ISSN: 2583-9888
DOI: doi.org/10.51219/JAIMLD/priyank-anurag/111

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Journal of Artificial Intelligence, Machine Learning and Data Science

https://urfpublishers.com/journal/artificial-intelligence

Vol: 1 & Iss: 1

Research Article

Lane Margining of High-speed IO Devices to Validate the Signal Integrity

Priyank Rathod* and Anurag

Intel Corporation Folsom, CA, USA

Citation: Rathod P, Anurag. Lane Margining of High-speed IO Devices to Validate the Signal Integrity . *J Artif Intell Mach Learn & Data Sci 2022*, 1(1), 400-402. DOI: doi.org/10.51219/JAIMLD/priyank-anurag/111

Received: 01 October, 2022; **Accepted:** 18 October, 2022; **Published:** 20 October, 2022

***Corresponding author:** Priyank Jayantilal Rathod, Intel Corporation Folsom, CA, USA, E-mail: rathodpriyank@gmail.com

ABSTRACT

The continuous development of high-speed digital devices has posed significant challenges in ensuring signal integrity and reliability. This is mainly due to the criticality of data rates and performance. Maintaining strong and error-free communication in the presence of noise, crosstalk, and other signal integrity issues has become increasingly crucial. Lane margining is an essential approach to guaranteeing the reliability and robustness of high-speed communication interfaces. This technique dynamically adjusts and optimizes communication lane operational parameters to enhance signal integrity margin. It helps identify the optimal settings for reliable data transmission and detect potential signal integrity problems early. This paper provides a comprehensive discussion of lane margining in high-speed devices.

Keywords: High-Speed IOs, Voltage Margining, Timing Margining, Jitter, BER, Voltage-Time-Offset, Eye Diagram, Static Eye

1. Introduction

In the realm of high-speed digital devices, the relentless pursuit of faster data rates and higher performance has ushered in an era of unprecedented challenges in signal integrity and device reliability. As these devices operate at the edge of technological capabilities, even minor perturbations in the signal can lead to significant degradation in performance, making the margining of lanes an essential practice. Lane margining, encompassing both voltage and timing aspects, emerges as a critical technique to ensure the robustness and reliability of high-speed communication interfaces. This introduction sets the stage for a comprehensive exploration of lane margining, including voltage and timing margining, within the context of high-speed devices, aiming to enhance our understanding and methodologies to tackle the challenges posed by the next generation of digital communication systems. The performance of any system heavily relies on the input and output of the system. To verify the signal integrity of any system or the IP block, the focus is to reduce the error rate referred to as the bit error rate induced during the communication. The most popular approaches are based on a statistical eye consisting of the ISI probability distributions at different sampling phases[1-3].

2. Margining

This methodology explores voltage Margining, a process crucial for identifying the operational boundaries that ensure error-free data transmission by adjusting voltage levels. Concurrently, it examines timing Margining, which involves adjusting timing parameters to define reliable signal transmission windows. By integrating both voltage and timing Margining, lane margining offers a holistic approach to optimizing the operational margins of high-speed devices, addressing the multifaceted challenges of signal integrity. This exploration aims to enhance the understanding and methodologies for tackling the complexities

of next-generation digital communication systems, providing insights into the tools, applications, and implications of lane margining for researchers, engineers, and designers. Through this, the paper seeks to pave the way for developing more robust and efficient systems capable of meeting the demands of future technologies.

