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WHERE THE CHIP MEETS THE BOARD

Approaching Perfect Receiver Tolerance Tests:

Using an AWG to De-Embed the test fixture while Embedding channel response.

Yash Pathak, BitifEye
[yash.pathak@bitifeye.com]

Philipp Schleicher, BitifEye
[philipp.schleicher@bitifeye.com]

Afshin Attarzadeh, BitifEye
[afshin.attarzadeh@bitifeye.com]

Sebastian Muschala, BitifEye
[sebastian.muschala@bitifeye.com]

Julien Henaut, BitifEye
[julien.henaut@bitifeye.com]

Alexander Schmitt, BitifEye
[alexander.schmitt@bitifeye.com]

Ransom Stephens, BitifEye
[ransom.stephens@bitifeye.com]

Abstract

Stressed-Receiver Tolerance testing (Rx testing) requires a reference transmitter that generates a test signal with specifically calibrated impairments combined with a test interconnect with a specified worst-case differential insertion loss frequency response. A test fixture is necessary for connecting the reference transmitter to the receiver being tested, the DUT (device under test). The test fixture may include cables, connectors, adapters, splitters, etc., whose response is necessarily included in the stressed-signal calibration. Calibration of the stressed signal is the most time-consuming and difficult step in Rx testing. This paper introduces an approach that has been effective in Rx testing for the HDMI and MIPI standards: Use of an AWG (arbitrary waveform generator) to embed the required test channel response and specified signal impairments – like jitter and noise – directly into the test signal. The technique simplifies the tests and makes them more repeatable: calibration time is reduced, and physical compliance/variable- ISI boards are eliminated along with most of the test fixture cables and connectors. We show how to embed channel characteristics in impaired waveforms along with common pitfalls, and then turn to a communication channel model for automotive standards that typically have long channels and disparate cables.

Authors Biographies

Yash Pathak is a Project manager at BitifEye Digital Test Solutions. His team is developing, receiving tests targeted towards emerging Automotive standards. Prior to this, he has actively developed receiver test solutions for HDMI 2.1. He did his master's in information technology focusing on micro-electronics and power electronics from the University of Stuttgart.

Philipp Schleicher is a Senior Software Engineer at BitifEye, developing receiver test solutions for automotive standards. Philipp holds an MSc in Information and System Technology from the University of Ulm, Germany, and has since been actively involved in software development in areas ranging from embedded software to desktop applications and web services.

Afshin Attarzadeh is a Senior Software Engineer at BitifEye, which he joined in 2017. He holds an MSc in Information Technology in Embedded Systems Engineering from the University of Stuttgart and has worked actively in developing industrial controlling devices and the associated software interfaces since 2007.

Sebastian started with BitifEye as a student in 2014 focusing on Hardware solutions. After graduating with a bachelor's degree in electrical engineering and a specialization in electronics he began working as an R&D Engineer for USB3 Rx test solutions, expanding into USB4, USB4v2, SATA, DP, HDMI PHY and ARC. He remains dedicated to his hardware roots.

Julien is the COO and R&D manager at BitifEye Digital Test Solutions. He is currently leading a team of 20 engineers to establish a reference and push the limits of high-speed Physical layer receiver testing in over 12 of the most advanced digital bus standards. Julien graduated from the French National School of Civil Aviation and the ISAE-Supaero in Electrical and telecommunication engineering for Aerospace. Back on earth, he worked for over ten years on creating numerous new Io(R)T products with a particular focus on making our cities and mobility smarter.

Alexander Schmitt received his Ph.D. in mechanical engineering in 1994, the year he joined HP Test & Measurement, which became Agilent Technologies in 1999. In 2005, Alexander co-founded BitifEye and serves as CEO ever since. BitifEye is a Solutions Partner with Keysight Technologies, specialized on high speed digital interconnect test.

Ransom Stephens is Consulting Senior Scientist at BitifEye, where he provides insights when he can and wisecracks when he can't. Dr. Stephens helps engineers advance to higher data rates with targeted training, including the classes he teaches at Oxford University's Department of Continuing Education.

Introduction

Receivers play a pivotal role in ensuring that data is received accurately. A degraded signal quality due to factors like jitter, noise, crosstalk, and inter-symbol interference (ISI) can compromise the integrity of the data received. Therefore, modern receivers are equipped with an arsenal of sophisticated tools like multiple equalization technologies, clock data recovery (CDR), symbol decoders, and forward error correction (FEC) to combat these challenges. However, ensuring that these receivers' function optimally under stressed conditions demands rigorous testing.

Traditional stressed-receiver tolerance testing, often referred to as Rx testing, is an arduous process [1]. The compliance-test channel, typically a tangible physical medium such as a trace on a printed circuit board (PCB) or a set of worst-case cables, mimics the real-world conditions under which the receiver would function. Introducing impairments like ISI, insertion loss (IL), and reflections, and then evaluating the receiver's performance, provides invaluable insights into its robustness. Yet, this traditional method, with its intricate test setups and painstaking calibration procedures, is anything but efficient. The complexity involved in integrating multiple instruments, adapters, and fixtures often acts as a bottleneck, slowing down the entire testing process.

