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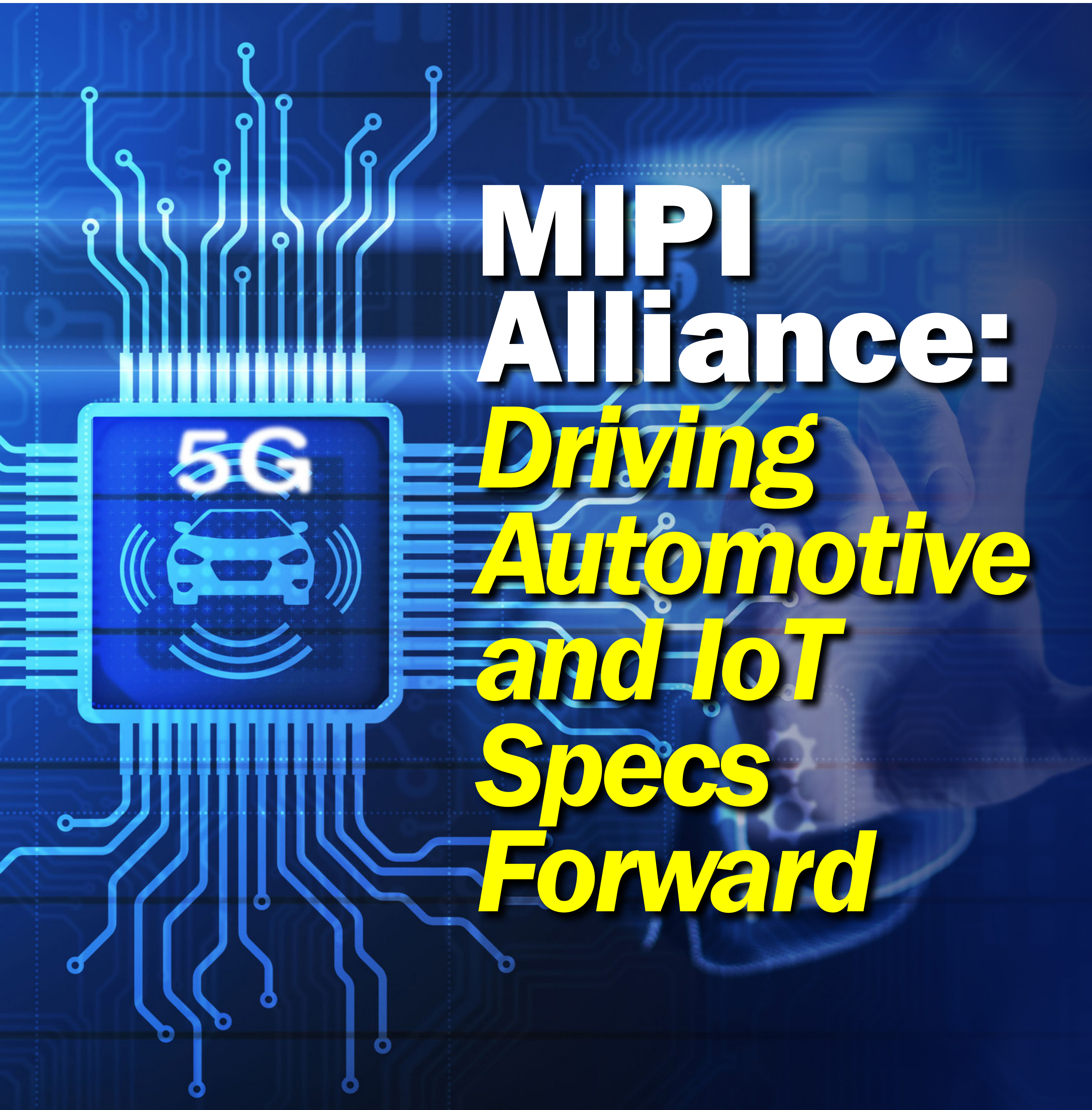

MIPI Alliance: *Driving Automotive and IoT Specs Forward*

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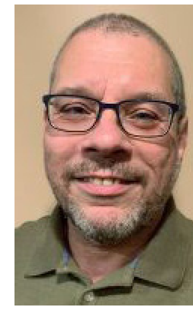
CONTENTS



David Maliniak
Editor
Microwaves & RF

STANDARDS BODIES are the unsung heroes of our industry, ensuring that system elements interoperate seamlessly and standing as a bulwark against unproductive and fractious competing standards efforts. I'm old enough to remember "standards wars" like VHS vs. Betamax and Blu-ray vs. HD DVD. Such industry squabbles only serve to waste time, money, and engineering efforts while keeping lawyers busy sorting out the mess. Meanwhile, the rest of us scratch our heads trying to figure out which of the competing standards/formats to invest in.

On the other hand, successful standards efforts, exemplified by those undertaken by the MIPI Alliance around mobile devices, are win-win scenarios. They serve to help member OEMs shorten time-to-market and create economies of scale, and at the same time, they help consumers by way of overall lower retail prices and by smoothing a path toward broad market acceptance of mobile technologies that benefit everyone.

In this eBook, you'll find articles on two of the many standards initiatives of the MIPI Alliance:

- The RF Front-End Control Interface (RFFE), which simplifies design, configuration, and integration of RF front ends in 5G, automotive, industrial, and IoT use cases.
- The A-PHY serializer-deserializer (SerDes) physical layer interface, aimed at providing automotive OEMs and their suppliers with end-to-end connectivity for cameras, sensors, and displays that comprise advanced driver-assistance systems (ADAS), in-vehicle infotainment (IVI) systems, and, ultimately, fully autonomous vehicles.

It's our hope that the information you'll find in these articles will be helpful to you in present and future design projects.

CHAPTER 1:

MIPI's RF Front-End Interface Spec Expands its 5G Purview

DAVID MALINIAK, editor, Microwaves & RF

The latest version of the MIPI Alliance's widely deployed RFFE specification enables more rapid and dynamic configuration changes within and across RF front-end subsystems.

In the latest version of its RF Front-End Control Interface (MIPI RFFE) specification, the MIPI Alliance has expanded the spec's applicability to 5G use cases that move beyond mobile applications and into the realms of automotive, industrial, and the Internet of Things (IoT). MIPI RFFE v3.0 is designed to deliver the tighter timing precision and reduced latencies that manufacturers need to satisfy the RF requirements of the 3GPP 5G standard.

MIPI RFFE simplifies the design, configuration, and integration of the increasingly complex RF front end—which encompasses the power amplifiers, antenna tuners, filters, low-noise amplifiers (LNAs), and switches—connecting with the modem baseband and/or RFIC transceiver. As the number of RF bands involved in both uplink and downlink communications has exploded in the rollout of 5G, the subcarrier spacing (SCS) windows among RF packets have narrowed. MIPI RFFE v3.0 addresses the decreased reconfiguration windows and lower-latency switching among various bands and band combinations demanded in the 3GPP 5G standard by delivering enhanced triggering features and functionality, which results in fast, agile, semi-automated and comprehensive control of individual RFFE subsystems.

MIPI RFFE v3.0 utilizes multiple, complementary triggers to synchronize and schedule changes in register settings, either within a slave device or across multiple devices:

- **Timed triggers**—Allows for tighter, synchronized timing control of multiple carrier aggregation configurations
- **Mappable triggers**—Enables groups of control functions to be remapped to other triggers quickly and easily
- **Extended triggers**—Boosts the number of unique triggers available in the RF control system and accommodates increasingly complex radio architectures

With the enhanced triggering functions, MIPI RFFE v3.0 improves throughput efficiencies and reduces packet latency, while also improving the precision in trigger placement. For back-to-back triggering operations, for example, the specification delivers a 20X improvement in timing precision.