As the demand for high-performance and high-speed devices grows, calculating these margins becomes even more essential to ensure reliable operations, particularly in High-Volume Manufacturing (HVM) conditions. Research in statistical simulation frameworks for high-speed IO devices provides a means for analyzing Lane Margining. Modeling random jitter sources like supply noise and clock jitter and deterministic jitter sources, such as ISI, crosstalk, and Duty Cycle Distortion (DCD) provide a comprehensive understanding of the factors influencing Voltage and Timing Margining[4]. Analyzing these margins at a target bit error rate by modeling transmitter, channel, and receiver components to predict system voltage and timing margins helps accurately estimate system performance at multi-gigahertz data rates[5]. In systems where the nonlinear behaviors of various link elements can have a significant impact on the performance of the system, a novel approach of regression analysis can be utilized to calculate voltage and time Margin, which provides a more robust and time-efficient way to generate voltage, time margin distributions for analysis[6]. This allows for modeling complex relationships between multiple independent variables (design parameters) and dependent variables (performance metrics like voltage and time margins) through an exhaustive evaluation of all possible combinations of corner cases in the design space. Identifying the statistically significant factors helps optimize the system design and manufacturing process to mitigate the impact of non-deterministic characteristics either by adjusting design parameters to maximize margins or ensuring that performance remains within acceptable limits under all conditions.

2.1. Voltage margining

Voltage margining refers to adjusting the voltage levels within a communication lane to identify the operational boundaries that ensure error-free data transmission. This technique is pivotal in determining the voltage tolerance of a device, which is crucial for maintaining signal integrity amidst variations in power supply, temperature, and other environmental factors. By systematically varying the voltage levels and monitoring the error rates, voltage margining provides insights into the optimal voltage settings that maximize the signal-to-noise ratio (SNR) and minimize bit error rates (BER). This process enhances the reliability of high-speed devices and contributes to their energy efficiency by identifying the minimum voltage levels required for stable operation.

Voltage margining can be leveraged even in CPUs to enhance their performance, resulting in substantial energy savings through strategic voltage scaling without detrimentally impacting system performance[7]. Voltage margins-essentially the difference between the actual operating voltage and the minimum voltage required for reliable operation-represent a significant opportunity for energy optimization. Voltage levels can be adjusted and tailored to the specific characteristics of different CPU cores and workloads, optimizing energy consumption while maintaining performance integrity. By carefully analyzing and exploiting these margins, mainly through the innovative use of a severity metric for undervolting conditions, CPUs can operate more efficiently. A deeper understanding of voltage margins and the development of sophisticated metrics and models to guide voltage scaling decisions can provide the means to maintain or even improve the performance of CPUs while significantly reducing power usage.

2.2. Timing margining

Parallel to voltage margining, timing margining addresses the temporal dimension of signal integrity. It involves deliberately adjusting timing parameters, such as clock skew and data arrival times, to define the temporal windows within which signals can be reliably transmitted and received. Timing Margining is instrumental in combating the challenges posed by signal distortion, propagation delays, and synchronization issues exacerbated at higher data rates. By identifying the timing margins, engineers can ensure that the devices are resilient to timing variations, thereby enhancing the overall system performance and reducing the likelihood of data corruption.

High data rate devices like DDR4 SDRAM make it crucial to perform timing margining since, at these elevated rates, the timing margins become narrower. It's essential to verify that the memory subsystem can perform WRITE/READ operations without data integrity issues under these conditions. For these devices, timing margin can help identify worst-case margins, taking into account variations such as trace length on the Printed Circuit Board (PCB), which in turn can assist in determining the potential vulnerabilities in the memory subsystem's design and operation. By quantifying timing margins, system architects and designers can make informed decisions to optimize the memory subsystem for both performance and power efficiency, such as influencing the selection of termination settings to enhance margins to improve system reliability[8].

3. The Convergence of Voltage and Timing Margining in Lane Margining

As a holistic approach, Lane margining integrates both voltage and timing margining to comprehensively assess high-speed devices's operational margins. This dual focus allows for a more nuanced optimization of the communication lanes, ensuring that electrical and temporal parameters are within the bounds that guarantee reliable data transmission. The synergy between voltage and timing Margining is crucial in addressing the multifaceted challenges of signal integrity in modern digital systems, where the interplay between electrical and temporal characteristics can significantly impact performance. Research into issue analysis shows that more than 40% of customer returns are attributed to circuit and bus electrical marginality[9]. This is due to process-product interaction defects with parametric sensitivity and semi-systematic location distribution, which are increasing proportionally with scaling due to integration techniques and fundamental scaling factors.