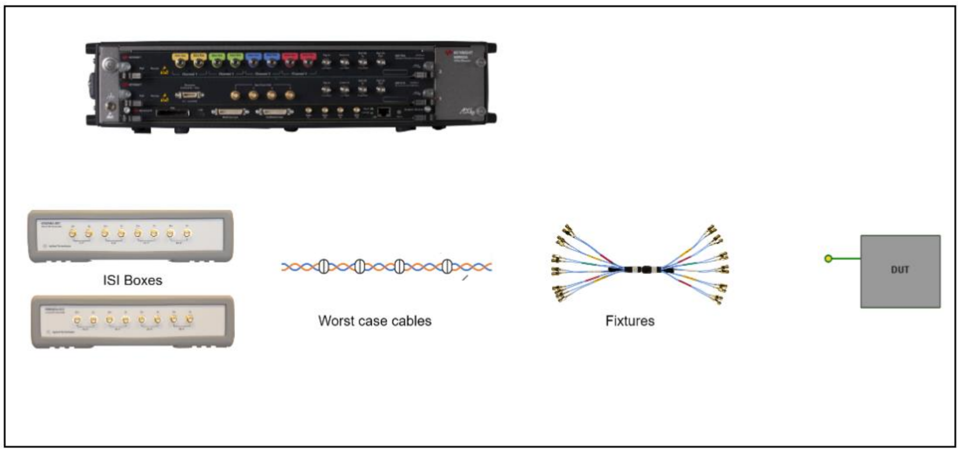


Figure 1: Typical components for a receiver test

In this paper, we highlight an approach that has simplified Rx testing. The cornerstone of this approach is the use of an arbitrary waveform generator (AWG) [2]. By integrating channel characteristics and test fixture attributes directly into the waveform generated by the AWG, we obviate the need for a physical compliance-test channel.

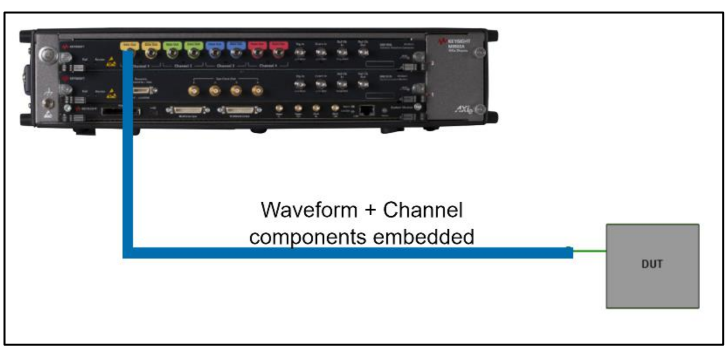


Figure 2: Simplified test setup, with the channel components a part of the generated waveform

While this technique might seem straightforward on paper, its execution demands meticulous attention to detail. While they are powerful tools, deep memory, high bandwidth AWGs have inherent limitations [3, 4] that must be accounted for to create waveforms with the desired features. Moreover, the procedure of embedding or de-embedding the electrical characteristics of channels, test fixtures, connectors, and even amplifiers as described by their S-parameters into our waveforms is fraught with potential pitfalls. Addressing these challenges forms the core of our discussion.

The paper details the challenges of HDMI and MIPI C/D-PHY Rx testing, providing insights into the modelling of inter-lane crosstalk in waveforms, our discussion seeks to offer a comprehensive overview of the proposed methodology.

The latter part of our paper delves into the potential applications of our technique in emerging automotive standards. With the automotive industry poised to integrate high-speed serial communication channels, defining a suitable communication channel model becomes imperative. Our exploration aims to chart a path forward, providing a blueprint for the future of receiver tolerance tests.

Simulating a stressed channel

What is a channel model?

A channel model in the context of receiver (Rx) testing refers to a mathematical representation of the physical channel through which a signal passes from a transmitter (Tx) to a receiver. This model is used to predict and analyze the performance of the Rx under various conditions by simulating the effects of the channel on the signal. Channel models are crucial for understanding how different impairments such as attenuation, distortion, noise, reflections, and crosstalk affect the integrity of the received signal. For Rx testing, particularly in high-speed digital standards like HDMI and MIPI, the channel model is employed to stress-test the receiver. The model typically represents the worst-case conditions that the Rx might face in real-world operation. A channel model typically factors in the Physical and Electrical characteristics of a channel.

Physical Characteristics:

Geometry: The physical dimensions and layout of the channel, including length, width, and separation of conductors.

Materials: The dielectric properties of substrates and conductive properties of materials used in the transmission path.

Electrical Characteristics:

The linear time invariant (LTI) characteristics of a channel and all its components are contained in its S-parameters:

Reflection and transmission response: Specific S-parameters describe the channel's reflection (S11, S22) and transmission (S21, S12) across a range of frequencies. They are essential for understanding the channel’s behavior at high frequencies, especially for signals with fast rise times.

Impedance Profile: The channel's characteristic impedance and how it varies with changes in geometry or materials.

Coupling: The capacitive and inductive coupling of multiple channels that dictates how signals on separate channels can interfere, crosstalk.

Propagation Delay: The time it takes for a signal to travel from the transmitter to the receiver.

Attenuation: Frequency-dependent loss of signal strength due to conductor losses and dielectric losses.

Inter-symbol Interference (ISI): Resulting from the band-limiting, non-uniform frequency response properties of the channel that causes increasing signal distortion with propagation-delay.

Modelling Techniques:

Statistical Models: Capture the random aspects of the channel, such as noise and jitter, using probability distributions.

Deterministic Models: Use fixed equations and parameters to represent known, predictable channel behaviors and impairments.

Empirical Models: Based on direct measurements of channel characteristics, often used when simulation-based models are insufficient.

Our discussion focusses on using the electrical characteristics defined by the channel s-parameters to emulate the effects of a physical channel on the waveform generated by an AWG.

Embedding/de-embedding a channel model.

