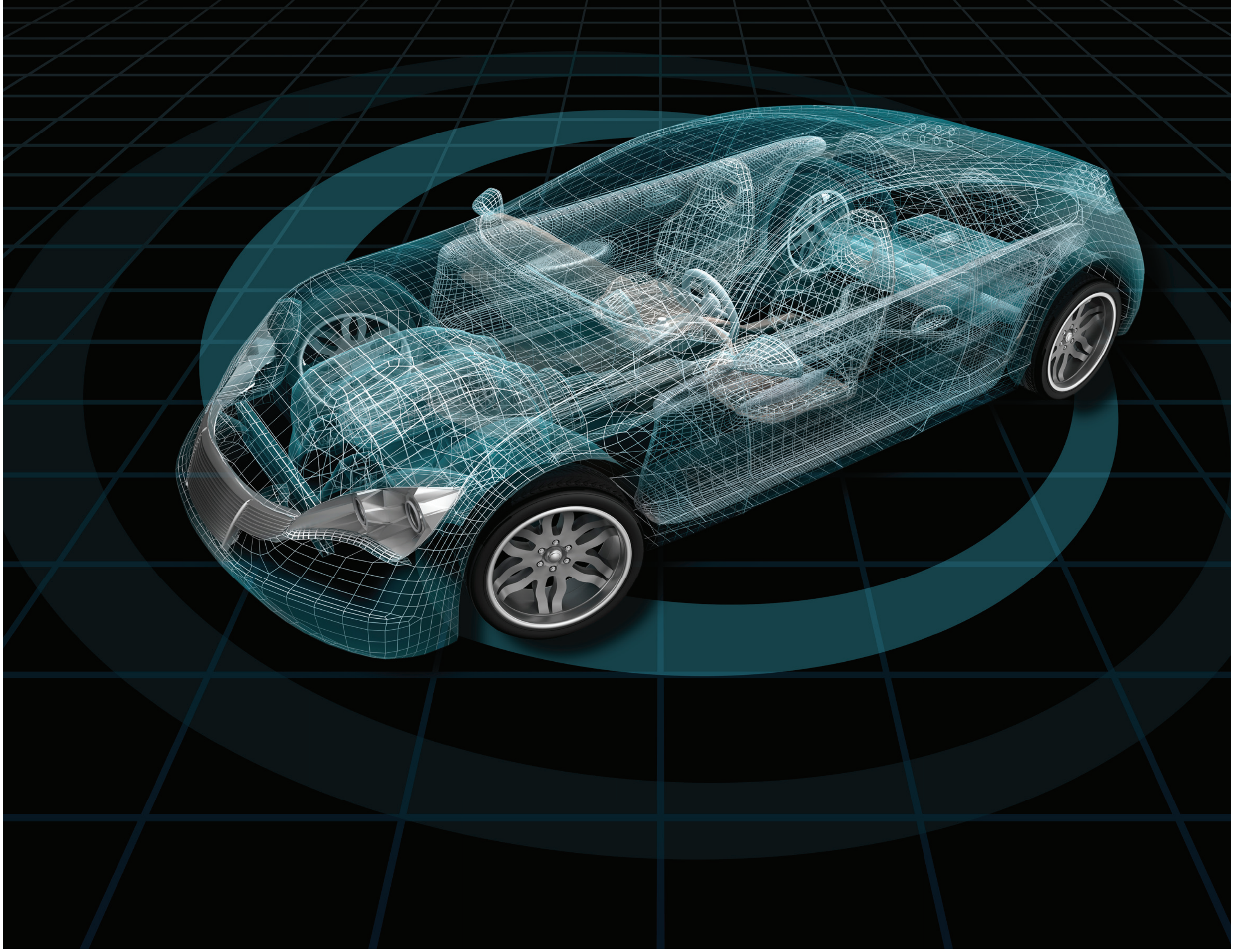
Driving the Wires of Automotive

MIPI specifications in automotive and the A-PHY solution



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MIPI Alliance: Driving the Wires of Automotive

It's not uncommon to hear new cars with advanced electronics referred to as "smartphones on wheels" or "mobile data centers." Regardless of the analogy used, there's no doubt that today's increasingly connected vehicles are very different from the cars of yesterday, sharing more in common with a continuously connected device that's just a fraction of its size: the mobile smartphone.

Consumers may see the use of mobile technologies in automotive in "visible" features such as high-resolution front cluster displays connected to back-up rear cameras, infotainment displays with GPS navigation, and multi-wireless Bluetooth, Wi-Fi and 4G/5G cellular connections. This can be imagined in Figure 1 with the notion that many "smartphone-like" subsystems may be placed around the car to achieve this functionality.