Because MIPI RFFE v3.0 is backward compatible with prior generations of the specification, original equipment manufacturers and device vendors can migrate to 5G systems more quickly and easily, without changes to the physical layer of the control interface. The RFFE specification was initially released in 2010 and has seen numerous revisions since that time. Each release has provided additional functionality for developers to aid in the demand for newer RF front-end features.

"With MIPI RFFE v3.0, the specification has been streamlined and optimized to deliver the specific capabilities required to thrive in today's 5G rollout across the Frequency Range 1 (FR1) of traditional sub-6-GHz cellular bands," said Jim Ross, MIPI RF Front-End Control Working Group Chair. "The working group is always looking to refine the specification to continue differentiating and benefitting our user community, and we welcome engagement in requirements gathering for Frequency Range 2 (FR2) and the ongoing evolution of the next-generation MIPI RFFE for the subsequent stages of 5G deployment."

MIPI Alliance, www.mipi.org

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BACK TO TABLE OF CONTENTS

CHAPTER 2:

MIPI RFFE Version 3.0: More Precise Timing for 5G

WILLIAM G. WONG, Senior Content Director, *Electronic Design* and *Microwaves & RF*

Bill Wong, Electronic Design's Senior Editor and Content Director, talks with Jim Ross, chair of the MIPI RF Front-End Control Working Group, about how MIPI RFFE v3.0 relates to the ongoing 5G global rollout.

What types of developers would especially welcome the arrival of MIPI RFFE v3.0?

Anyone doing wireless communications and connecting to the 5G network is going to be interested in this new version of MIPI RFFE. In the 2G and 3G communications eras, it was almost strictly mobile applications that were concerned with control of the radio-frequency front end (RFFE). But 5G is bringing widespread change across all wireless communications—across the Internet of Things (IoT), industrial applications, automotive applications, and so on.

In this way, RF control for all of the wireless components that undergird these varied applications is foundational to 5G rollout everywhere. MIPI RFFE already is established as the de facto industry standard for control of the RF front end, so the release of this new version benefits everyone leveraging the 5G network moving forward.

What headaches are these developers experiencing, and how does MIPI RFFE v3.0 help them?

RF front-end system architects benefit from v3.0 because it enables more flexibility by delivering precise timing control of the RF components. Time collisions of multiple RFFE command sequences create a lot of headaches for developers, and now, simultaneously, 5G is bringing about an explosion in the number of RF bands to be managed, and the reconfiguration window has narrowed.

In developing MIPI RFFE v3.0, the working group concentrated on addressing the 3GPP 5G standard where it stands today. So, the new release substantially enhances the interface's triggering features and functionality, and it streamlines and optimizes specifically for today's challenges.

Tell us more about MIPI RFFE's trigger features—what are triggers, and how do they relate to the timing-control requirements of 5G?

Since its initial release, MIPI RFFE has featured triggers, which basically equip the RF subsystem to configure multiple RF devices with very tight timing control. In v3.0, the working group specified more complementary triggers for synchronizing and scheduling register-setting changes. "Timed triggers," "mappable triggers," and "extended triggers" in MIPI RFFE v3.0 work in combination with one another to boost throughput efficiency and reduce packet latency.

Version 3.0 brings a transformational impact on timing precision—a 20X improvement, for example, for back-to-back triggering operations. In this way, the new version of MIPI RFFE enables fast, agile, semi-automated, and comprehensive control of individual RFFE subsystems and delivers against the more challenging timing requirements presented by the Frequency Range 1 (FR1) of traditional sub-6-GHz cellular bands of 5G.

How does v3.0 change business opportunities for RF device vendors, baseband and transceiver vendors, original equipment manufacturers (OEMs), or other users?

The technical advances of RFFE v3.0 allow OEMs and device vendors to quickly migrate to 5G systems without changing the physical layer of the interface. This backward compatibility is crucial. MIPI RFFE already has a large ecosystem of adopters and devices; the interface has been implemented in billions of devices using wireless connectivity worldwide—handsets, smartwatches, automobiles, and more.

What's next for the MIPI RFFE working group?

We are already looking at a number of ideas for the next release of the interface, such as time-stringent RF front-end control for massive MIMO (multiple input, multiple output) and the 5G NR (new radio) FR2 (Frequency Range 2) operating in millimeter-wave (24.25 to 56 GHz) bands, for example. We are always evaluating new features that the user community needs to flourish.

We are currently in the requirements-gathering phase for the next generation of the interface, so this is a great time to get involved. The working group is especially eager for more input from the system or master side of the RF industry, but we welcome contributions from anyone in the industry, anywhere in the world.

JIM ROSS has contributed to the MIPI RF Front-End Control Working Group *since its inception in 2008 and has served as the group's chair since 2011.*

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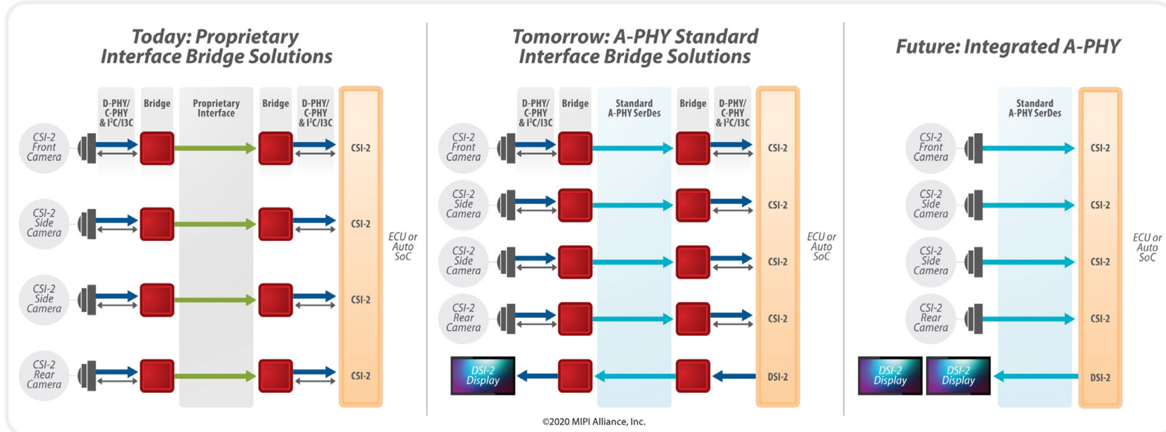
BACK TO TABLE OF CONTENTS



CHAPTER 3:

MIPI Alliance Releases A-PHY SerDes Interface for Automotive

DAVID MALINIAK, editor, Microwaves & RF

First industry-standard asymmetric long-reach physical layer interface enables ADAS, IVI, and other surround-sensor applications; A-PHY v1.0 forms foundation of comprehensive MIPI automotive SerDes implementations.

The MIPI Alliance has released its MIPI A-PHY v1.0, said to be the first industry-standard, long-reach serializer-deserializer (SerDes) physical layer interface. The new specification, available to MIPI members, provides an asymmetric data link in a point-to-point topology, providing high-speed unidirectional data, embedded bidirectional control data and optional power delivery over a single cable.