The workflow begins with deciding whether to embed the S-parameters into a waveform (typically used when simulating the behavior of a signal as it passes through a device under test or channel) or to de-embed them (used when attempting to remove the effects of fixtures or components and isolate the behavior of the device under test).

At first glance the basic algorithm is straight-forward.

1. Read the frequency domain channel parameters.
2. Convert these parameters into time domain (impulse response).
3. Finally, define the AWG waveform by convolving a discrete form of the nominal waveform with the impulse response.

But these simple steps hide the subtle details essential to generating a waveform with the integrity suitable for playback on an AWG.

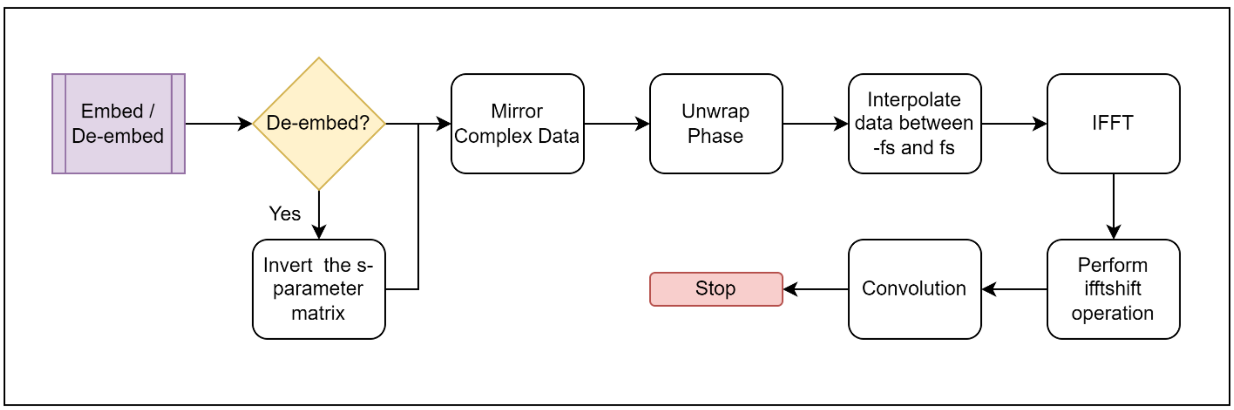


Figure 3: Process for embedding or de-embedding network parameters

Embedding or De-Embedding: The S-parameters are typically represented as a complex matrix whose elements are functions of frequency. If de-embedding is required, it's necessary to calculate the inverse of the S-parameter matrix, S^{-1}; the effects of a network are removed when the S^{-1} operates on the network transfer function. If embedding is the goal, it's not necessary to invert the S-parameter matrix, and the process would typically move directly to mirroring the complex data.

Mirror Complex Data: S-parameters are provided for positive frequencies only, but for a time-domain transformation using the inverse fast Fourier transform (IFFT), a symmetric spectrum is required. Mirroring the data involves creating a negative frequency spectrum that is the complex conjugate of the positive frequency spectrum. This symmetry ensures that the resulting time-domain signal is a real-valued function.

Unwrap Phase: The phase of the S-parameters can sometimes be wrapped at 360-degree intervals. Phase unwrapping is necessary to remove discontinuities and prevent distortions in the time-domain representation [5]. The unwrapping ensures a continuous phase response, which is necessary to obtain accurate IFFT results.

Interpolate Data Between -f_s and f_s: This step fills in the gaps between the known S-parameter data points, extending the data across the entire frequency range from $-f_s/2$ to $f_s/2$, where f_s is the sampling frequency of the AWG. This is done to ensure that when the IFFT is applied, it uses a complete dataset that covers the entire frequency band of interest. The interpolation should maintain the radial integrity of the complex data points. By interpolating along the arc in the complex plane that connects the two known points, rather than in a straight line between them, we can preserve the relationship between magnitude and phase across frequencies.

IFFT (Inverse Fast Fourier Transform): The interpolated data is then transformed from the frequency domain to the time domain using the IFFT. This generates the impulse response of the network, which is a time-domain representation of the S-parameters.

The IFFT output, which is a time-domain impulse response, may need to be shifted to ensure causality. The shift operation moves the zero-time point to the center of the impulse response array. This shift makes the impulse response causal, meaning that the effect follows the cause in time and aligns the response for the convolution operation.

It is essential that the simulated impulse response is physically meaningful. Otherwise, the convolution of the impulse response and the signal would produce erroneous results, possibly leading to incorrect conclusions about the performance of the system under test. By ensuring causality, the simulations remain true to the physical systems they are meant to represent.

Convolution: Finally, the waveform generated by the AWG is convolved with the shifted impulse response. Convolution in the time domain corresponds to multiplication in the frequency domain. When embedding, this step applies the channel response to the signal; when de-embedding, it removes the channel response from the measured signal. The result is a waveform that has either had the network's S-parameters applied (embedding) or removed (de-embedding).

Considerations for AWG limitations

Clipping:

If the sample data sent to an Arbitrary Waveform Generator (AWG) contains values above 1 or below -1, then the AWG's digital-to-analog converter (DAC) cannot generate voltage levels beyond its defined maximum and minimum output levels [2]. Any sample value that exceeds the maximum range of the DAC will be clipped – values above +1 would be set to +1, and values below -1 would be set to -1, resulting in a flat-top waveform at the points of clipping. The resulting waveform can be severely distorted in shape and with spurious high-frequency components.

