WHITE PAPER

How to Overcome IVN Physical Layer Testing Challenges

Meet the increasing demands of in-vehicle networks

KEYSIGHT

Introduction

Electric and electronic (EE) architectures in the automotive industry are evolving to support increasingly complex requirements, including the role of sensor-based driver assistance systems (ADAS) and autonomous driving (AD) applications. There is a proliferation of display technology inside and around the vehicle, including high-resolution dash panels, side view mirror panels, and infotainment options comparable to consumer electronic device services.

Many sensors, including cameras, lidar, and radar, capture the high-resolution data that transmits or aggregates with other sensor data for further processing by an ADAS / AD application. As for surround-view camera systems, multiple cameras may also feed video to displays inside the vehicle.

The application requirements drive the choice of EE, including the total number of sensors and the bandwidth necessary to transfer the data. The vehicle manufacturer must consider several factors when choosing the architecture, including cable harness complexity and weight, how to reuse sensor data across multiple functions, and whether the ecosystem of Tier 1 original equipment manufacturers (OEMs) can supply interoperable devices over the production lifetime of the vehicle.

The demands placed on in-vehicle networks (IVNs) by these application requirements push for communication links with high throughput. Communication links must support higher data rates than closed ones. Proprietary systems currently offer to meet these demands.

While the OEMs are free to implement an architecture that best suits their goals for market differentiation and cost, it becomes clear that closed, proprietary communication links can be prohibitive in their ability to support this vision.

A supply chain with sensors and electronic control units (ECUs) from different vendors would better serve the OEMs to ensure they can link up and function as expected. Achieving interoperability is possible when vendors use standardized communication links and conduct testing using approved methods of implementation (MOI). The advent of standardized in-vehicle communication links like automotive serializer / deserializer (SerDes) and automotive Ethernet makes this vision possible.

The Implications of Higher Data Rates

Application requirements determine the choice of EE architecture implemented in the vehicle. The architecture places a minimum performance requirement on the communication links used. For example, a specific zonal architecture has a minimum bitrate associated with the IVN necessary to support it. It is important to consider that connected multiple sensors send raw, high-resolution data to the zonal ECU. Figure 1 illustrates that aggregating various sensors onto a single link to reduce cable weight and cost leads to higher throughput requirements.