A-PHY v1.0 offers:

- High reliability: Ultra-low packet error rate (PER) of 10-19 for unprecedented performance over the vehicle lifetime
- High resiliency: Ultra-high immunity to EMC effects in demanding automotive conditions
- Long reach: Up to 15 meters
- High performance: Data rate as high as 16 Gb/s with a roadmap to 48 Gb/s and beyond; v1.1, already in development, will provide a doubling of the high-speed data rate to 32 Gb/s and increase the uplink data rate to 200 Mb/s

In conjunction with the availability of A-PHY v1.0, the Alliance today introduced MIPI Automotive SerDes Solutions (MASS). MASS will provide automotive OEMs and their suppliers with end-to-end high-performance connectivity solutions for the growing number of cameras, sensors, and displays that enable automotive applications such as advanced driver-assistance systems (ADAS), connected in-vehicle infotainment (IVI), and, ultimately, fully autonomous vehicles. These solutions, with unprecedented functional safety and security built in at the protocol level, will help automakers integrate new and emerging safety features such as low-latency backup cameras, lane-keeping and sign-detection sensors and 360° camera, LiDAR, and radar systems. MASS also will support multiple high-resolution instrumentation, control and entertainment displays.

MASS protocol stack

As the physical layer cornerstone, A-PHY's primary mission is to transfer high-speed data between cameras and displays and their related domain ECUs. Through the development of additional supporting specifications, MASS will allow proven higher-layer protocols from MIPI (such as MIPI CSI-2 and DSI-2) and third parties to operate over physical links spanning an entire vehicle, eliminating the need for proprietary “bridges” and PHYs. For OEMs and system integrators this equates to simplified networks and reduced costs, weight and development time.

With A-PHY as the physical layer, the MASS protocol stack consists of:

- Higher-layer protocols such as MIPI CSI-2 and DSI-2, with updated versions to be available later this year and early 2021.
- Protocol adaptation layers (PALs) that map protocols to A-PHY’s A-Packet format for transmission over A-PHY. PALs for MIPI CSI-2 and DSI-2, and for lower bandwidth interfaces such as I^2C, I^2S, GPIO, and Ethernet100, are expected to be completed later this year, and an I3C PAL can be expected in 2021. In addition, MIPI is working with other organizations to leverage additional established protocols. As one such effort, MIPI has extended its liaison with VESA and is actively developing an adaptation layer for use with its DisplayPort and Embedded DisplayPort standards.
- MIPI camera service extensions (CSE) and display service extensions (DSE) in development will add functional safety and security capabilities required for ADAS, self-driving and other applications, and will also provide high-bandwidth digital content protection (HDCP) as required for display applications.

MASS will address functional safety over heterogeneous protocols and numerous topologies, including daisy chaining, according to ISO 26262. System-level engineers can use this architecture to build systems that meet ASIL (Automotive Safety Integrity Level) requirements at any level, from ASIL B to ASIL D. MASS also will provide end-to-end security to include authentication, integrity and confidentiality for data protection of MASS camera, sensor and display components.

MIPI member companies participating in the A-PHY Subgroup include: Beijing ASL Technology Co., Ltd.; BitifEye Digital Test Solutions GmbH; Intel Corporation; Luxshare-ICT, Inc.; MediaTek Inc.; Mixel, Inc.; ON Semiconductor; Parade Technologies Ltd.; Primesoc Technologies; Prodigy Technovations Pvt. Ltd.; Qualcomm Incorporated; Robert Bosch GmbH; Sony Corporation; STMicroelectronics; Synopsys, Inc.; Tektronix, Inc.; Teledyne LeCroy; Toshiba Electronic Devices & Storage Corporation; Valens Semiconductor; and others.

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☞ BACK TO TABLE OF CONTENTS

CHAPTER 4:

MIPI Specifications and Testing

KURT ERICKSON, Elevate Semiconductor

The mobile industry processor interface (MIPI) standard defines industry specifications for the design of mobile devices such as smartphones, tablets, laptops and hybrid devices.

MIPI interfaces play a strategic role in 5G mobile devices, connected car, and IoT solutions, defining three unique physical (PHY) layer specifications: MIPI D-PHY, M-PHY and C-PHY. MIPI D-PHY and C-PHY physical layers support camera and display applications, while the high-performance camera, memory and chip-to-chip applications are supported on top of the M-PHY layer.

MIPI is managed by MIPI Alliance which is a collaboration of mobile industry leaders which include Intel, Nokia, Samsung, Motorola, TI, ST etc. The objective of MIPI Alliance is to promote open standards for interfaces to mobile application processors. This will help in having new services to mobile users at faster rate.

In the mobile market, MIPI Alliance specifications are targeted to mobile devices that operate on mobile networks. Typical devices are smartphones, tablets, laptops and hybrid devices. MIPI Alliance provides specifications that serve manufacturers' various needs for physical layer, multimedia, chip-to-chip or inter-processor communications (IPC), control/data, debug/trace, and software integration applications.

All of the specifications are designed to address three characteristics essential to successful mobile designs: 1) low power to preserve battery life; 2) high-bandwidth to enable feature-rich, data-intensive applications, and 3) low electromagnetic interference (EMI) to minimize interference between radios and other subsystems in a device.

Smartphones

The smartphone industry is the largest single market for MIPI specifications. All major chip vendors use MIPI Alliance specifications and all smartphones on the market include at least one MIPI specification. MIPI specifications are used in hundreds of millions of smartphones.

MIPI Alliance specifications cover the full range of interface needs in a device. The specifications can be applied to integrate the modem, application processor, camera, display, audio, storage, antennas, tuner, power amplifier, filter, switch, battery, sensors, and other components.

Component vendors and device manufacturers use MIPI Alliance specifications because the technologies simplify designs, reduce design costs and shorten time-to-market for efficient, high-performing products. And fundamentally, each specification is optimized to ensure three performance characteristics needed in a mobile device: low power to preserve battery life, high-bandwidth to enable feature-rich applications, and low electromagnetic interference (EMI) to optimize performance of radios and subsystems.

Tablets, laptops and hybrid devices

Devices that converge mobile and computing capabilities are important markets for MIPI Alliance specifications. MIPI specifications helped establish and advance the tablet market and many organizations in the PC industry use MIPI specifications in mobile-connected laptops, tablet/laptop hybrids and other devices. Typical use cases for MIPI specifications in these devices include connecting and managing power consumption for high-definition displays and minimizing the number of wires deployed through hinges to connect cameras or displays.

Specifications

MIPI specifications address only the interface technology, such as signaling characteristics and protocols; they do not standardize entire application processors or peripherals. Products which utilize MIPI specs will retain many differentiating features. MIPI is agnostic to air interface or wireless telecommunication standards. Because MIPI specifications address only the interface requirements of application processor and peripherals, MIPI compliant products are applicable to all network technologies, including GSM, CDMA2000, WCDMA, PHS, TD-SCDMA, and others.

MIPI Testing

You need to design mobile devices that address the evolving data storage, data transfer, display, camera, memory, power, and other requirements defined by MIPI specifications. Customers demand higher performance, real time streaming of multimedia content and feature-rich applications.

Transmitter test

You need to test the performance of your MIPI transmitter device to ensure it is not the root cause of signal impurities at the receiving end of the transmission line. MIPI D-PHY, M-PHY and C-PHY all have unique transmitter test challenges. With hundreds of tests to be performed, you can save significant test time by using automated compliance test software.

Receiver test

You need to test your MIPI receiver device to ensure it can properly detect the digital signal content of an input signal. It is important to test it against a worst-case stress condition to account for signal degradation in the transmission channel. You need an accurate high-speed signal stimulus, as well as bit error detection capabilities, to test the performance of your MIPI receiver. Automated compliance test software enables you to quickly test all key parameters of your designs.