Sometimes de-embedding can amplify certain frequencies. If the de-embedded S-parameters or impulse response include significant gain at certain frequencies, the resulting compensated waveform can extend beyond the ±1 range when the inverse channel transformation is applied. In practice, it's important to ensure that the waveform data is normalized and scaled properly to avoid such issues. But scaling the signal reduces the vertical resolution of the AWG. The compensation applied by de-embedding is usually near symbol transitions within the waveform. To bring the sample values within ±1, the entire waveform must be rescaled.

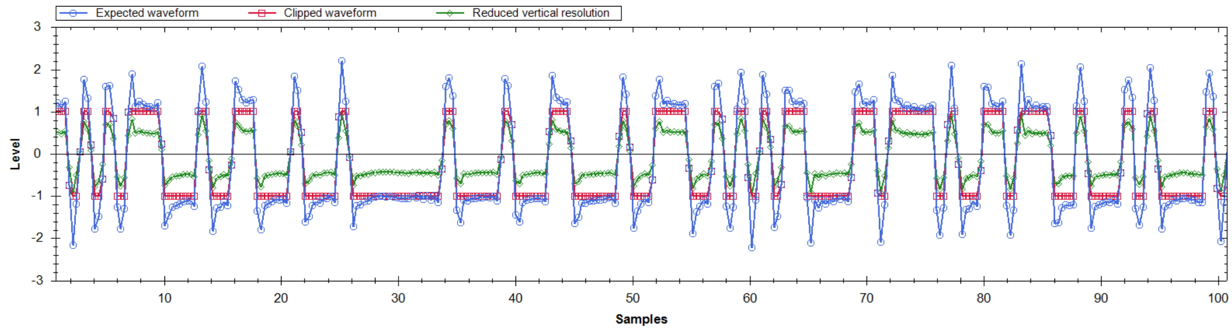


Figure 4: The effect of a clipping on a unscaled waveform. The expected waveform when 'played' by an AWG would result in the signal being clipped to within ±1. This would negate all compensation that was applied to the waveform and can also result in loss of data.To ensure that the compensation is correctly applied, the samples should be normalized (green)

Noise and Measurement Artifacts:

Embedding can also inadvertently enhance noise and measurement artifacts. Since embedding involves mathematical operations that can amplify or attenuate components of the signal, any noise or impairments already applied to the waveform will be affected, potentially pushing parts of the waveform outside the nominal range.

Mismatched Impedance:

If the impedance used in the embedding process doesn't match the actual impedance through the signal path, the resulting waveform could be distorted, leading to overshoots or undershoots that cause clipping.

Causality:

Embedding can introduce non-causal behavior that can manifest as unrealistically high-frequency content and lead to unwanted artifacts in the generated waveform. This topic is further explored in subsequent sections of the paper.

Note on Pre-emphasis and channel de-embedding.

Pre-emphasis and 'pre-transmission' de-embedding are sometimes used interchangeably, but the two processes serve different purposes and operate in different domains of the signal transmission and measurement process.

Pre-emphasis is an approximate proactive correction, a simple transmitter-based equalization scheme applied to a signal prior to transmission that pre-distorts the waveform in a way that emphasizes its high-frequency components to partially compensate for the low-pass nature of the channel. Pre-emphasis or equivalently, in this context, de-emphasis, is usually combined with equalization at the receiver.

On the other hand, channel de-embedding can be a post-measurement technique applied by, for example, an oscilloscope, that mathematically removes the channel response from a measured signal so that the signal or device under test can be analyzed as if the channel were not present. An AWG can also be used to pro-actively de-embed the channel, or part of the channel. Consider a test fixture. If the inverse s-parameter matrix of the test fixture is applied to the waveform prior to transmission by the AWG, the signal at the test fixture output would not include the test fixture response – essentially de-embedding the test fixture but now, at the transmitter end.

However, it's important to note that pre-emphasis is applied with the intent that the channel will still affect the signal, and it assumes a complementary de-emphasis at the receiver. In contrast, channel de-embedding is used to analyze what the signal would look like without the channel's influence at all, often for diagnostic or design purposes rather than for actual signal transmission.

All of this to say: pre-emphasis modifies the signal to survive the channel, whereas channel de-embedding is a method of analyzing the signal as if the channel had no effect. For compliance testing, the two cannot be interchanged. Pre-emphasis would be typically combined with channel embedding to construct a test setup which accurately mimics a real-world scenario. When pre-emphasis is defined as a transmitter requirement, typically channel de-embedding cannot be used.

Application specific challenges and examples

HDMI

Rx compliance testing for HDMI 2.1 FRL introduces the need to emulate both the worst channel model (WCM) on the target lane and crosstalk between the target lane (victim lane) and aggressor lanes.