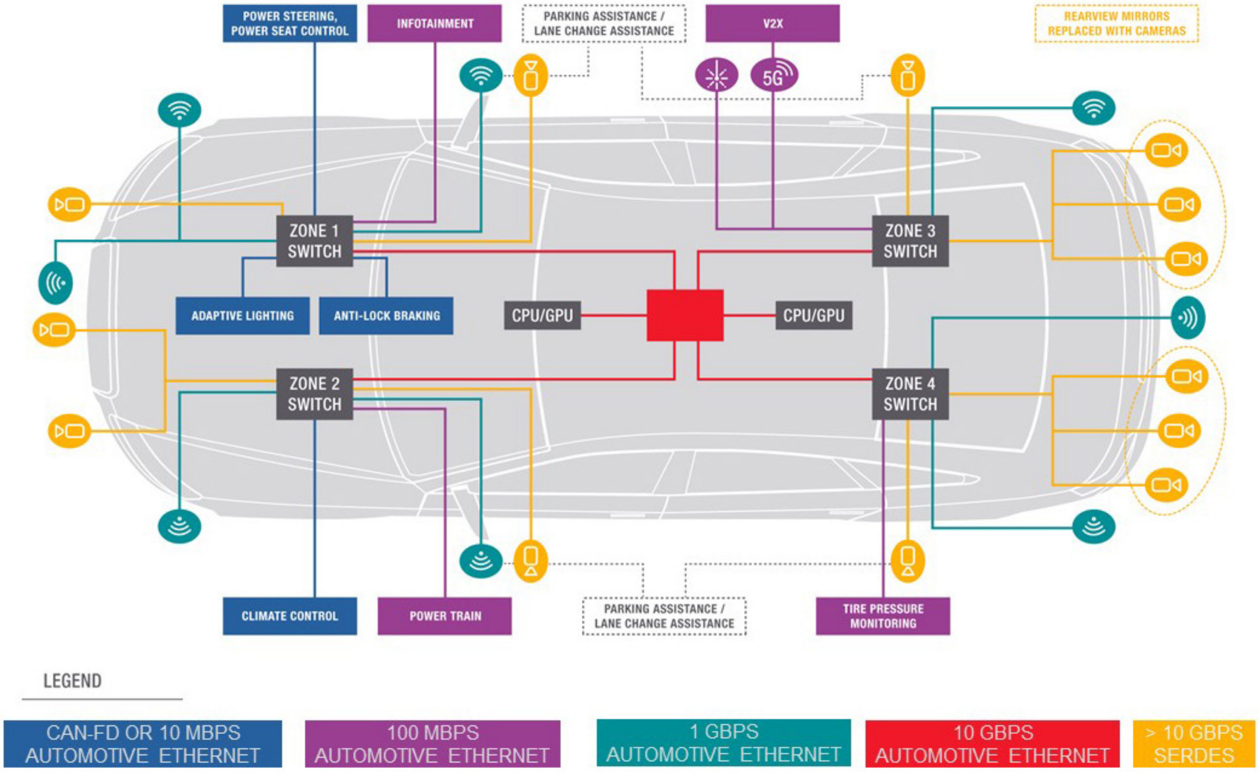


Figure 1. The zonal architecture of new vehicles

Traditional NRZ telecommunications

The traditional non-return-to-zero (NRZ) telecommunication modulates a signal between two voltages to indicate a logical 1 or 0. When application requirements demand a doubling of the bitrate, it's achievable by doubling the NRZ signal's fundamental frequency of operation.

While this solves the data throughput problem easily, it introduces multiple issues from the perspective of signal integrity and data fidelity. The data transmission's unit interval, or bit period, is halved, resulting in a doubled horizontal eye closure caused by a given (fixed) source of timing interference, known as jitter.

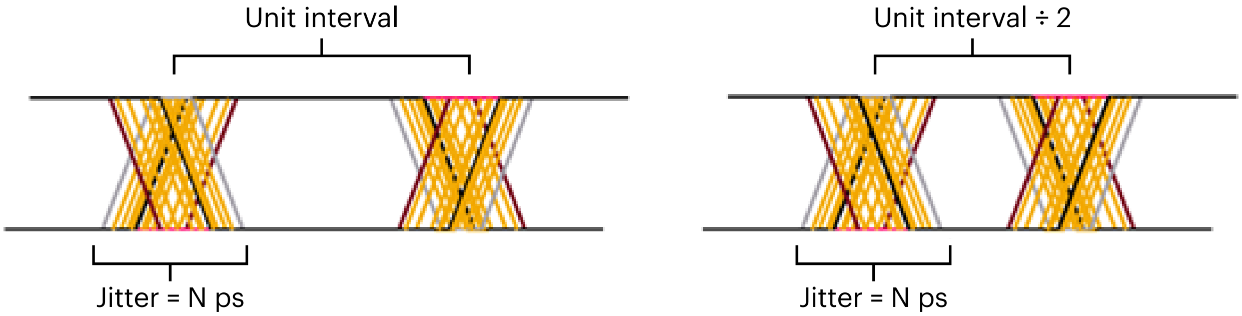


Figure 2. When the symbol rate doubles, the jitter eye closure appears pronounced

The receiving circuit operates within its boundary conditions, requiring a data-valid window at the input pin that is open enough to receive bits at an acceptable error rate.

Many consumer electronics standards have addressed this issue by limiting the quantity of jitter present on the transmitted signal. This technique has resulted in well-defined test methods that clarify which types of jitter are important, the maximum allowed quantities, and how to emulate the receiver's filter response inside the measurement instrument. When standard committees clearly define test requirements and implementation methods, the deployment of the solution occurs at certified test labs or on the bench for pre-compliance measurements.