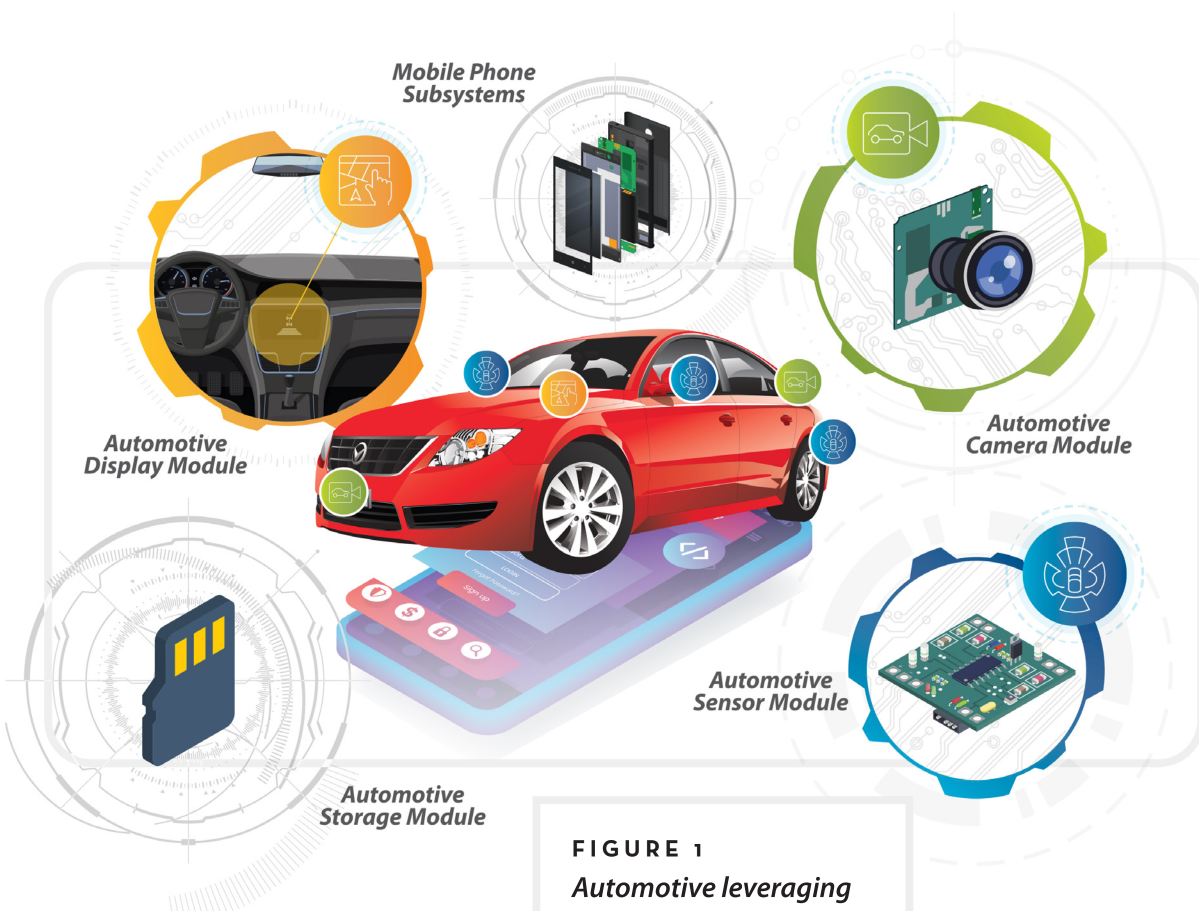


FIGURE 1
Automotive leveraging the mobile smartphone

Source: MIPI Alliance

However, perhaps the greater convergence is happening behind the scenes in advanced electronics for Advanced Driver Assistance Systems (ADAS) and Automated Driving Systems (ADS) and the interconnects or interfaces that enable them to perform as a system, much as in the continued fast pace of technology integration that's happened in the smartphone over the past decade.

This paper is designed to provide an understanding of MIPI specifications for wired connectivity interfaces in automotive today, heavily leveraged from MIPI's influence over the mobile smartphone ecosystems, and share how new enhancements and specifications are being developed with automotive applications in mind. In particular, it will provide an in-depth look at the upcoming MIPI A-PHY physical layer specification, which will provide a solution for the "long-reach, high-speed challenge" of connecting the highest speed electronic components throughout a vehicle. MIPI initiated development of A-PHY in 2017 to drive the convergence of multiple proprietary long-reach interfaces in automotive toward one standard with a strong roadmap vision for the future.

The Changing Industry

The auto industry is being transformed by several global trends, including a growing embrace of electric vehicles, increasing vehicle automation, tighter safety and fuel economy standards, and new ownership models such as car sharing.