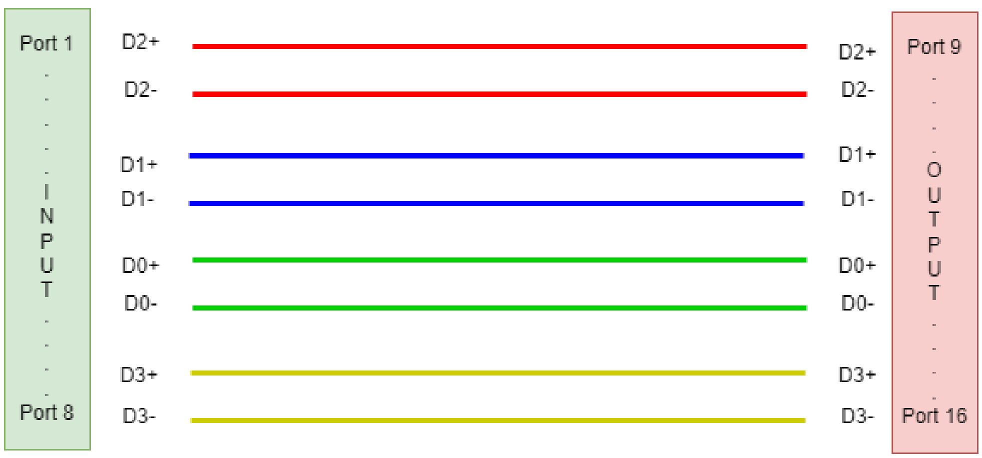


Figure 5: Generic port mappings for HDMI 2.1 Worst cable model

The HDMI forum provides the worst cable characteristics for a compliant HDMI channel—a 16-port s-parameter file that includes the transmission characteristics and crosstalk artifacts of the 4 HDMI lanes.

E.g.: For lane 0 (D0) we have the following combinations:

- D0D0 - differential characteristics for Lane 0 (ports 1,2 -- 9,10)
- D1D0 - crosstalk coupling between Lane 1 and Lane 0 (ports 1,2 -- 11,12)
- D2D0 - crosstalk coupling between Lane 2 and Lane 0 (ports 1,2 -- 13,14)
- D3D0 - crosstalk coupling between Lane 3 and Lane 0 (ports 1,2 -- 15,16)

When generating the compliant waveform for Lane 0, the standard requires embedding the differential characteristics D0D0 to the test mode pattern and including the crosstalk effects that correspond to the correct victim lane (D0 in this example) and aggressor lanes (D1D0, D2D0, D3D0).

It is crucial to ensure that the port mappings are correctly read from the S-parameter touchstone files. As discussed earlier, S-parameter files can have different port mappings.

CASE A: Ports 1, 2 as input and ports 3,4 as output OR

CASE B: Ports 1, 3 as input and ports 2,4 as output.

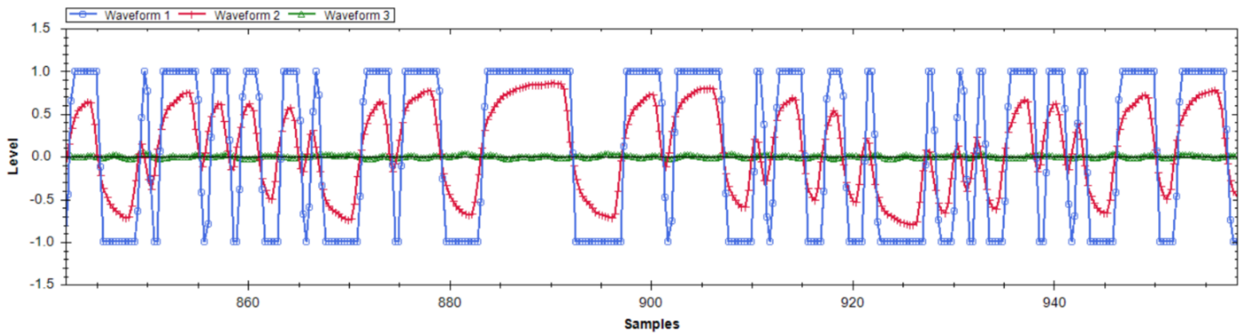


Figure 6: Waveform 1 represents HDMI Lane 0 signal with no impairments. Waveform 2 represents D0D0 characteristics embedded onto Waveform 1 and Waveform 3 represents a signal with the effects of Lane 2 acting as an aggressor.

Determining port assignments in an S-parameter file can be achieved by looking at the S21 matrix element. If S21 looks like an insertion loss, starting out with a nearly 0 dB value at low frequency, then the port assignments were labeled as in case A [6]. If S31 looks like an insertion loss and has a nearly 0 dB value at low frequency, then the port assignments were labeled as in case B.

In a typical S-parameter file representing a two-port network, S21 or S31 would indicate the insertion loss between two ports.

In files representing crosstalk, such as D0D1, D0D2, and D0D3, S-parameters describe the unwanted signal coupling from one pair of differential ports to another, not direct transmission.

For near-end crosstalk (NEXT), the S-parameters would indicate the strength of signal coupling from the aggressor pair to the victim pair at the near end, coupling between ports 1, 2 (victim) and 3, 4 (aggressor). For far-end crosstalk (FEXT), the S-parameters would indicate coupling at the far end, coupling between ports 1, 2 (victim) and 11,12 (aggressor).

Where we expect insertion loss S-parameters to start near 0 dB at low frequencies, since the near and far ports are for the same differential pair of conductors, we don't expect the same behavior in crosstalk-coupling S-parameters because the conductors are separated by dielectric.

