Analyzing the Impact of Supply Noise on Jitter in GBPS Serial Links on a Merged I/O-Core Power Delivery Network

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Abstract: In this paper, the impact of integrating large number of I/O (Input-Output) and Core power Delivery Network (PDN) on a 6 layers Flip-Chip Ball Grid Array (FCBGA) package is investigated. The impact of core induced supply noise on high-speed I/O interfaces, and high-speed I/O interface's supply noise coupling to adjacent high-speed I/O interfaces' jitter impact are studied. Concurrent stress validation software is used to induce SSO noise on each individual I/O interfaces; and at the same time; periodic noise is introduced from Core PDN into the I/O PDN domain. In order to have the maximum coupling impact, a prototype package is designed to merge the I/O and Core PDN as one while impact on jitter on each I/O interfaces are investigated. In order to understand the impact of the Core to I/O and I/O to I/O noise, the on-die noise measurements were measured and results were compared with the original PDN where each I/O and Core PDN are standalone and isolated are used as a benchmark.

Keywords: Simultaneous switching output (SSO), PCI-Express (PCIe), Serial-ATA (SATA), Universal Serial Bus (USB), Power delivery network (PDN), Flip-Chip Ball grid array (FCBGA)

1. Introduction

Most SSO supply noise validation of high speed interfaces such as PCIe, SATA, USB, Core logic etc. is approached as case to case basis.¹⁾ Some concurrent test makes use of the device's DFT modes to execute simultaneous tests on different IP blocks like combining scan concurrently with analog tests like RF tuners or serial ATA on an Automated Test Equipment (ATE) is discussed in.²⁾ Layout-aware worst case test pattern³⁾, heuristic method in generating worst case power drop test pattern by accumulating high and low-frequency effects⁴⁾, and mixed signal validation approach that comprehends both the logic and analog aspects of the circuits during power-up sequence⁵⁾ were attempts to develop a known worst case test environment to maximize supply noise creation in the validation setup. Recent publication⁶⁾ has questioned the use of scan test mode to create a worst case test pattern "Scan test mode is vulnerable to power supply noise because switching activity is typically three to four times higher than in normal mode as a result of the DFT strategy. This leads to excessive

voltage drop during scan testing. In some cases, voltage drop in scan mode has been so excessive that it has resulted in inadvertent logic value toggling and test result corruption".

It's not always clear when these interfaces are put in a common validation eco-system and stressed concurrently, what will be the functionality and performance limiter. This paper describes the impact of integrating large number of I/O (Input-Output) and Core power Delivery Network (PDN) on a 6 layers Flip-Chip Ball Grid Array (FCBGA) package. Power supply noise droop of each High Speed I/O interfaces is maximized by implementing a concurrent test in exercising PCIe, SATA and USB to actively transmit data on all the lanes on the electrical board; and at the same time; exerting power gate/ungate noise onto the chip to serve as a natural aggressor from the core logic into the I/O interfaces. To make matter worst, a test package is designed to merge all of these high speed interfaces and core logic power rail as one common power rail on the package so that the injected and coupling noise were maximized. The on-die noise measurements were measured and results were compiled to conclude the findings of this study.

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2. Test Vehicle Design and Concurrent Test Experimental Setup

2.1. Package Test Vehicle Design

In order to increase the chances of failure, the original package, Lucerne (Fig.1) was re-designed to merge the high speed serial link power rails together. All the 1.05V power rails were merged as one. The power rails involves in the merger includes USB2, PCIe, SATA2, Core, ME, EP and VE and all the digital and analog PLLs of the high speed serial link. This had allowed the high frequency noise coupling from one to another easily via a common power plane. Two test package vehicles were built: Jasper and Milford Sound (Fig. 2 & 3). Jasper is the test package whereby a conservative merger was done; where I/O and I/O power rails were merged, and core to core as one power rail. Meanwhile, Milford Sound is the 2nd test package with aggressive power rail merger. All the 1.05V high speed serial link interfaces were merged as one power rail together with the core logic Vcc power rail. Both the test packages used the healthy silicon and both packages have similar footprint as the POR silicon; whereby they were ready to be mounted on the motherboard.