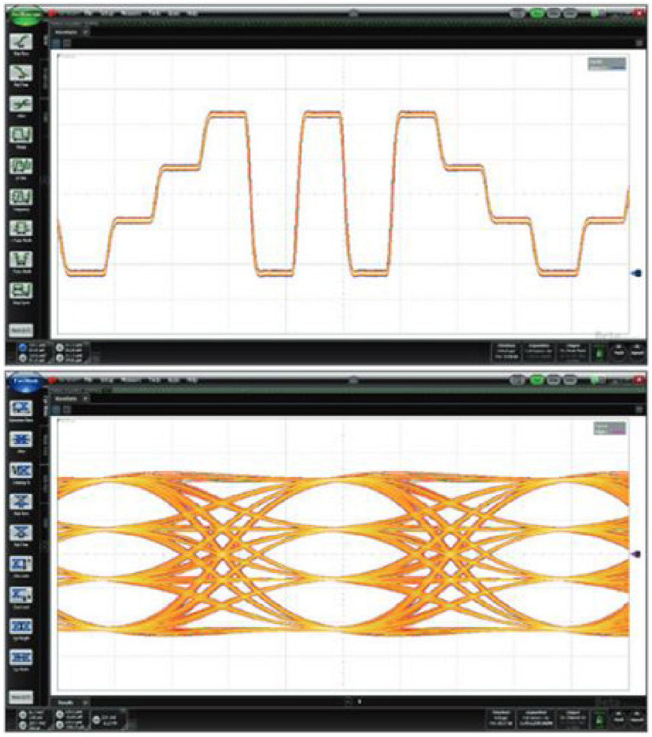
Early indications of test failures result in correspondingly early fixes, along with optimized product cost and release timelines. While using jitter, other parameters are also measurable at the physical media attachment (PMA), such as peak output voltage, vertical eye opening, or slew rate. Various industries have proven the importance of this type of test, placing conformance requirements on several transceiver-level tests. Examples of standards like this would be PCI Express® and USB.

Increasing the signal's bitrate has other consequences as well. Remote sensors and displays in the vehicle require cables of 10 to 15 meters, which is much longer than other standards used in consumer electronics and computing industries. It is also true that cable attenuation, such as insertion loss (IL), can increase with frequency for a given cable type and length. Increasing the bit rate of traditional NRZ links for low-voltage differential signaling (LVDS) is insufficient to achieve the required data rates over extended cable lengths.

PAM signaling and its impact on signal integrity

Automotive variants of Ethernet and SerDes have adopted pulse amplitude modulation (PAM) signaling formats to increase the density of information transmitted by each symbol. Compared to traditional NRZ, PAM introduces intermediate voltages, transmitting multiple bits per symbol. Figure 3 shows the same symbol clock, or Baud using PAM4 signaling, furnishes twice the throughput as NRZ modulation.

You can achieve the same bitrate for PAM4 running at half the symbol rate of an NRZ modulation, which provides a clear advantage to minimize the impact of insertion loss while maximizing cable length. As a result, PAM modulation is an essential feature of modern standards for automotive IVN.



- Four amplitude levels
- Every symbol has 2-bits of information (two times the throughput for the same Baud rate)
- Lower SNR, more susceptible to noise

Figure 3. PAM4 signaling and eye diagram

While PAM signaling addresses channel length requirements, it is crucial to consider that it introduces several new complexities to the overall system implementation, starting with signal-to-noise ratio (SNR). Since a PAM4 signal must have three eye openings in the same voltage swing as a single NRZ eye, vertical interference plays a critical role in the successful operation of the receiver.

Furthermore, the non-linear characteristic of the PAM4 transmitting device negatively impacts the already challenging SNR environment at the receiver. For this reason, most PAM4 technologies must implement measurements and test limits for transmitter linearity.

Transmitter jitter and linearity are examples of critical measurements at the transmitter level that predict the quality of operation at the downstream receiver. While specific transmitter measurements address the predictive nature of receiver operation, others gain insight to expose essential characteristics of the transmitted signal itself. One such example is power spectral density (PSD). This critical transmitter measurement ensures adherence to in-vehicle requirements for radiated electromagnetic interference (EMI). This measurement ensures that electrical systems near the in-vehicle network will only be exposed to interference within their design guidelines.

The Evolving Complexity of Receiver Testing

For example, in the consumer electronics industry, it was quite customary for early standards to emphasize transmitter PMA testing because it was sufficiently deterministic of receiver performance. However, this changed when standards moved to faster line rates, operating at multiple gigabits per second. Whereas signal equalization techniques once occurred exclusively in the transmitter, higher bitrates saw the implementation complexity move toward the receiver.