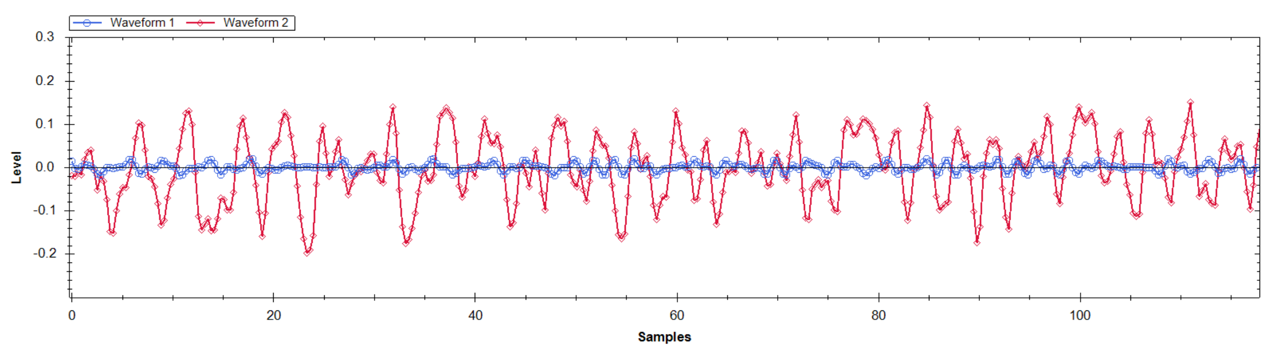
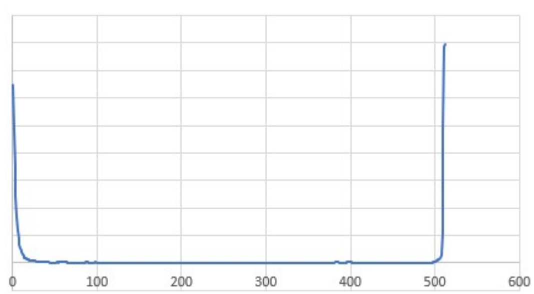


Figure 7: Waveform 1 represents the actual expected impact of D1D0 on the signals on the aggressor lane. Waveform 2 represents the resulting waveform when wrong port mappings are assumed.

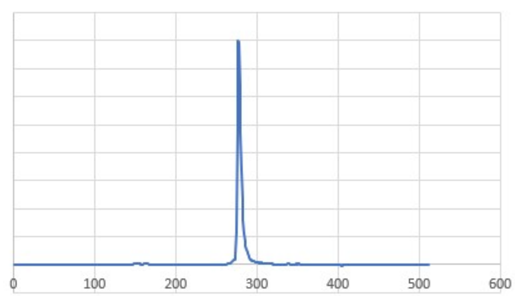
MIPI C-PHY, D-PHY

The channel model defined for C-PHY and D-PHY cables includes physical characteristics, and interconnect and package models. The channel model must be constructed by *cascading* multiple S-parameter models. Signal impairments, on the other hand, are combined by *convolving* multiple impairments with each other to generate a single filter. With hundreds of millions of samples, convolving a single filter is faster than convolving multiple filters, but, due to the nature of IFFT, the result of the convolution doesn't always line up with the time at which the impulse should occur, time-zero. The IFFT assumes that the signal is periodic, which can lead to the assumption that parts of the signal exist before the actual start time of the impulse, and the signal can appear to respond before the impulse occurs—an obvious causality violation since the laws of physics require that a cause must precede its effect.

Imagine listening to a loudspeaker that produces a sound (the impulse) at time zero. The sound waves reach the ear (the response) shortly after. In a causal system, we can't hear the sound before the loudspeaker produces it. But if we were to calculate the loudspeaker's impulse response with IFFT and didn't correct for this artifact, we might incorrectly conclude that some of the sound reached our ears before the speaker even made noise.



8(a)



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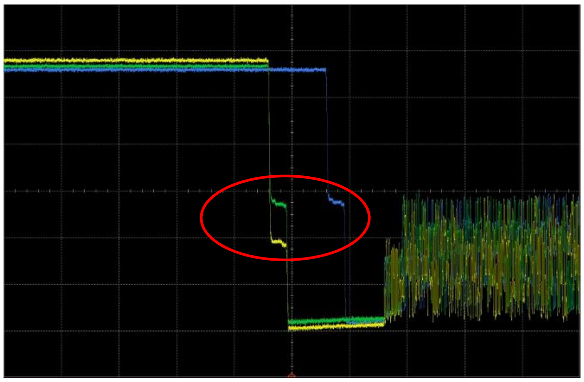
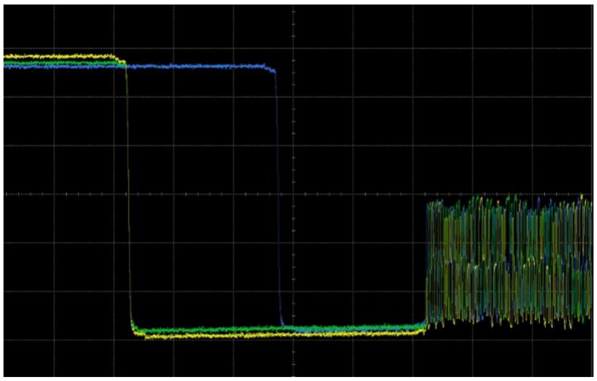


8(c)



8(d)

Figure 8: (a) Uncorrected impulse response of an s-parameter model used for MIPI C-PHY. This response appears to have 'two' impulse peaks and when not corrected would result in the final waveform having unwanted artifacts as seen circled in red (c). With a simple FFT shift operation, we effectively center the response (b) and the resultant waveform after convolution gives an accurate representation of the channels effect on the signal.

To assure causality in the model, we apply a 'shift' operation after the IFFT. Shifting the impulse response to its correct place in the sequence. The shift does not alter the character of the impulse response — it's like adjusting the hands of a clock without changing how fast it's ticking. The shift effectively delays the entire impulse response just enough so that the responses that appeared before the main impulse are placed after it. The resulting model with the convolution of the corrected impulse response and waveform gives the accurate distorted signal (Figure 8).