Protocol test

Protocol validation occurs predominately at the interface layer. There are many different protocols supported on the PHY layer of the MIPI specifications, including CSI-2, DSI-1, DigRF, CSI-3, UFS, UniPro, SSIC, and MPCIe. Each protocol has its own unique requirements and tests. For both MIPI D-PHY and M-PHY protocols, there is a stack between the physical and link layer, as well as between the transport and high-level application layer. To truly identify where an error exists, it is ideal to be able to "see into" that stack.

How MIPI Interfaces Enable 5G Smartphones

The first wave (phase 1) of high-end 5G smartphones is expected to be an enhancement of the high-end 4G devices currently on the market. Major enhancements will include the addition of the new 5G NR RF subsystem, and the evolution of other subsystems to enable better user experiences and richer multimedia capabilities. For example, these 5G smartphones may have three to four high-resolution rear cameras with high-frame-rate/slow-motion video capture capability, an enhanced microphone array, multi-channel audio and stereo speakers.

The 5G modem and application processor use MIPI specifications such as CSI-2 for cameras and DSI-2 for the display, as well as either the low-power, high-bandwidth, pin-efficient MIPI D-PHY or C-PHY physical layers. MIPI RFFE for RF front-end devices control, and MIPI UniPro with M-PHY for high-performance flash storage are all becoming ubiquitous in 5G designs. MIPI I3C, SoundWire, SLIMbus and upcoming VGI specifications are expected to be adopted in many upcoming 5G smartphone platforms as well.

MIPI CSI-2

MIPI CSI-2 is the most widely used camera interface in mobile and other markets. It has achieved widespread adoption for its ease of use and ability to support a broad range of high-performance applications, including 1080p, 4K, 8K and beyond video, and high-resolution photography.

Designers should feel comfortable using MIPI CSI-2 for any single- or multi-camera implementation in mobile devices. The interface can also be used to interconnect cameras in head-mounted virtual reality devices; automotive smart-car applications for infotainment, safety, or gesture-based controls; imaging applications for client content creation and consumption products; camera drones; IoT appliances; wearables; and 3D facial recognition security or surveillance systems.

The latest release, MIPI CSI-2 v3.0, delivers enhancements to the specification designed to enable greater capabilities for machine awareness across multiple application spaces, such as mobile, client, automotive, industrial IoT and medical. RAW-24, for representing individual image pixels with 24-bit precision, is intended to enable machines to make decisions from superior quality images; an autonomous vehicle, for example, could decipher whether darkness on an image is a harmless shadow or a pothole in the roadway to be avoided.

Smart Region of Interest (SROI)—for analyzing images, inferencing algorithms and making better deductions—could enable machines on a factory floor, for example, to more quickly identify potential defects on a conveyor belt, or medical devices to more surely recognize anomalies such as tumors. And Unified Serial Link (USL)—for encapsulating connections between an image sensor module and application processor—is crucial for reducing the number of wires needed in IoT, automotive and client products for productivity and content creation, such as all-in-one and notebook platforms.

MIPI CSI-2 can be implemented on either of two physical layers from MIPI Alliance: MIPI C-PHY v2.0 or MIPI D-PHY v2.5. It is backward compatible with all previous MIPI CSI-2 specifications. Performance is lane-scalable, delivering, for example, up to 41.1 Gbps using a three-lane (nine-wire) MIPI C-PHY v2.0 interface, or 18 Gbps using four-lane (ten-wire) MIPI D-PHY v2.5 interface under MIPI CSI-2 v2.1.

Testing of MIPI-Specification-Based Devices

The latest trend for semiconductor device manufacturers is to add several high-speed MIPI® specification-based ports to a single device. This enables feature-rich implementations of imaging- and display-intensive applications, although it also poses significant challenges for production test engineers who are tasked with creating high-fault coverage testing solutions on automated test equipment (ATE). Such fault coverage often entails creating a parallel, at-speed, system-oriented functional test while simultaneously grappling with the limitations of legacy ATE and the complexity of the MIPI protocols being tested.

There are three high speed PHY-layer standards defined by MIPI, and they are used for different applications:

D-PHY is a variable speed unidirectional clock synchronous streaming interface, with low speed in-band reverse channel and supports interfaces for camera (CSI), and display (DSI).

M-PHY is performance driven, bidirectional packet/network oriented interface supporting interfaces like camera (CSI), storage (UFS), DigRF, and the UniPro, LLI, SSIC, M-PCIe which are used for inter-processor communications

C-PHY is a variable speed unidirectional, embedded clock streaming interface, with low speed in-band reverse channel and supports interfaces for camera (CSI), and display (DSI).

Each interface provides a wide range of parameters including clocking method, channel compensation, number of pins, maximum amplitude, data rate and format, bandwidth per port, data encoding, and clock recovery. The D-PHY, M-PHY, and C-PHY MIPI interfaces are not controlled by a compliance program because they are not accessible to users. However, validation of specification conformance is important to semiconductor vendors and system integrators to ensure interoperability between components.

The MIPI specifications and Conformance Test Suite (CTS) requirements for components are quite complex and testing them is challenging. Connectivity to the Device Under Test (DUT) while making sure signal integrity is maintained, creating the worst-case stimulus for the DUT while not overstressing it, or getting test result information from the DUT are examples of such challenges.

BER test solutions offer the flexibility to test all types of MIPI receivers accurately by providing accurate high speed signal stimulus and bit error detection capabilities. More complex C-PHY and D-PHY signal stimulation can be addressed with high performance arbitrary waveform generators. Automated test software helps to reduce test development and execution time while ensuring repeatability and accuracy.

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☞ **BACK TO TABLE OF CONTENTS**

CHAPTER 5:

MIPI A-PHY: A Resilient Asymmetric Data Transport for a Vehicle's Lifespan

EYRAN LIDA, Chief Technology Officer and Co-Founder, Valens Semiconductor

Through analysis of the complex automotive noise environment, this article shows why MIPI A-PHY is the best means of ensuring the integrity of data links over a vehicle's lifetime.

In September 2020, the MIPI Alliance announced the release of its new A-PHY specification, the first industry-standard, long-reach, serializer-deserializer (SerDes) physical-layer (PHY) interface. MIPI A-PHY v1.0 serves as the foundation of an end-to-end system designed to simplify the integration of cameras, sensors, and displays across a vehicle.

The specification provides a robust, multi-gigabit asymmetric data link, providing high-speed unidirectional data, embedded bidirectional control data, and optional power delivery over a single cable. MIPI A-PHY offers a near-zero packet-error rate (PER) of 10-19 for unprecedented performance over the vehicle lifetime, ultra-high immunity to electromagnetic-interference (EMI) effects in demanding automotive conditions, cable reach up to 15 meters, and data rates as high as 16 Gb/s with a roadmap to 48 Gb/s and beyond.

In this article, we will analyze the complex automotive noise environment—in particular, its unique characteristics when compared with conventional non-automotive communication links. Our analysis shows that specific mechanisms for noise cancellation and error correction that target the negative effects of automotive EMI are needed to ensure safe and resilient operation of high-throughput data links over the vehicle's lifespan. We will detail the mechanisms that were incorporated into A-PHY to ensure the integrity of data links over the vehicle's lifetime.