These are all generally requiring that cars become smarter, connected and more automated, which means additional electronics. As vehicles progress along the Society of Automotive Engineers (SAE) levels of driving

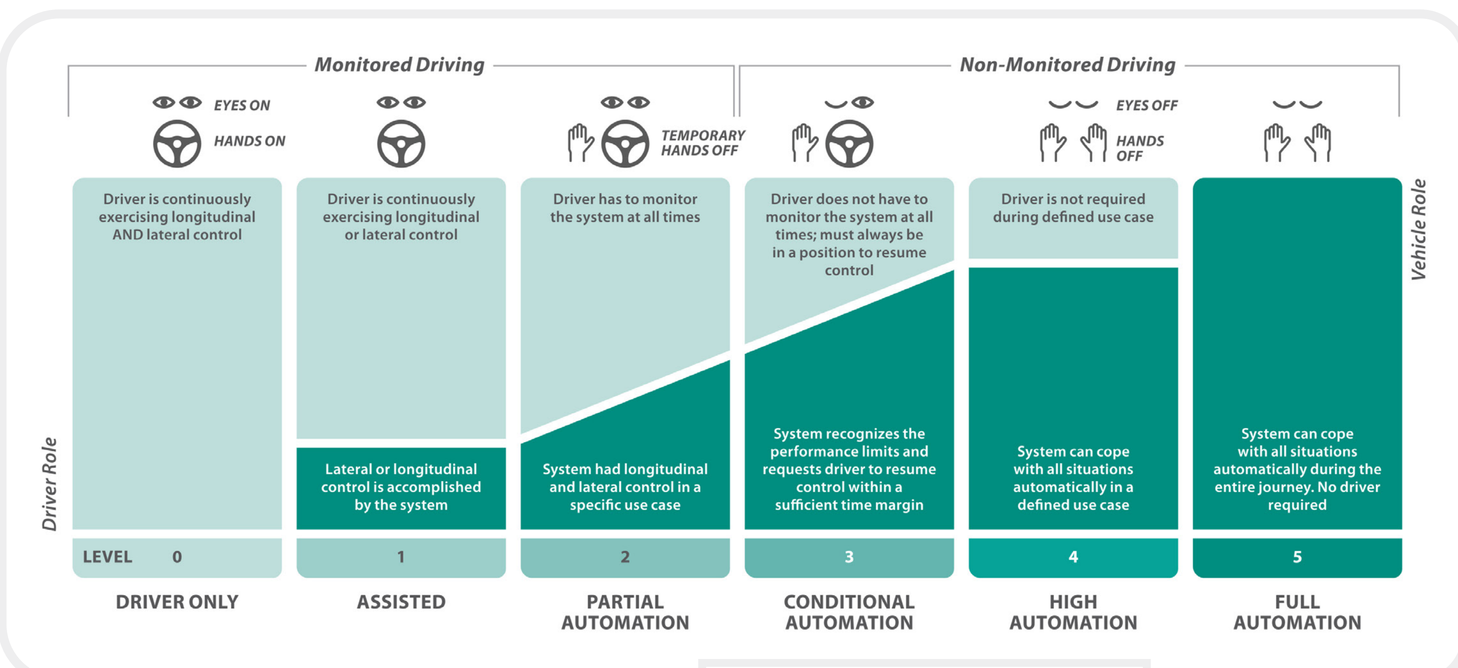


FIGURE 2

Levels of driving automation

Source: ZF TRW / Mike Lemanski

automation shown in Figure 2, they will be enabled by increasingly sophisticated sensor electronics and processing, brought together by high-speed interconnects.

The sensors driving automation can be broken down into four specific types, each generating data at extremely high rates: optical cameras at rates of 12 Gbps and rising, radio-based radars at 5 Gbps, light-based lidar sensors at 1 to 2 Gbps, and ultrasonic sensors in the range of 25 to 150 Mbps. Data from each sensor is delivered to the one or more "central" processors or electronic control units (ECUs) by a high-speed interface, often a dedicated one.

A key automotive sensor is the optical camera, which leverages technologies from the billions of cameras developed for the smartphone market. A look at the automotive camera market reveals this explosive growth on the early roads to automation. As shown in Figure 3, studies predict the automotive camera market will grow to **$7.5 billion in annual revenue by 2023, with compound annual growth of 24.3% from 2018 to 2023**. Taking the view out further, annual revenue for all ADAS technologies is predicted to reach more than $65 billion by 2026.