Automotive

Our previous DesignCon 2023 paper, 'Noise in Traffic: Signal Emulation for Automotive Apps' [4] focused on the challenges of testing automotive SerDes receivers in noisy environments. A key part of the paper presented a strategy for receiver testing that uses a 'golden transmitter' (Tx) as the signal source for receiver testing in automotive standards like Automotive Ethernet (AE) and A-PHY. The golden Tx is a standards-compliant serializer capable of active link negotiation controlled by test equipment (TE) that can inject impairments like wideband noise before the signal is transmitted. The problem of achieving the necessary dynamic range to generate a combination of wideband gaussian noise and high amplitude transient and RFI noises is addressed by use of a special active fixture.

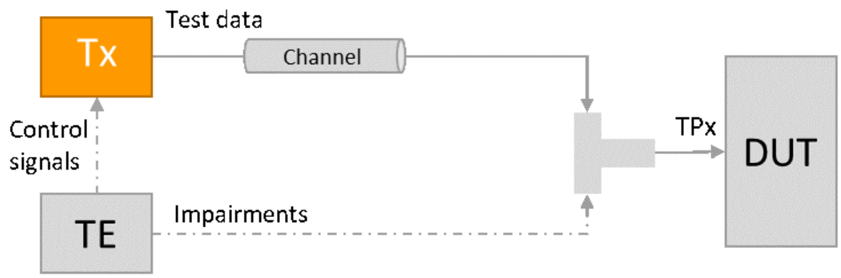


Figure 8: Typical Automotive receiver test setup. The TE is used for noise generation and injected into the channel through a test fixture. Payload data is generated by a qualified 'golden transmitter'.

The fixture amplifies the lower frequencies of the Fast Transient noise (40-200 MHz) where most of the power is concentrated. This way, we can reduce the amplitudes of these frequencies at the generator and prevent the FT from consuming the whole dynamic range of the AWG.

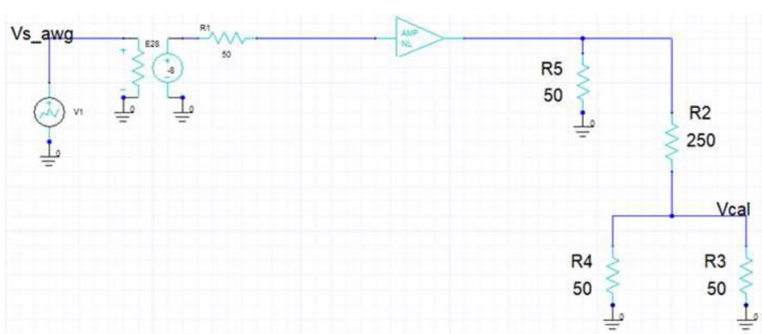


Figure 9: Schematics of the A-PHY noise injection fixture.

To ensure that the combined noise generated at the injection point (Test Point) conforms to the specification, the frequency response of the fixture must be de-embedded. Specifically, the fixture must be de-embedded from the low amplitude, wideband, unbounded gaussian noise, but not from the bounded fast transient noise, since we need amplification to overcome the dynamic range problem. Since the waveforms for these noise sources are computed individually, it is straightforward to de-embed the fixture characteristics from the gaussian noise while preserving the transient noise waveform.

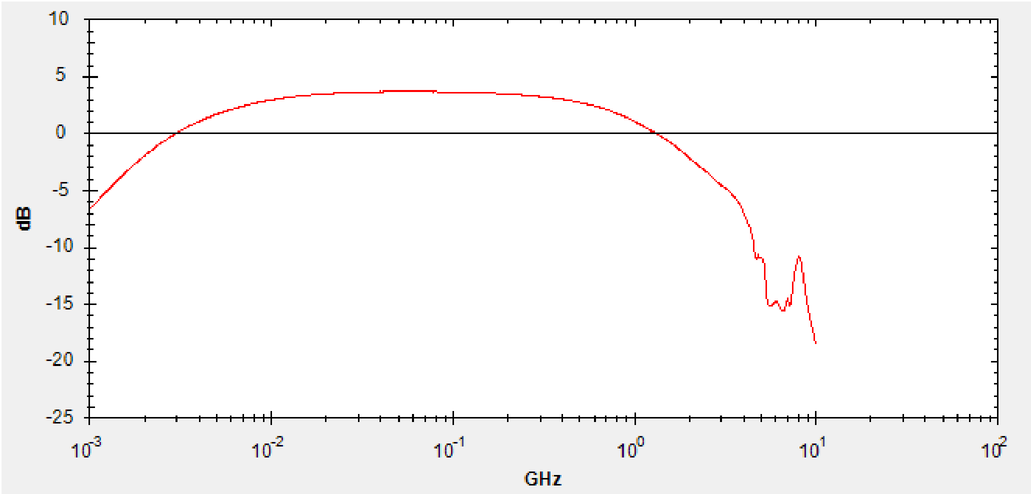


Figure 10: Through path characteristics of the fixture amplifier. X-axis represents 'Frequency [GHz]' and Y-axis represents Magnitude [dB]'.

Determining a convolution kernal for a fixture that includes an active component (amplifier) requires some thought. Active components, like transistors or integrated circuits, have characteristics that make their embedding more complex:

Non-linear Behavior: Active components exhibit non-linear behavior. Unlike passive LTI components, the response of active components varies with the input signal level, frequency, temperature, and other factors.

Power Dependency: Active components require a power source, and their performance can be significantly affected by variations in the power supply.

Frequency Response and Bandwidth: Active components have specific frequency responses and bandwidth limitations. When (de-)embedding these components, it's crucial to accurately model their frequency-dependent behavior, as it can significantly impact the signal integrity, especially at high frequencies.