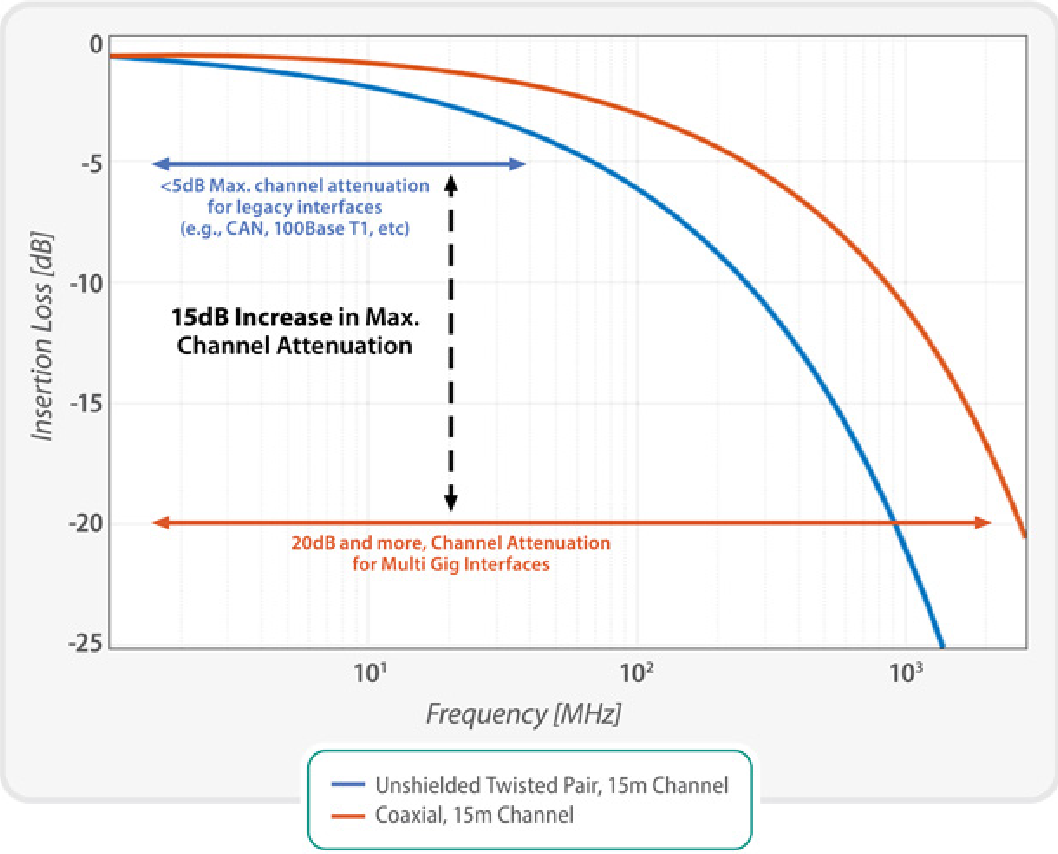
Challenges for Automotive Multi-Gigabit Links

Electrical/electronic (E/E) in-vehicle architectures are undergoing a radical transformation to meet the needs of emerging use cases and system requirements, as well as to overcome the challenges that they present. Here are a few examples:

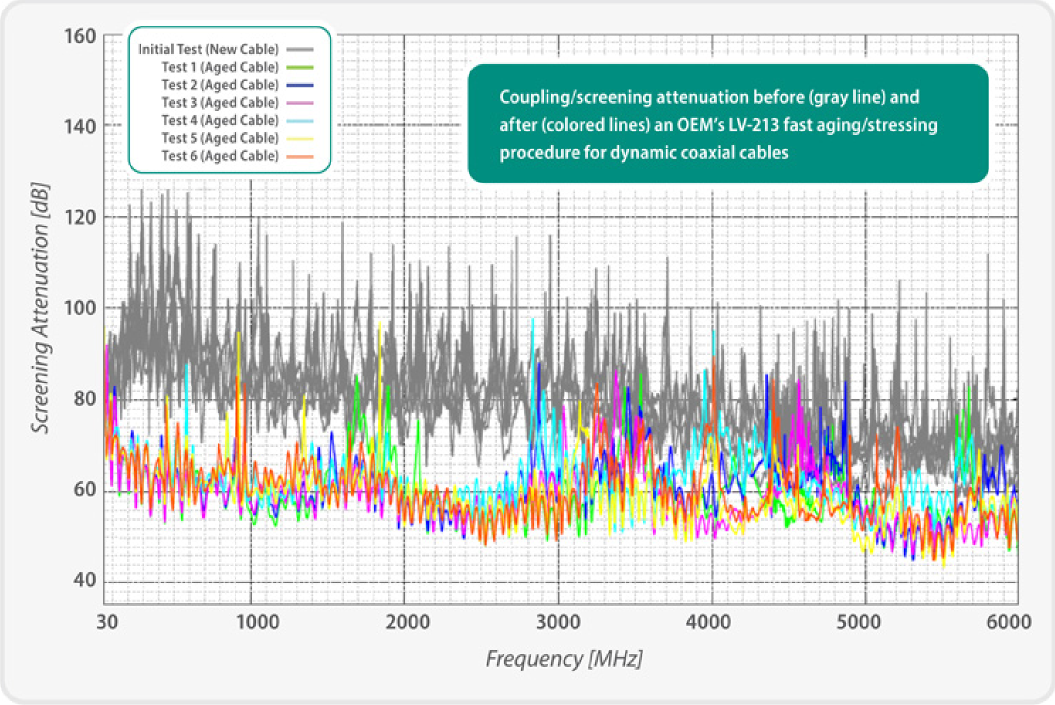
- High-quality, multi-sensor fusion requires long, high-throughput, safety-critical links between electronic control units (ECUs) and multiple sensors at the edges of the vehicle.
- High-quality displays require high-throughput links to multiple vehicle displays to ensure best-in-class user experiences.
- Harsh in-vehicle environments present significant challenges to multi-gigabit communication technologies, which require shielded cables to tolerate high EMI levels.
- Increasing data rates are pushing conventional automotive communication technologies to their limits, and they can no longer provide the required immunity margins to guarantee safe vehicle lifespan operation over shielded cables.

The significant increase in symbol rates needed to support higher bandwidths requires PHY interface operation at much higher in-band frequencies, which in turn imposes—or creates—limitations on the transmission. Factors such as decreased in-band transmitter power density to meet emission limits, decreased signal power at the receiver due to increased channel attenuation (**Fig. 1**), and decreased cable-shielding effectiveness (**Fig. 2**) leading to more noise coupling into the signal, all result in a significant degradation of signal-to-noise ratio (SNR) at the receiver.

To further complicate matters, cable-shielding degradation gets worse with cable



1. Higher symbol rates lead to increasing frequencies on physical-layer interfaces, which in turn results in limitations on data transmissions. Numerous factors can contribute to degradation in SNR at the receiver in an in-vehicle data link, one of them being an increase in channel attenuation.