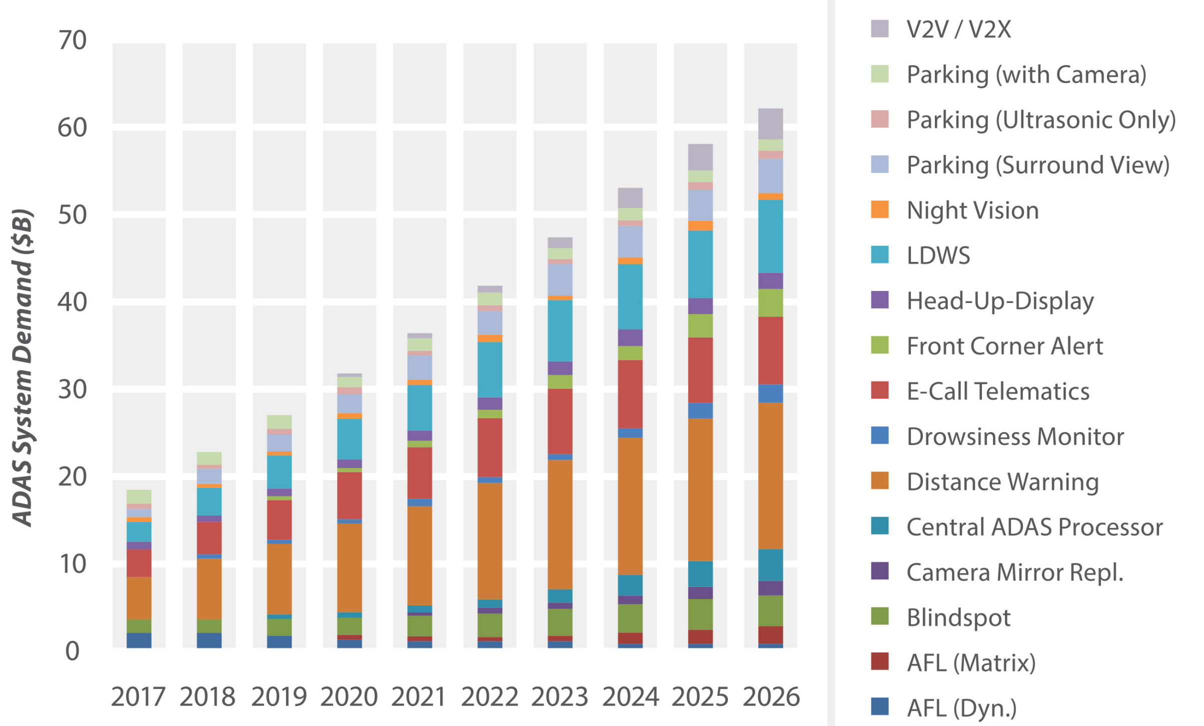


FIGURE 3

Automotive ADAS growth forecast

Source: Strategy Analytics

Estimates of the number of cameras per car vary widely, as shown in Figure 4, but production volume of hundreds of millions of cameras per year is reminiscent of the large volumes seen in smartphones. Current estimates are 8-12 cameras per car in the immediate future.

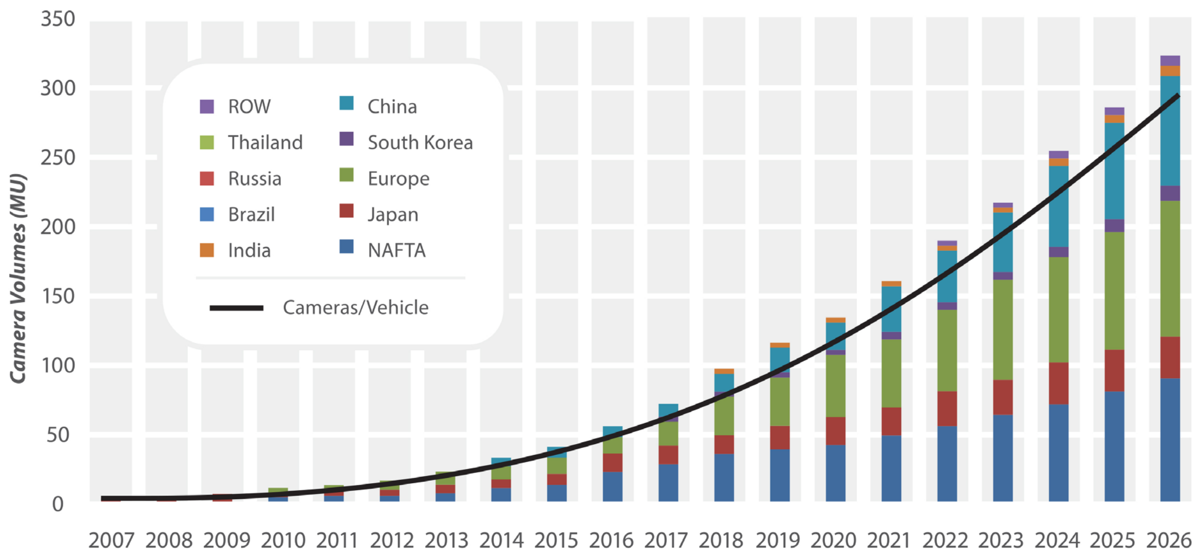


FIGURE 4
Worldwide automotive camera sensors forecast

Source: Strategy Analytics

In this rapidly evolving landscape, while the existing broadly embraced automotive interfaces such as LIN and CAN see continued use for lower-speed (mainly control applications), auto manufacturers and suppliers have no clear standardized solutions for high-speed interfaces between cameras and ECUs, and for the most part they have had to rely on proprietary solutions. While these solutions may employ good technology themselves, the many competing solutions cause confusion in the marketplace, and the lack of a single standard limits economies of scale. In mid-2015, MIPI Alliance identified the need for a unified in-vehicle connectivity specification that would meet the automotive industry's need for high speed, low latency, functional safety, light weight, low power consumption and the desired economies of scale. Since that time, MIPI has been working with automotive OEMs to define the requirements and understand the challenges of the noise channel. In the last two years, MIPI has produced several incremental versions of its Automotive Requirements Document (ARD).

