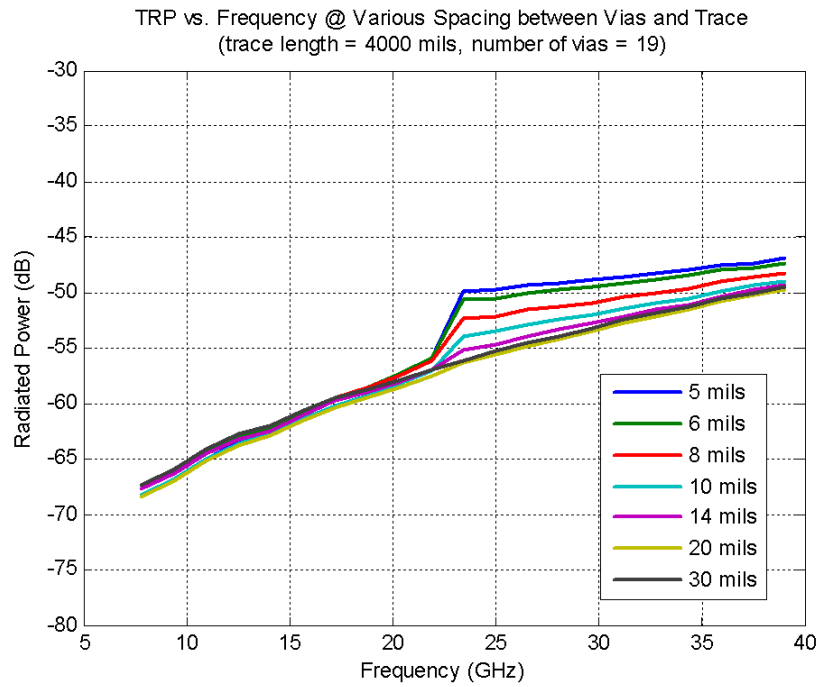


Figure 25: Results for anti pad under differential pair

Proposed Layout Rules

A number of general and practical layout rules for SerDes interfaces operating in the GHz range can be derived from this study. These rules can be adjusted according to specific needs.

1. Minimize the number of bends. Route the differential pair as straight as possible.
2. If you must turn, use a single 45 degree bend if possible
3. If you must turn 90 degrees, use two 45 degree turns, keeping in mind that increasing the inner segment length generally reduce EMI.
4. If you must sidestep an obstacle while routing in a straight line, use two 45 degree turns instead of two 90 degree (or four 45 degree) turns
5. If you must jog around an obstacle while routing in a straight line, use four 45 degree turns instead of four 90 degree (or eight 45 degree) turns
6. Turning using arcs shows modest improvements over mitered 90 degree bends, but can still be considered.
7. The spacing between two parallel differential pairs should be as large as practical.
8. Distribute parallel differential pairs evenly
9. Minimize intra-layer skew
10. Use the same via padstack on differential pairs
11. Avoid routing one leg of a differential pair over an appreciable amount of anti pads. Specific simulation may be required.

More rules can be added by studying and simulating additional cases.

A number of layout rules can be obtained from this study. These rules can be adjusted according to specific requirements.

Conclusion

In this paper, we simulated various common layout imperfections from SerDes differential pairs to determine their impact on system level EMI. In some cases, we uncovered some trends that will allow us to make layout recommendations. For example, we determined that it is better to spread out differential pairs, to keep intra-layer skew at a minimum or to avoid mismatched padstacks, for examples. In some other cases we discovered the need to further investigate and that the final recommendation may not be straightforward. Finally, we outlined a methodology that will help EMC Engineers develop their own custom set of layout rules

References

- [1] Archambeault, B.; Diepenbrock, J.C.; Connor, S., “**EMI Emissions from mismatches in High Speed Differential Signal Traces and Cables**”. *Electromagnetic Compatibility, 2007. EMC 2007. IEEE International Symposium on* 9-13 July 2007 Page(s):1 - 6
- [2] Y. Kami and R. Sato, “Analysis of radiation characteristics of a finitelength transmission line using a circuitconcept approach,” *IEEE Trans. Elecrmmugn. Compat.*, vol. EMC-30, no. 2, pp. 114-121, 1988.
- [3] C. R. Paul, “Frequency response of multiconductor transmission lines illuminated by an electromagnetic field,” *IEEE Trans. Electromugn. Compaf.*, vol. EMC-18, no. 4, pp. 183-190, 1976.
- [4] A. K. Agrawal, H. J. Price, and S. H. Gurbaxani, “Transient response of multiconductor transmission lines excited by a nonuniform electromagnetic field,” *IEEE Trans. Electromugn. Compat.*, vol. EMC-22, no. 2, pp. 119-129, 1980.
- [5] Nakamura, T.; Hayashi, N.; Fukuda, H.; Yokokawa, S.,” Radiation from the transmission line with an acute bend” *Electromagnetic Compatibility, IEEE Transactions on* Volume 37, Issue 3, Aug. 1995 Page(s):317 - 325