The two significant differences when the power supply rail was merged, was that the power delivery network (PDN) impedance profile and the total amount of on-die capacitance (C_{die}) would change. The PDN impedance profile would be lowered, as a larger amount of vias, a larger size of power planes and pins were bounded as one single power rail. Likewise, the C_{die} of a merged power rails would be larger. Using one common power rail connectivity, the C_{die} of one buffer is easily accessible by the other buffer family using the lower impedance path of the package power plane connection. For example, when Display Port and PCIe are sharing a common power plane design, there is a possibility that the display port's C_{die} is visible to PCIe, and PCIe's C_{die} is visible to display port, thus giving more margins to high frequency noise suppression when these buffers are operating. On the contrary, the supply noise from one IO buffer is also made easier to couple from one to another.

2.2. Concurrent Stress Test Setup

Concurrent test on 1.05V merged plane involved the following tests:

- CMM4 pattern was running on all 5x PCIE ports
- SATApower state was exercised to toggle power state change on all 5 SATA ports except OS port
- USB Test packet was exercised to toggle all 14 USB

Fig. 1. Lucerne Package: Standalone I/O, PLL and Core PDN.

Fig. 2. Jasper Package: I/O and PLL merged & partial Core merged.

Fig. 3. Milford Sound Package: All Core and I/O are merged.

ports; with eye data collected on port 2

All the tests above are industrial compliance test that must be passed in order to achieve certification of product health. In addition to the industrial compliance tests above,

Table 1. Industrial product qualification v.s. concurrent stress validation setup.

Industrial Product Qualification Validation Setup	Concurrent Stress Validation Setup
One port at a time	All ports simultaneously (worst port eye-diagram and jitter is measured)
One interface at a time	All interfaces simultaneously
Logic and Analog tests are separately tested	Logic and Analog tests are tested simultaneously
All ports need to pass eye-diagram and jitter specification	All ports need to pass eye-diagram and jitter specification
One port transmitting at a time	All ports transmitting and receiving simultaneously
One port receiving at a time	All ports transmitting and receiving simultaneously
Analog Front End transmission validation	Analog Front End transmission and data bit validity check
Analog Front End receiver eye-diagram validation	Analog Front End received eye-diagram and digital data bit validity check
Power Delivery Noise validation check on one interface at a time	Power Delivery noise validation check on all interfaces running at once
Cdie measurement on one interface	Cdie measurement on all interfaces on merged power plane
Across all temperature and skew corners	Selected known worst case temperature and skew corner only

additional tests were exercised simultaneously in attempt to inject noise into the system and serve as aggressors to the I/O circuit.⁷⁾

To showcase how severe the concurrent test was imposed onto the system for the purpose of this research project, table 1 below compares side by side the difference between industrial product qualification execution and the concurrent stress test setup.

3. Results and Discussion

There were 5 packages tested with the concurrent stress test i.e: Lucerne, Jasper, Milford Sound, Jasper and Milford Sound without die-side capacitor (DSC). The packages without DSC were measured to ensure that the existence of DSC would not mask out the power delivery noise and alter the jitter tolerance on the circuit; shifting the circuit's

vulnerability to a higher level than the typical range. Table 2 shows the summary of noise and eye data collected for the 3 major interfaces of PCIe, SATA and USB; which all belong to the 1.05V high speed serial data interfaces. These I/O interfaces were transacting at GBps speed and at the same time stressed with concurrent traffic and power gate/ungate noise from the digital core logic. From its standalone power plane (Lucerne) to a semi-merged power plane (Jasper) and the fully merged power plane (Milford Sound), PCIE and SATA looked healthy even as the magnitude of noise had increased from ~50 mV to ~100 mV; and with on-package capacitor removed (no DSC). The passing of compliance eye test has indicated that PCIe and SATA had ample margin preventing the eye spec violation or the PDN design did not coincide with the operating clock frequency of the current excitation and thus, the noise on the PDN barely made any significant impact to the circuit operations and degraded its eye performance.

On the other hand, the USB interface had shown intermittent failure although the noise magnitude did not increase much from 67 mV to 80 mV. Jasper which had the semi-merged power plane failed all eye spec miserably; although Milford Sound (with DSC) which had the most pessimistic merged power plane was able to survive some of the eye tests; and only failed when the DSC was removed and core noise was introduced. This showed that the failure was intermittent and was not consistent with the noise magnitude increase (65 mV and 100 mV fail, while 75 mV passes). In other words, the noise magnitude was not the dominant factor that drives the failure of the eye; it was some other parameter that causes the eye failure.

Table 2. PCIe, SATA and USB Noise and eye summary table on 5 test packages.