Unifying the Mobile Industry

The outlook for automotive electronics on the road to autonomy is not unlike the mobile industry outlook in the early 2000s. The MIPI Alliance was formed in 2003 by ARM, Nokia, STMicroelectronics and Texas Instruments at a critical juncture in the cellphone market: the demand for smart, multimedia handsets was exploding, yet the fragmentation of essential interface technologies hindered product design and development. Within its first year, the Alliance welcomed Intel, Motorola, Samsung and Philips to the organization and introduced specifications that would remove a significant pain point in the complexity of phone design—how to connect cameras to the central application processor. Very quickly thereafter, MIPI set the goals of connecting the application processor to higher resolution displays and early 3G cellular modems.

It was this work that helped to propel wired interface standardization within mobile. Following initial interface specification development for camera, display and modem connectivity, MIPI Alliance introduced specifications for a range of other essential needs in devices, such as interfaces for audio and power management.

Now in its 16th year, MIPI Alliance has developed roughly 50 specifications that cover the full range of interface applications in a mobile device, including those connecting application processors to modems, cameras, displays, audio, storage, sensors, antennas, antenna tuners, power amplifiers, filters, switches, batteries and other elements. These standardized specifications have helped to facilitate interoperability among component suppliers, simplify device designs (hence reducing cost), and optimize performance and power, while allowing manufacturers to focus on product differentiation and reduce their time to market.

As a result, today all major chip vendors and smartphone manufacturers use MIPI Alliance specifications, and every smartphone on the market uses many different MIPI Alliance specifications. The organization itself has more than 300 member companies that reflect the breadth of the mobile and mobile-influenced ecosystem, including handset manufacturers (OEMs), semiconductor companies, silicon IP provider companies, test equipment companies, camera and display module providers, sensor providers, and most recently, automotive OEMs and their Tier 1 suppliers.

Over the years, MIPI specifications have been implemented in an ever-broadening array of devices, going well beyond mobile handsets into wearables, medical devices, drones, industrial equipment and vehicles, a trend referred to as "mobile-influenced."

As evidence of this growing ecosystems, currently more than 45% of MIPI member companies report they are involved in the Internet of Things sector, and nearly 40% work on automotive engine/control/ADAS applications. In addition, 45% are involved with automotive infotainment.

Among the reasons MIPI specifications have been so broadly embraced are specific technical attributes, captured within the four “pillars” of MIPI interface performance in the mobile environment:

- **High performance.** MIPI specifications enable high-speed and low-latency transmission interfaces between components such as cameras and application processors. When system designers use MIPI interface specifications, they needn’t worry these interfaces will become performance bottlenecks that undermine the user experience.
- **Low power.** MIPI specifications are designed to be highly energy efficient, which is key to providing the long battery lives consumers demand in smartphones and wearables. For example, this commitment to low power has been a key enabler for IoT devices that rely on batteries lasting years, or more than a decade in some cases.
- **Low EMI.** The smaller the device, the less space between components, which translates into a higher risk of EMI which can undermine a device’s performance and reliability. MIPI interface specifications reduce EMI through a combination of factors, including low voltage swings on the high-speed PHYs; and critically supporting slew rate control on these interfaces allowing OEMs the flexibility to adjust the EMI profile within the end device.
- **Low pin count.** High performance per wire conductor allows the ecosystem’s chip, device and module manufacturers to minimize pin count, leading to fewer interconnections on chips, and across printed circuit board (PCB) traces. The resulting reduced complexity also reduces manufacturing costs, thus expanding the addressable market for devices, especially in the highly price-sensitive IoT space.

Of course, the overriding advantage of MIPI specifications is that of successful standardization developed within a vibrant ecosystem of interoperability, as well as backward compatibility and wide adoption supported by a future roadmap. Furthermore, within a given application area, MIPI protocols are organized in a layered fashion. For example, one protocol may lie above a physical layer interface and in turn have a command set above the protocol. Add in software and a family of debug tools, and MIPI implementations reduce design complexity and cost, simplify integration and speed time to market. Figure 5 illustrates the layered structure of the MIPI camera and display application stacks, with the CSI-2 and DSI-2 interface protocols that operate over the D-PHY and/or C-PHY physical layers. Above the protocol layers reside the command sets for camera (CCS^{SM}) and display (DCS^{SM}). The MIPI I3C interface serves as the Camera Control Interface.