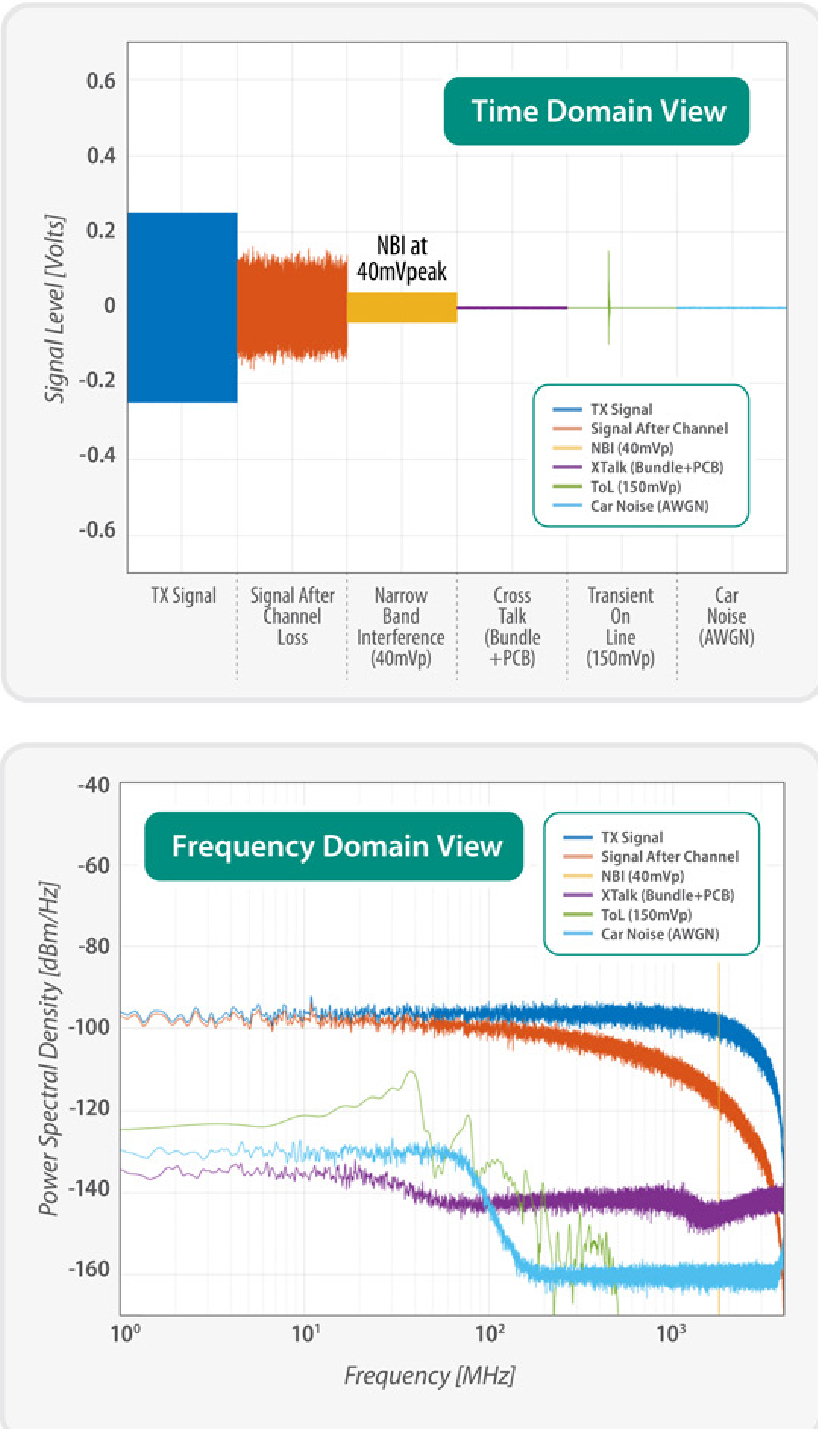
2. Another factor in SNR degradation at the receiver is decreased cable-shielding effectiveness, which allows for more noise coupling into the signal.

aging and flexing. Figure 2 shows how repetitive flexing of a coaxial cable results in a 25- to 30-dB decrease in screening attenuation at higher frequencies. That means the cable characteristics can change significantly over the lifetime of the vehicle—and, if not addressed by the PHY, the attenuation could have a direct impact on the resilience of the link over time.

Automotive Noise Environment

Having determined that the receiver on the link suffers from an impaired SNR when running at higher symbol rates, it's also important to consider the noisy automotive environment. The vehicle is exposed to many electromagnetic noise components, the main elements in this environment being:

- *Narrowband interference (NBI)*: Continuous narrowband noise, comprising a single or few contributions from a large external-to-the-vehicle transmitter(s). These noise components have bounded peaks and are very likely to be an issue. Standard electromagnetic-compatibility (EMC) tests, such as bulk current injection and RF ingress, test the receiver's immunity to such noises.
- *Transients on line (ToL)*: Large electrical transients with short duration (up to ~200 ns) but with very high amplitude.
- *Alien crosstalk noise (Xtalk)*: Continuous broadband noise caused by neighboring aggressors in the cable harness and on-PCB traces.
- *Vehicle-environment additive white Gaussian noise (AWGN)*: Continuous broadband environment noise comprising contributions from multiple independent sources, normally distributed with unbounded noise peaks but with low probability of occurrence.



3. Shown are time- and frequency-domain views of the transmitted signal at the receiver’s input. The system is transmitting at a symbol rate of 4 Gbaud at 500 mV p-p over a channel with ~20-dB attenuation at its 2-GHz Nyquist frequency.

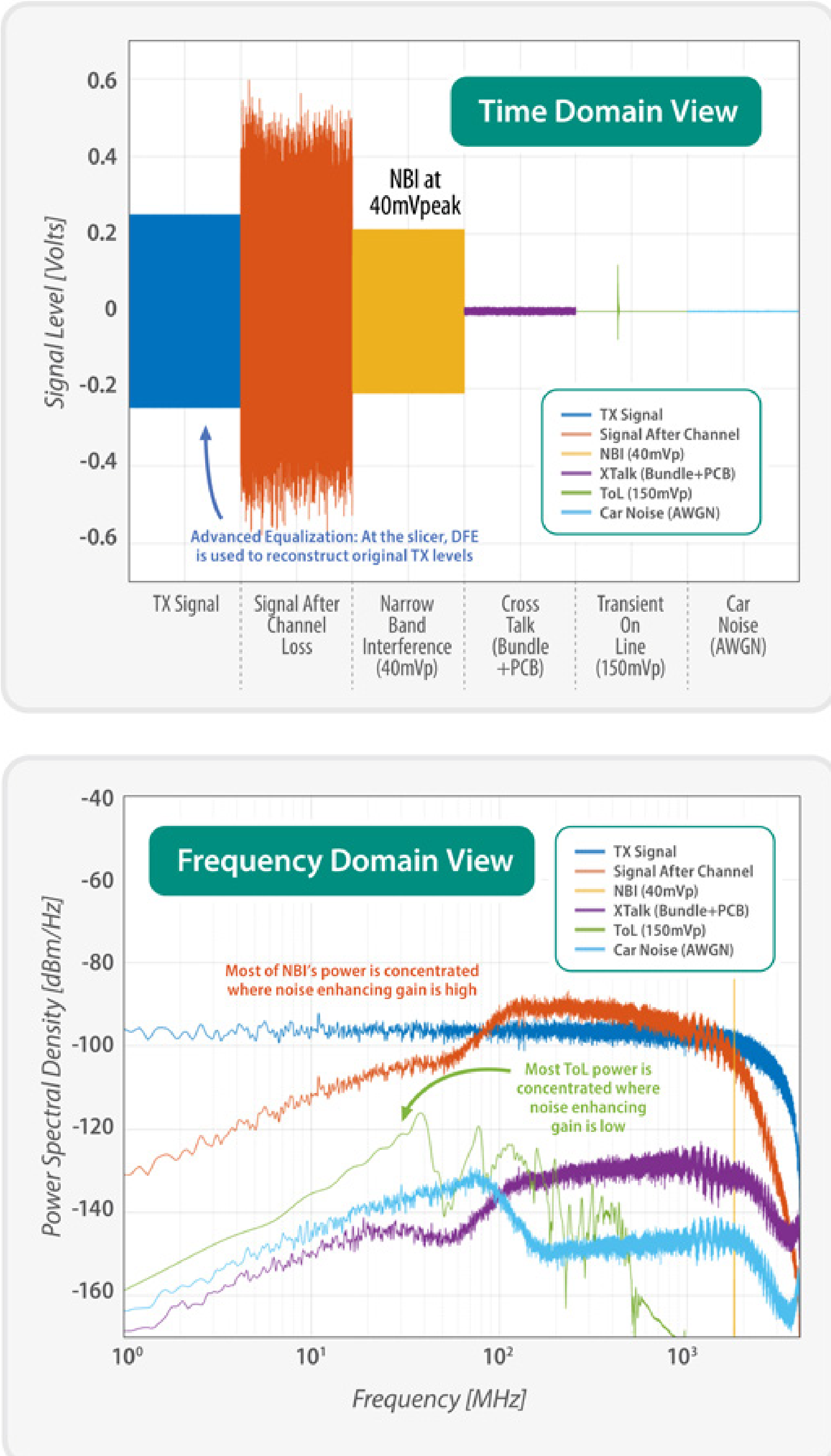
As shown in Figure 2, the screening attenuation (SA) of "new" shielded cables can be 20 to 30 dB better than their worst-case SA, because SA degrades with in-car installation and during the vehicle's lifespan due to cable aging and stressing. Based on a study of this phenomena, MIPI Alliance determined that A-PHY shall offer immunity to at least 40-mV-peak NBIcoupled on the receiver's pads. By comparison, other standards assume a maximum of ~6-mV peak NBI,though recent work suggests that immunity to much larger NBI peaks is required (90 dBμV RMS above 30 MHz, while MIPI's 40-mV peak equals 89 dBμV RMS).