Modern communications links use receivers with digital architectures that employ digital signal process (DSP) filtering and equalization, along with novel, physical layer (PHY) error correction techniques like Reed Solomon forward error correction (RS-FEC) and retransmission, to name a few. Receivers must be capable of receiving highly-attenuated signals traveling through lossy channels that use modulation formats with an inherently low signal-to-noise ratio (SNR).

This functionality is necessary because automotive environments have dynamic interference sources that occupy a broad spectrum of frequencies. All this is to say that predictive transmitter testing — while still necessary — will certainly not be sufficient to ensure that the receiver’s complexities perform adequately in a worst-case scenario. For this reason, users must reconsider the assumptions of what the IVN receiver test should look like.

The receivers in today's high-speed IVNs are performing complex tasks compared to the lower speed standards of the past. Whereas analog implementations were the past standard, a modern receiver's implementation involves analog-to-digital converters that forward data to complex DSP functions, including equalizers, echo cancellation, and data slicers.

The collective performance of these functions is responsible for maintaining adequate levels of bit error ratio (BER). The BER is a common metric that expresses the ratio of bits received in error to the total number of bits received. The target BER for any link is a threshold that, when exceeded, propagates an unacceptable number of errors to the higher layers of the link. In the automotive IVN, these failures can be far worse than a suboptimal user experience. A missing video frame or corrupted sensor data can lead to the catastrophic failure of systems meant to ensure driver, passenger, and pedestrian safety.

Different types and combinations are possible when the receiver's design includes equalization. A continuous time linear equalizer (CTLE) is one of the most common equalizer types. The CTLE acts as a filter that emphasizes the frequency content that will most help the receiver while attenuating frequencies.

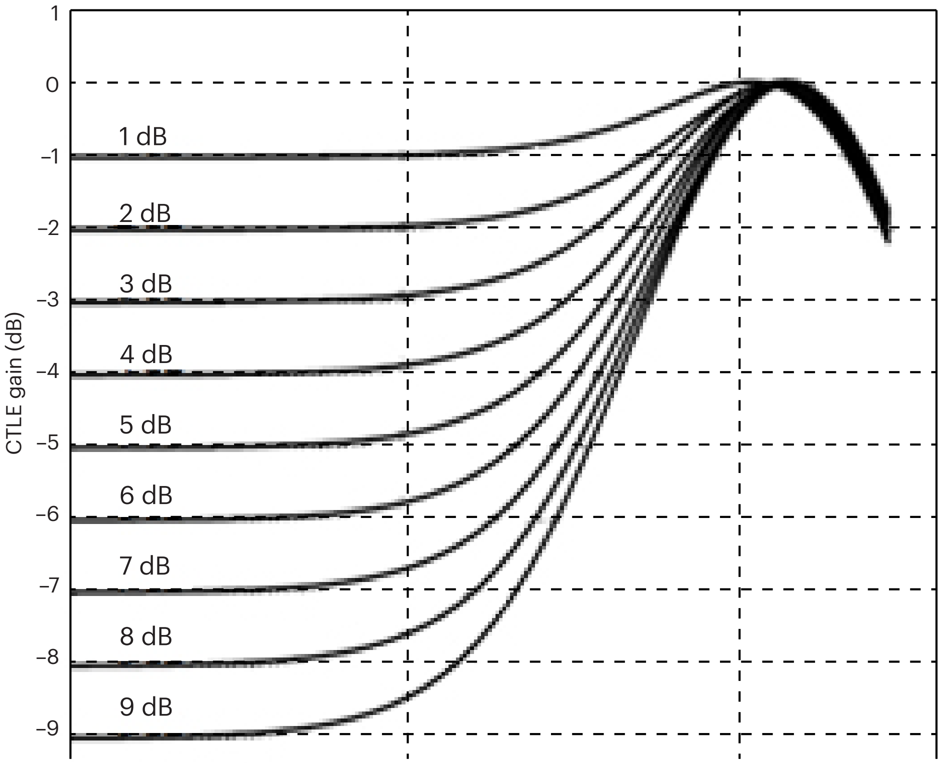


Figure 4. Example CTLE transfer function for gains of 1 dB to 9 dB

Figure 5 illustrates the impact of modern receiver architecture on its ability to interpret the symbol sequence of the transmitted data. It shows a popular 8 Gbps SerDes standard used to show a signal with and without the application of a CTLE. Processing the raw unequalized signal on a real-time oscilloscope simulated the effect.