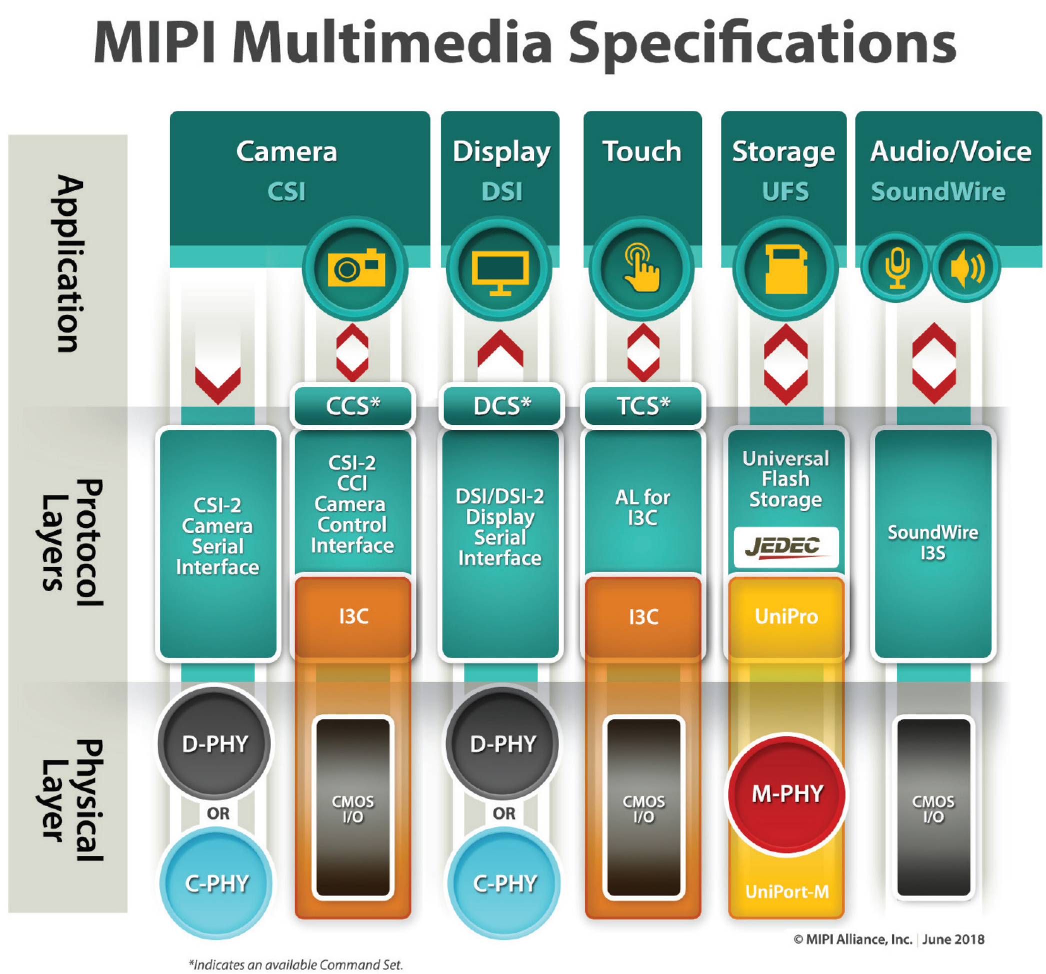


FIGURE 5

Illustration of the MIPI layered protocol approach for its "multimedia" applications

Source: MIPI Alliance

Already on the Road Today: MIPI in Automotive

In this section, and summarized in Table 1, we describe some of the key MIPI interface specifications that are being reused from the mobile ecosystem into automotive.

Given the development of MIPI Alliance's initial specifications for relatively small devices such as smartphones and tablets, it's clear that these interfaces are "short reach" and cannot be expected to traverse the length of a car, except for the new MIPI A-PHY specification in development. However, as Figure 1 has identified, these developments will be directly leveraged into the modular subsystems of the car, making them more valuable than ever. Specialized PHYs including A-PHY will support these longer distances and will generally carry the established mobile protocols, such as CSI-2 and DSI-2.

MIPI Specification	*Description*	*Automotive Use*	*Features*
CSI-2	Camera Serial Interface protocol	Protocol for cameras, lidar, radar sensors	• High pixel count • High frame rate • Functional safety • Transportable over A-PHY
DSI-2	Display Serial Interface protocol	Protocol for dashboard and rear displays and HUDs	• HD and beyond • High frame rate • Content protection • Transportable over A-PHY
C-PHY	3-phase physical layer for CSI-2 & DSI-2	Short-reach physical layer for cameras and displays	• High performance (Gbps), low power • Embedded clock • Symbol rate encoding
D-PHY	Differential physical layer for CSI-2 & DSI-2	Short-reach physical layer for cameras and displays	• High performance (Gbps), low power • Simple clock-forwarding • Differential signaling
I3C	Control and data bus protocol and interface	Sensor and general purpose data and control interface within a module	• High performance (10s Mbps) and low power relative to legacy interfaces • Multi-point • Transportable over A-PHY
RFFE	RF control protocol	Front end control within a wireless module	• High performance (10s Mbps), low power • Multi-point • Low latency
SoundWire	Digital audio and control interface	Audio interface within a module	• Simple, low cost • Multi-point • Flexible topologies
UniPro	Data transport protocol for UFS over M-PHY	Transport protocol for UFS storage	• High reliability and QOS via bit-rate monitoring
M-PHY	Differential physical layer for UFS storage	Short-reach physical transport for UFS storage	• High performance and low power • Full duplex (dual simplex)
A-PHY	Long reach physical layer for MIPI protocols, including CSI-2 and DSI-2	Long reach interface to cameras, lidar, radar, sensors & displays	• High performance • High noise immunity • Functional safety

TABLE 1
MIPI interface specifications for Automotive

Source: MIPI Alliance

MIPI CSI-2: The Camera, Lidar and Radar Interface

Since its introduction in 2005, MIPI CSI-2 has become ubiquitous in several industries. In automotive, it has been widely adopted as an interface for cameras, and increasingly for radar and lidar sensor subsystems. With support from the high-bandwidth D-PHY and C-PHY physical layers, and support from the A-PHY physical layer in development, CSI-2 supports a wide range of applications, resolutions, frame rates, color depths and high-dynamic-range capabilities with flexible-pin-count PHY configurations.