As less in-band signal power reaches the receiver, its equalizer needs to amplify more of the incoming signal to reconstruct the original transmit levels' separation at its slicer, which is where decisions are made about the signal level. Certain elements in the receiver amplify both the data signal and its coupled noise, while a decision-feedback equalizer (DFE) improves the reconstruction of the original transmit levels without noise amplification.

The following diagrams illustrate the different noise sources described above, with the dark blue representing the transmit signal and the orange representing the signal after channel loss. **Figure 3** shows time- and frequency-domain plots of a system transmitting at a symbol rate of 4 Gbaud at 500 mV p-p over a channel with ~20-dBattenuation at its 2-GHz Nyquist frequency.

It's also important to examine the receiver to see how these signals look at the slicer—that is, after the addition of the analog front-end and feed-forward equalizer (FFE) gains (**Fig. 4**). Even when we use a relatively advanced equalization and filtering that affords only ~15-dB amplification of the noise, we can see the large impact of the NBI relative to the desired reconstructed transmit levels. As seen in the frequency domain, it's due to most of the NBI power is concentrated at a frequency where the noise-enhancing gain in the equalizer is high. By comparison, ToL noise occurs at a lower frequency that experiences much lower noise-enhancing gain.

The conclusion from this analysis is that high-throughput automotive links



are EMI-limited and not AWGN-limited, as are conventional long-distance, non-automotive communication links. Thus, we need specific mechanisms for noise cancellation and error correction that target the negative effects of automotive EMI to ensure safe and resilient operation of high-throughput data links over the vehicle's lifespan.

Enter MIPI A-PHY

MIPI A-PHY v1.0 is an asymmetric, high-throughput, resilient automotive interface that employs dynamic pulse-amplitude modulation (PAM), just-in-time NBI cancellers (JITC), and PHY-level retransmission (RTS) mechanisms for its higher-speed gears to ensure maximum link robustness:

- *PAM:* A-PHY uses different modulation schemes for each speed gear, ranging from NRZ-8b/10b up to PAM16. In speed gears 3, 4, and 5, subset modulation (using lower-order modulation) protects packet headers, important data types, and retransmitted packets (**Table 1**).
- JITCs: The built-in noise cancellers provide more than 36 dB of just-in-time NBI cancellation.
- *RTS:* Dynamically modulated local retransmission provides a post-RTS PER of <10-19. This translates to a mean time between packet errors of more than 10,000 years, even with a link operating at 100 Gb/s.

The scale of the challenges resolved by A-PHY also plays out in the type of noise profiles present in the vehicle. Noise attacks can be either gradual or instant (**Fig. 5**), and the ISO standard for EMC testing allows for both types of attack profiles. More specifically, multiple constant wave and amplitude-modulation NBI attack profiles may be encountered and can be either gradual or instant, while pulse-modulation NBI and ToL attacks are, by definition, instant in their nature.

When NBI noise instantly attacks, some data packets are damaged before the JITC can converge and cancel the NBI. To overcome this, RTS is used to recover the data packets that were damaged before the JITC converged.

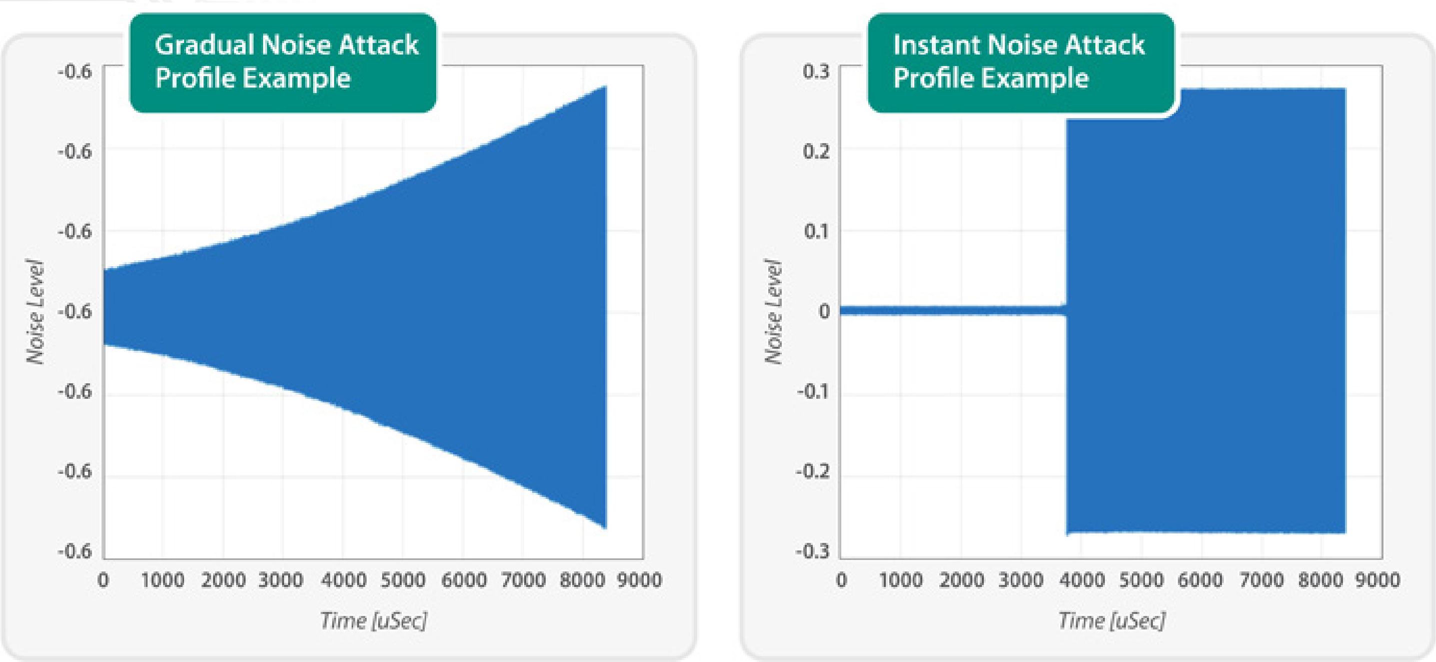
4. In these images, we see time- and frequency-domain views of how the same signals look at the receiver’s slicer—that is, after the addition of the analog front-end and feed-forward equalizer (FFE) gains.