Lane margining is implemented by moving the data or error sample location in high-speed IO PHY for error monitoring. A powerful tool used to assess the quality of digital signals in high-speed communication systems, including those in high-speed IO (Input/Output) interfaces, is an eye diagram, as shown in **(Figure 1)**. It is particularly relevant when discussing the margining process, as it visually represents how well a system can tolerate variations in timing (timing margin) and voltage (voltage margin) without error. It is created by overlapping segments of a digital signal's waveform on top of one another, spanning one or more bit periods.

The "eye" opening in the middle of the diagram represents

the time window in which the signal can be reliably sampled without error. Variations in the timing of the signal's transitions, seen as the horizontal thickening of the edges of the eye, indicate jitter. The vertical thickening of the waveform within the eye diagram represents amplitude noise or variations in the signal's voltage levels. Less jitter means more stable signal timing and clearer eye-opening, and lower noise levels contribute to a taller eye-opening, indicating better signal integrity.

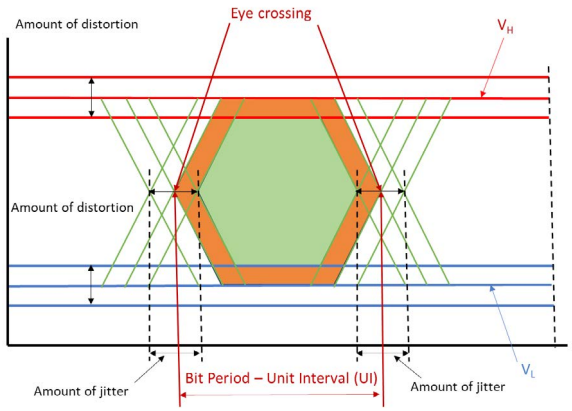

Figure 1: Eye Diagram for Margining.

The eye diagram is crucial for evaluating how different factors, such as voltage levels, timing offsets, and environmental conditions, affect the signal quality of high-speed IO interfaces. Margining involves adjusting these factors to find the limits (margins) within which the system operates reliably.

Timing Margining involves shifting the sampling point of the receiver back and forth to determine how much timing variation the system can handle before errors occur. The process assesses the horizontal margins of the eye diagram.

Voltage Margining comprises adjusting the voltage levels to determine the system's tolerance to amplitude variations. It evaluates the vertical margins of the eye diagram.

Analyzing the eye diagram helps to identify and quantify the system's lane margins, ensuring that high-speed IO interfaces can operate reliably under various conditions. Margining, supported by eye diagram analysis, is essential for optimizing the design and testing of digital systems to minimize errors and improve overall system robustness.

3.1. Lane margining as solution

Lane margining allows for detecting marginal faults and circuits that could usually pass traditional testing but fail under particular operating situations. It accomplishes this by changing the data or error sample position in high-speed IO PHY for error monitoring.

Lane Margining addresses the following issues:

1. Early Detection of Performance Variation: Lane margining enables the early assessment of design performance variation tolerance, allowing for adjustments before production.
2. Effective Screening in Production Tests: By implementing lane margining in production tests, manufacturers can identify and mitigate marginal IO defects, reducing Detectable Defects Per Million and enhancing product quality[9].
3. Addressing Marginal Circuits: Lane margining helps detect marginal circuits that could escape traditional testing methods, thereby reducing the risk of customer returns due to circuit and bus electrical marginality.

4. Conclusion

In conclusion, lane margining emerges as a pivotal methodology in the realm of high-speed digital systems, offering a holistic approach to optimizing communication lanes through the integration of voltage and timing margining. Using statistical simulation frameworks to analyze these margins and leveraging the eye diagram as a visual tool, engineers can precisely assess and adjust the operational margins, ensuring that high-speed IO interfaces maintain robust performance under varying conditions. This approach optimizes signal integrity and significantly reduces the incidence of operational failures and customer returns, marking a significant stride towards achieving robust and fault-tolerant communication lanes.

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