Si	Stress Combination									
	A		A + B		A + B + C		A + B + C + D		A + B + C + D + E	
	Noise (mV)	Eye	Noise (mV)	Eye	Noise (mV)	Eye	Noise (mV)	Eye	Noise (mV)	Eye
PCI-Express										
Lucerne	52.26	passed								
Jasper	57.44	passed	64	passed	64	passed	64.02	passed	72	passed
Jasper (no DSC)	85.16	passed	86.25	passed	88.19	passed	88.28	passed	85.58	passed
Milford Sound (with DSC)	56.83	passed	64	passed	64	passed	64	passed	85	passed
Milford Sound (no DSC)	60.27	passed	64	passed	69.72	passed	70.39	passed	101.4	passed
Serial- ATA										
Lucerne	44.93	passed								
Jasper	48	passed	48	passed	48.38	passed	48.58	passed	48	passed
Jasper (no DSC)	51.89	passed	51.98	passed	51.3	passed	53.8	passed	54.05	passed
Milford Sound (with DSC)	52	passed	59	passed	56	passed	60	passed	87.84	passed
Milford Sound (no DSC)	60	passed	60.25	passed	60.31	passed	66.67	passed	94.08	passed
Universal Serial Bus 2.0 (port12)										
Lucerne	67.39	passed								
Jasper	68.41	passed	60	passed	65.34	passed	76	passed	72.84	passed
Jasper (no DSC)	76	failed	73.08	failed	77.33	failed	78.59	failed	80.69	failed
Milford Sound (with DSC)	60.17	m. passed	60.55	m. passed	60.56	passed	68.89	m. passed	97	passed
Milford Sound (no DSC)	70.23	passed	65	failed	72.03	m. passed	77.58	failed	101.6	failed

Table 3. Eye results on all the USB ports on the system, on different test packages

		Legend:													
		A = Window + 5xPCIe, B= A+6xSATA, C = B + 14xUSB, D = C +10xSRAMs, E = C+PMC.													
Electrical Validation USB data (I/Os Concurrent + SRAM + PMC aggressor)		Passed Waived Failed													
		Port 0	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7	Port 8	Port 9	Port 10	Port 11	Port 12	Port 13
Nominal corner	Lucerne	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Waived	Passed
19" cable	Jasper	Passed	Passed	Passed	Waived	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Failed	Failed
	Milford Sound (SRAM)	Passed	Failed	Failed	Failed	Passed	Passed	Waived	Passed	Waived	Waived	Passed	Passed	Failed	Waived
	Milford Sound (PMC)	Passed	Failed	Failed	Failed	Passed	Passed	Waived	Passed	Waived	Passed	Passed	Passed	Failed	Waived

3.2. USB on-die noise to eye impact

As indicated in the table 2, the test data on USB was based upon the worst case port which was port12 on the system. Further investigation was needed to extend the study to the rest of the ports' eye to see how far the failure was stretched across all ports.

Eye results in table 3 shows that port1-3 were prompted to failure, while port 0, 4, 5, 6 & 7 were passing on Milford Sound when core noise were injected. Likewise, port12 was prompted to failure on all Lucerne, Jasper and Milford Sound; whether or not core noise was injected. Not all ports fail in conjunction to core noise injection; and some ports showed more vulnerability than others. Since the ports were all routed on a merged power rail; it was impossible to isolate the power delivery noise on each single port of port 1/2/3 from the other; thus, the issue dissection had to be examined from a different perspective other than power delivery noise measurement on each individual port.

To understand the issue better, port 2 (9" cable and 19" cable) and port 12 were selected for a detail eye plot and how it vary with known healthy eye plot.

In figure 4, RMS consecutive jitter was chosen for eye performance analysis. Apple to apple comparison between

all passing eye on Port2 with 9" cable against Port2 with 19" cable and Port 12 with 1" cable had easily shown the difference between the trend of RMS jitter range on passing and failing examples. Red marker indicates eye failure, yellow marker indicates marginally passed eye and no marker means passing eye. Notice that the left graph which showcase all passing eye data had RMS Consecutive Jitter all falling within 20-50ps range, while the case with Port2 and 19" cable had its RMS consecutive jitter skew towards 30-60ps range, Meanwhile, the case with Port 12 and 1" cable had shown a clear indication that any RMS consecutive jitter that exceeded 50ps or fell below 25ps was definitely a failing eye. This is a good graph to indicate that the USB routing (14" of trace length) had already achieved its maximum, and the margin to failure can be marked clearly on this graph. On the case of port2 with 19" cable, the 2 failing eye were encompassed within many marginally passing eye which were also residing within the 30-60ps jitter range. It was difficult to conclude the failing margin using this graph. Either these 2 failing eye data were outliers or the marginally passed cases were somewhat lucky escapes. Comparing port 2 and port12, both RMS consecutive jitter trend was different, whereby port2 19"

Fig. 4. (Left) RMS Consecutive Jitter on port 2 with 9" cable length to serve as a healthy baseline for comparison for Port 2 -19" cable (middle) and Port 12- 1" cable (right).