CSI-2 supports image sensors around the entire vehicle, including at the front for detecting pedestrians and other vehicles and on the sides for alerting drivers when they're drifting out of their lanes. Its support for RAW20-pixel format capability ensures highly nuanced image capture even when lighting changes suddenly and dramatically, such as when a vehicle exits a dimly lit tunnel into bright sunlight.

As shown in Figure 6, cars today may use more than a dozen different cameras, as well as radar and lidar sensors, all using the ubiquitous native CSI-2 interface. In addition to a camera in the rear for backing up, there may be a camera on each side of the vehicle to augment and eventually replace the side mirrors for blind spot detection and lane-keeping assistance. For automatic emergency braking or adaptive cruise control, there may be more cameras in the front of the car. Another camera-intensive application is self-parking, which can require up to six cameras in today's vehicles.

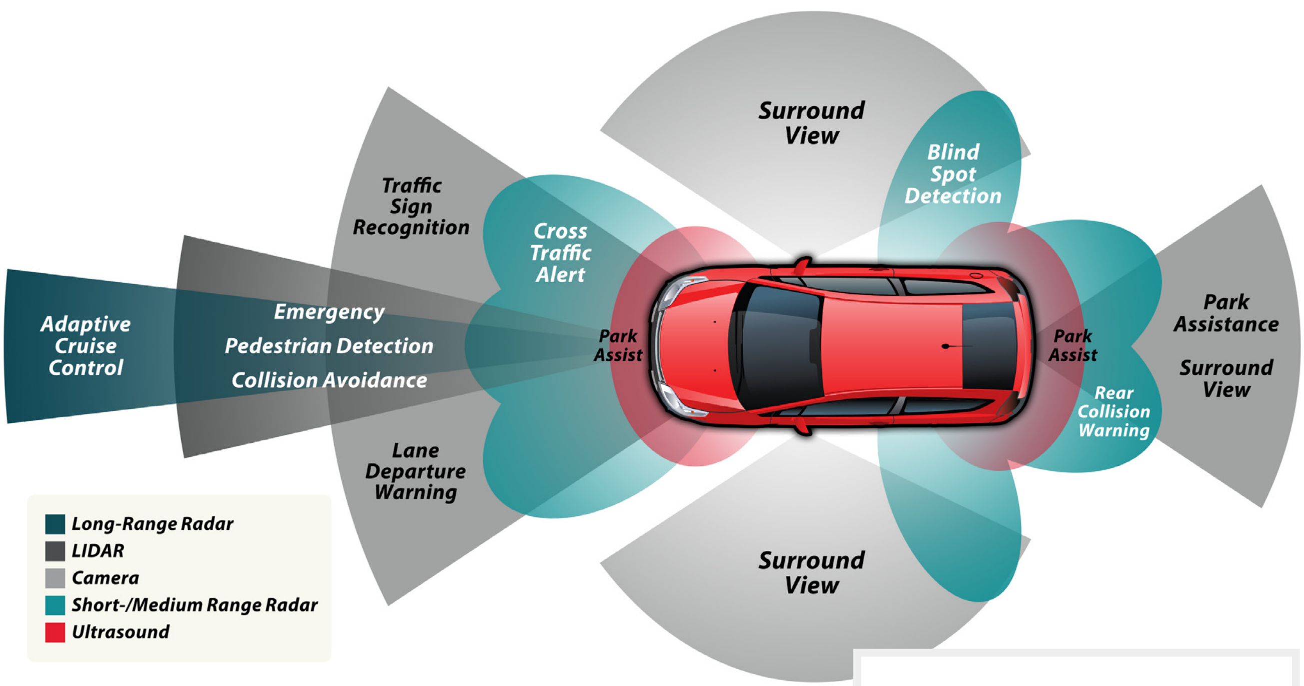


FIGURE 6

5 types of imaging sensors found in automobiles

Source: Michigan Tech Research Institute

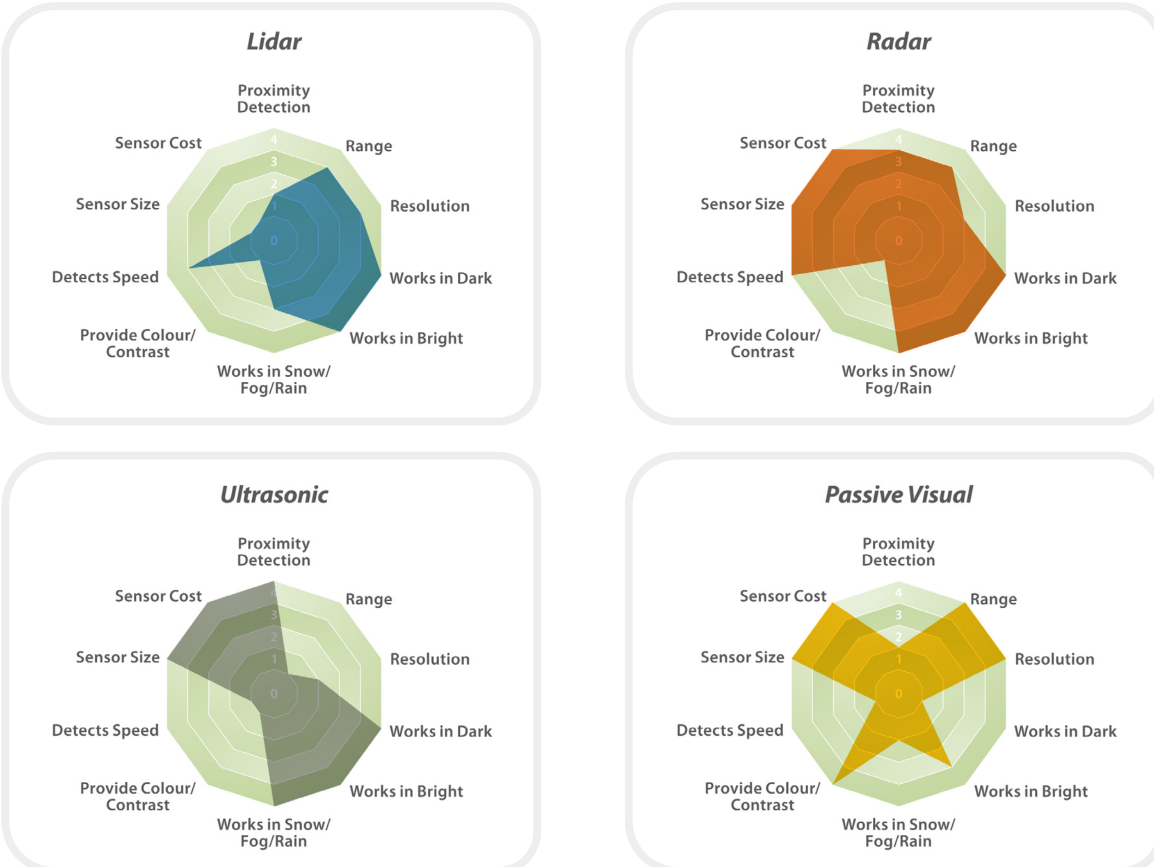


FIGURE 7

Spider diagrams showing strengths of various sensors found in automobiles

Source: www.cleantechnica.com

Figure 7 shows the various strengths of different types of automotive sensors. More than one type of sensor is needed for reliability, and often the sensors must be collocated to cover different ranges and speeds for high-speed driving, parking, stationary safety and collision avoidance.

In addition to a CSI-2 interface for each of these cameras, there may be additional CSI-2 interfaces for radar, lidar and other sensor systems. And as vehicle automation evolves toward Level 5 self-driving capability, the number of CSI-2 sensors could go much higher.