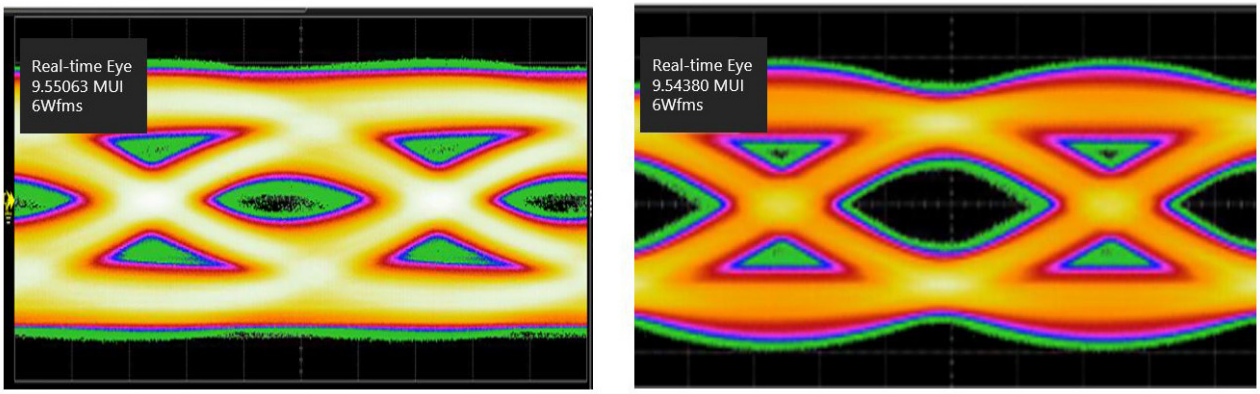


Figure 5. Comparing the signal's eye-opening with CTLE off (left side) and CTLE on (right side)

The central region of the eye diagram shows a stark difference in the eye-opening, both in voltage and time. When unequalized, the eye appears nearly closed; the receiver's data slicer detects the correct bit as often as it detects the wrong bit. The receiver cannot operate at acceptable BER levels until the eye opens through equalization. The CTLE is often the first of many error handling and correction techniques implemented at the hardware level of the IVN receiver.

Implementing additional features such as forward error correction, retraining, and retransmitting can also manage errors that filtering alone cannot mitigate. The complex interaction of all these mechanisms determines whether the receiver can dutifully fulfill its promise to transfer uncorrupted data to the upper application layers. No predictive transmitter testing can sufficiently prove how the receiver manages the data presented at the input pin.

Testing the robustness of a receiver's error correction and handling mechanisms can be insightful at various stages of the development process. Most notably, early silicon validation ensures the effectiveness of implementation choices made at design. Effective testing reveals the impact of equalizers and whether their settings are subject to optimization. Testing also gives you the successful operating range for error correction mechanisms in the presence of stressors, including channel attenuation and electrical interference.

Whether considering the receiver test at the PMA level or performing interoperability testing of production devices, the test setup handles introducing impairments that stress the receiver to determine the acceptable BER levels.

Despite differences in how a standard implements these features, it must have a way to initiate test modes and access diagnostic registers for performance metrics. Once the standard supplies these basic capabilities, you can use test instrumentation to impair signals intentionally.

Modern automotive Ethernet and SerDes standards clearly define the sources of impairment that any chip, sensor, or module can expect to encounter in a real-world automotive environment. The sources of impairment include various transient EMI events and broadband noise profiles that represent environmental noise or alien crosstalk in the harness or media dependent interface (MDI).

MIPI® A-PHY Automotive SerDes Receiver Test

As advancements in communications continue, new test specifications are in place to accurately identify critical metrics and the procedures necessary to measure them — one such metric is BER. In the example of the MIPI® A-PHY automotive SerDes standard, an active link occurs between the device under test (DUT) and a link partner. Figure 6 illustrates how the test setup introduces an amplified coupling circuit to inject generated noise profiles onto the link within the channel connecting the DUT to link partner.