The process described earlier, while still valid, can result is some unwanted artifacts due the non-linear characteristics of the fixture (figure 7).

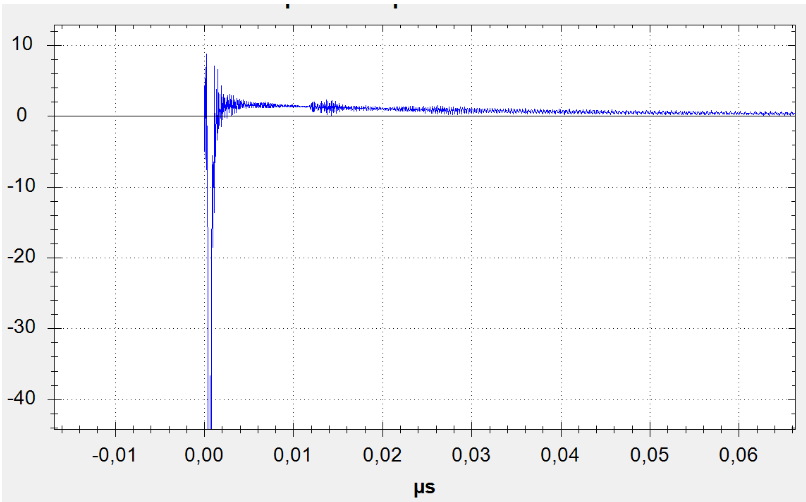


Figure 11:Noise and outliers on the impulse response of the noise injection fixture.

A simple windowing function can help mitigate these effects. To make the impulse response finite and implementable (thus creating a true FIR filter), a window function is applied. The Hamming window is a popular choice for this purpose. The primary purpose of the Hamming window is to truncate the theoretically infinite impulse response to a finite length. The Hamming window smoothly tapers the coefficients at the start and end of the impulse response to zero. This smooth transition helps in minimizing the truncation effects (like Gibbs phenomenon) that can occur when a sharp cut-off is applied. Windowing also helps in reducing the side lobes in the filter's frequency response. Side lobes are unwanted ripples in the frequency response of a filter caused by the truncation of the impulse response. A Hamming window reduces these side lobes, leading to a cleaner and more controlled frequency response.

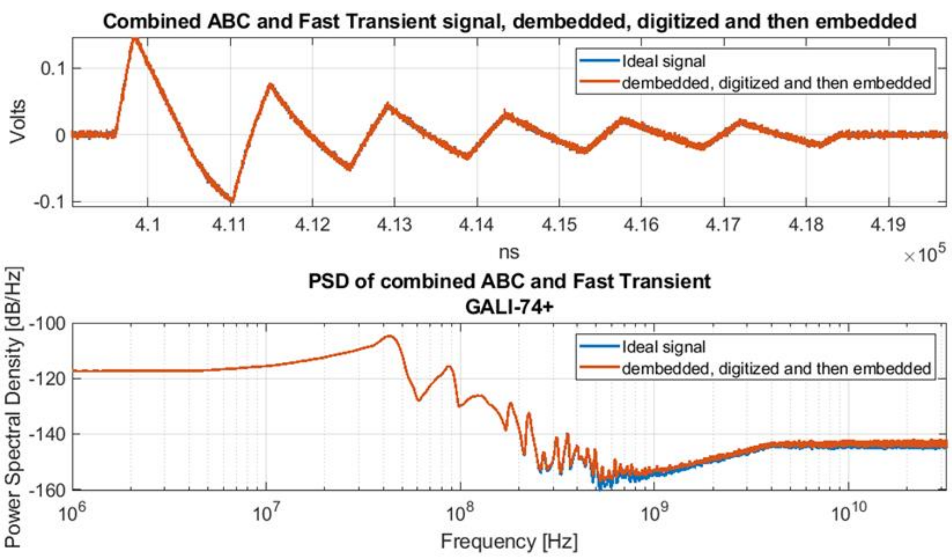


Figure 12:A-PHY combined noise profiles with the fixture effects properly compensated.

Conclusion

In this paper, we have explored the use of Arbitrary Waveform Generators (AWGs) for enhancing receiver tolerance tests in the context of HDMI and MIPI standards, extending our approach to emerging automotive standards. The methodology of embedding and de-embedding channel models using AWGs not only streamlines the testing process but also introduces a higher degree of accuracy and repeatability. This is particularly relevant for automotive standards, where the communication channels are often characterized by long channels and varied cable types, demanding more sophisticated testing strategies. The automotive industry is rapidly evolving, and the integration of high-speed communication channels is becoming increasingly critical. Future work should focus on tailoring the methodology to meet new and unique requirements of automotive standards like Automotive Ethernet and MIPI A-PHY, including challenges posed by longer channels and the diverse nature of automotive cable assemblies and connectors.

We are already approaching the limits of what the current generation of measurement instruments can achieve. The importance of simulations in the automotive world has already been a point of focus (DesignCon23 Panel: Revolutionizing In-Vehicle PHY Channel characterization (>10Gbps): Is Simulation the Solution?). Developing and implementing worst-case communication channel models for automotive standards will be crucial. These models should encapsulate the extreme conditions that automotive systems may encounter, ensuring that the receivers are robust enough to handle such scenarios for decades. As we move toward more connected and autonomous vehicles, the importance of rigorous and comprehensive receiver tests cannot be overstated. The methodologies and insights presented in this paper lay the groundwork for future innovations in this vital area of automotive technology

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