Fig. 5. (Top) PCIe On die-noise (Bottom) PCIe max total-jitter of Milford Sound.

cable obviously can withstand a higher RMS jitter before failing eye than port12 1" cable. This probably could be explained by the cable having better shielding/grounding compare to traces routed on board.

When comparing these RMS jitter data with on-die noise; Jasper (partially merged power plane) Port12 would not allow on-die noise to go beyond 75 mV before the eye breaks. Meanwhile, Milford Sound (with and without DSC) on port12 1" cable was a lucky escape whereby the eye did not break even-though the on-die noise had stretched beyond 75 mV and reaching almost 100 mV; and the RMS jitter was much smaller. Therefore, there is no hard and fast rule to dictate the right spec for peak to peak noise (mV) needed to maintain system health, and on-die noise is not the dominant factor that drives eye failure. To support the argument that on-die noise is not the dominant factor that drives eye failure, more case study is shown below on PCIe

3.3. Root Causing Eye Failure using System Margining Approach

By focusing on the last column on table 2, the USB2 port 12 eye diagram had failed consistently when PMC noise was added to the merged power plane; on both Jasper and Milford Sound. For simplicity, Milford Sound was used to reverse margining till the eye on USB2 became passing again.

From experimental perspective, system margining was done through modification of the PMC script to reduce the

Fig. 6. (Green) Old PMC induced noise (Orange) New PMC induced noise on Milford Sound's PDN.

Fig. 7. (Blue) Old PMC induced noise spectrum (Red) New PMC induced noise spectrum on Milford Sound's PDN.

intensity of power gate/ungate activity. Each time, USB eye was measured and checked if it could pass on Jasper and Milford Sound. After the moderation of PMC script to 300000 times slower than original version, all I/Os on the system had managed to run successfully passing all eye for at least 30min before system hangs. The noise data was compared and shown in figure 6 and 7.

The modification of PMC script had lowered the 240 MHz frequency spectrum and the various other spectrums' intensity and this reduces all the failing eyes to passing.

4. Summary & Conclusions

Minimizing the jitter due to power supply noise is the most important design goal for the power delivery system of High Speed Serial Link interfaces. This paper presented the results of using post-silicon concurrent stress suites to induce noise into the High Speed Serial link interfaces (PCIe, USB and SATA) using two test vehicle packages known as Milford Sound and Jasper. The stress method was by applying the realistic noise generated by concurrent traffic transmitting on each of these interfaces and core power gate/ungate activity; which periodically launch a close to ~100 mV peak to peak noise into these three High Speed Serial Link interfaces. Using 60 mV as our observation baseline, (which was the quoted power delivery target during our design simulation), we observed that USB interface

suffered the most failure on eye; whereas PCIe and SATA survived with some margin available.

The findings in this investigation were carried out with a new PMC script with noise injected into the High Speed Serial Link's merged power rail on Milford Sound. However, this time, the PMC script had been modified and the 240 MHz spectrum intensity was greatly reduced. Surprisingly, USB started to pass the eye test. Knowing that the 240 MHz was the operating frequency of USB2, it is believed that the eye is greatly influenced by noise spectrum overlaps with its operating frequency. Meanwhile, the noise profile of the new PMC script remains as ~ 100 mV whereby its magnitude had not reduced.

In conclusion, it is believed that jitter due to power supply noise is real and should be used to set-forth the power delivery target for power delivery network (PDN) analysis. The use of mV peak to peak noise is inevitably a loose guideline and very often does not define the relationship to the jitter failure well. As shown in the above case study, USB2 eye failed miserably even-though the noise was 65 mV with high 240 MHz component; and if the 240 MHz spectrum is reduced; USB2 eye passed happily even-though the noise had increased to ~ 100 mV. Clearly; mV noise is no longer a good judging criteria that should be used for power delivery analysis; especially the High Speed Serial Link PDN analysis. Although many will debate about its repeatability on a different product, different platforms;

different process corner, it is crucial that the power delivery noise spec be re-defined to encompass noise jitter sensitivity as its performance target.

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