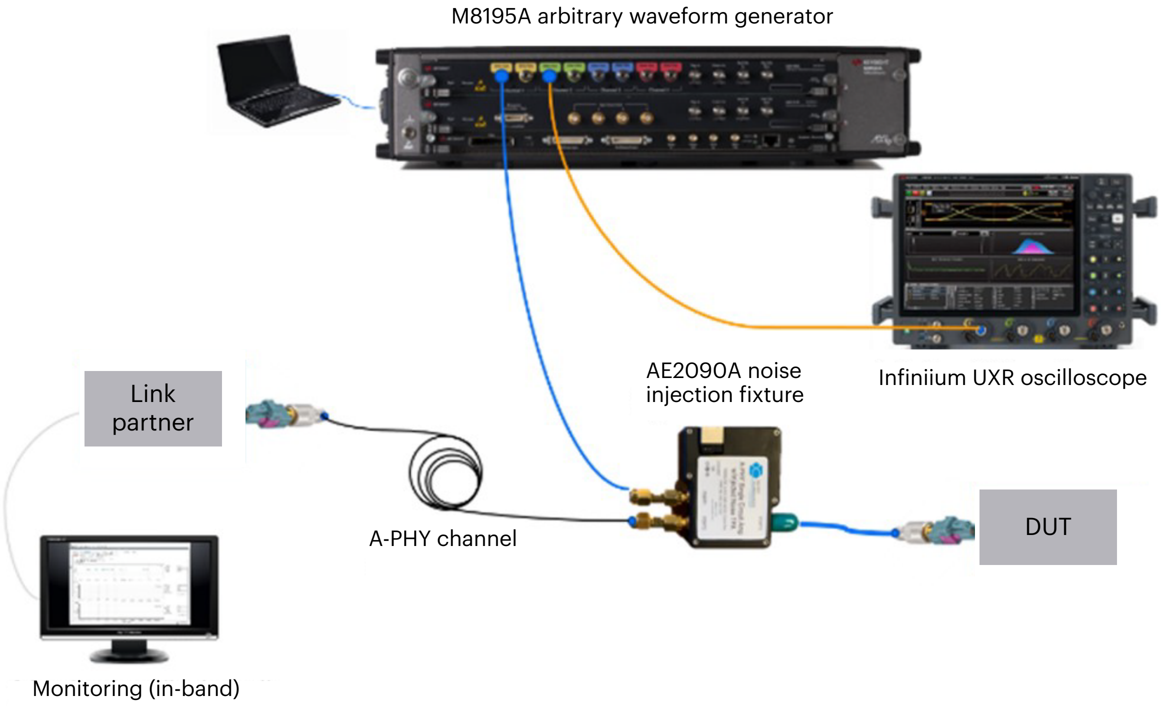


Figure 6. Automotive SerDes test setup for MIPI A-PHY receiver rest

You can monitor BER and other correlated link quality metrics in the DUT's register space, typically through a sideband communication channel such as an inter-integrated circuit (I2C). For example, the Keysight AE2010R MIPI A-PHY automotive SerDes receiver test software configures and monitors the DUT through such a sideband channel. The software also programs such as the Keysight M8195A AWG to output the noise profiles defined in the specification. This method enables testing any device against the compliance limits for a given standard. By varying the frequencies, amplitudes, and combinations of the noise profiles, you can characterize the operating range of their device beyond the compliance limits, enabling more robust implementations and the potential for competitive differentiation.

Conclusion

New application requirements drive new signaling paradigms, affecting our established notions of test and measurement. The emerging high-speed communication links discussed in this white paper are key enabling technologies for the EE architectures of the future. Engineering costs are associated with high-speed communications links that operate over long distances.

There is a dramatic increase in the implementation complexity of receivers and the associated need to test them. Signal integrity is easily comprised at higher frequencies. The overall performance of the IVN link is measured by assessing the performance of the transmitter, receiver, and channel.

While the purpose of test and measurement has remained the same, users can no longer use the past low-speed interconnects set up methods. New modulation formats, higher symbol rates, and extended cable lengths have left users wanting a standardized environment for test and measurement.

With the advent of standardized automotive communications links, the automotive industry stands to benefit from standardized test and measurement practices already proven in the data center and consumer electronics industries.

For More Information

For more insights on in-vehicle networks (IVN):

- Automotive In-Vehicle Network Test Solutions
- How to Test Automotive SerDes Receiver Conformance
- Automotive Serial and Networking Hardware and Connectors