To hasten and ensure successful JITC convergence, we use a retraining sequence. For example, **Figure 6** illustrates a 4-Gbaud PAM4, 40-mV-peak, 3-tone instant NBI attack, both with and without retraining of the JITC. As can be seen on the left side of the diagram, the four blue traces representing the slicer input at the receiver show clearly defined PAM4 levels until the noise attacks the signal. Just-in-time cancellation needs to occur while actual data is running on the link, and it's clear from the destruction of the PAM4 signal that the noise cancellation is unable to converge to overcome the noise.

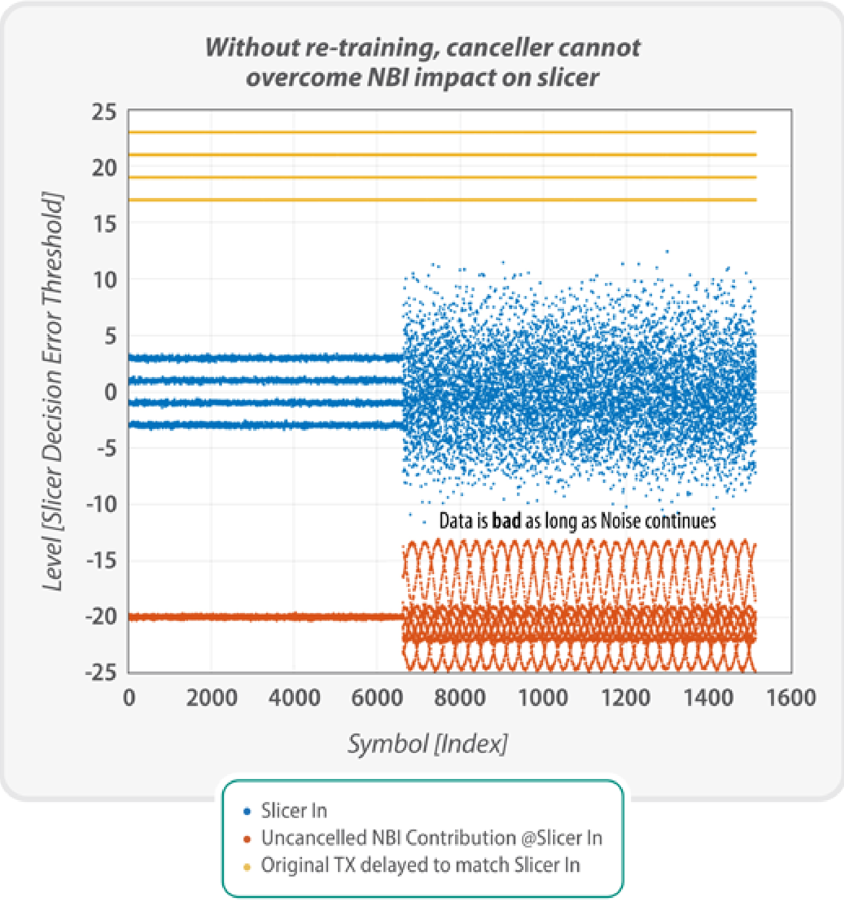
On the right side of the diagram, we see how the retraining process unfolds. The receiver requests the transmitter to transmit a retraining sequence comprising two-level known (predictable) data derived from the scrambler, which rapidly allows for JITC convergence

Gear Date Rate	Modulation [One modulation per Gear]	Working Frequency [GHz]	Net Application Data Rate [Gbps]
G1 2 Gbps	NRZ-8b/10b	1	1.5
G2 4 Gbps	NRZ-8b/10b	2	3
G3 8 Gbps	PAM4	2	7.2
G4 12 Gbps	PAM8	2	10.8
G5 16 Gbps	PAM16	2	14.4
Uplink, All Gears 100 Mbps	NRZ-8b/10b	0.05	0.055 (55Mbps)

Table 1: A-PHY speed rates (gears) and modulation schemes



5. Shown are examples of gradual and instant noise-attack profiles (left and right, respectively).



6. These images illustrate the impact of narrowband interference without (top) and with (bottom) JITC retraining.

and successful noise cancellation at the receiver—even while the noise continues. Following the convergence, PAM4 data is once again recognizable by the slicer. We then use RTS to retransmit the data packets that were damaged in the noise attack (not shown in the plot).

Comparison with Forward-Error-Based Systems

Table 2 shows a comparison of the in-vehicle noise handling of A-PHY's PAMx/JITC/RTS solution versus that of a PAMx/FEC (forward error correction) implementation.

For PAMx/FEC solutions, the instant NBI, crosstalk, and AWGN noise components are all handled by the SNR gain provided by the FEC, which is approximately 6 dB. In other words, those three components all share the same 6-dB SNR gain budget targeting a post-FEC BER of 10-12, which is the equivalent of a PER that's worse than 10-9 when using packets sized similarly to A-PHY's maximum packet size.

For A-PHY PAMx/JITC/RTS solutions, the instant NBI is handled by the JITC/RTS mechanism combination, which provides more than 36 dB of noise cancellation. Crosstalk and AWGN noise components are handled by the SNR gain provided by the RTS, which is about 4 dB. These noise-handling mechanisms enable A-PHY to achieve a PER of 10-19.

In addition, when dealing with ToL noise components, the A-PHY RTS mechanism can manage error bursts of thousands of symbols, while practical FEC implementations are restricted by the degree of interleaving. This greatly limits the duration of the error bursts that FEC systems can handle.

Conclusion

As has been shown, communication links within harsh automotive noise environments

Table 2: Comparison of A-PHY vs. FEC-based systems

Noise Component	PAMx/JITC/RTS	PAMx/FEC
Instantly attacking continuous NBI	Handled by JITC/RTS combination, reaching more than 36dB cancellation [can tolerate **10s of mVpeak** NBI]	Can only tolerate single digit mVp NBI
Xtalk	Share RTS' 4dB SNR gain and chosen separation between TX levels (modulation per PAMx)	Share FEC's (~6dB) SNR gain and chosen separation between TX Levels (modulation per PAMx)
AWGN	Designed to provide **<10^{-19}**, post-RTS PER	Designed to provide <10^{-12} post-FEC BER
Transients on Line	Handled by RTS, can handle error bursts of **1000s of symbols**... one-two full packets...	Handled by FEC's interleaving, but with limited burst duration per interleaving degree

are EMI-limited and not AWGN-limited.

A FEC-based solution will utilize most of its 6-dB SNR gain to overcome NBI and consequently offer no additional advantages against AWGN and crosstalk. The use of JITC in an A-PHY implementation removes the limiting NBI impairment, which enables the RTS mechanism to correct much longer error bursts. By comparison, a FEC-based solution can't utilize JITC because it's unable to handle instant NBI attacks without RTS.

In addition to its many technical benefits, MIPI A-PHY v1.0 brings a true standardized solution for long-reach SerDes, paving the way for a rich ecosystem of interoperable products and allowing OEMs and Tier 1 suppliers to move away from proprietary solutions. A-PHY also forms the cornerstone of MIPI Automotive SerDes Solutions (MASS), an end-to-end, full stack of connectivity solutions for the growing number of cameras, sensors, and displays that enable automotive applications. These solutions, with unprecedented functional safety and security built in at the protocol level, will help automakers integrate new and emerging safety and other features.

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