The CSI-2 protocol operates over the D-PHY/C-PHY physical layer interfaces described below. The established CSI-2 v2.1 specification continues its progression toward supporting higher performance cameras. In particular, it offers support for cameras with resolutions of 40 megapixels and up, video capture beyond 4K/120fps and 8K/30fps, and the RAW20 color depth format introduced to support advanced vision capabilities for embedded system cameras and autonomous vehicles. CSI-2 v2.1 also supports data compression using enhanced differential pulse-code modulation (DPCM) to compress data while preserving edge detection, which is applicable to vehicles driving in low light for functions such as road sign detection. The recently released CSI-2 v3.0 (September 2019) CSI-2 specification already includes specific features for automotive applications, including the following:

- Unified Serial Link (USL) with embedded control signaling, alleviating the need for additional I^2C control and GPIO wires.
- CSI-2 over C-PHY v2.0 imaging conduit, delivering up to 41.1 Gbps over MIPI Standard Channel using 3 lanes.
- CSI-2 over D-PHY v.2.1 imaging conduit, delivering up to 18 Gbps over MIPI Standard Channel using 4 lanes.
- Support for RAW20 color depth format.
- RFI mitigation via Pseudorandom Binary Sequence (PRBS) scrambling to alleviate interface power spectral density emissions, which may generate radio frequency interference with sensitive in-car radio devices.
- Smart Region of Interest (SROI), enabling individual sensor modules to identify objects locally without sending data to the ECU.

Today, CSI-2 underpins the higher data transfer rates of automotive cameras for ADAS, such as rear-view and surround-view assistance as well as collision mitigation and avoidance systems. Automotive SoCs ubiquitously support CSI-2 interfaces to receive the image data from multiple cameras distributed around the car, and the number of cameras and sensors on board is expected to escalate quickly.

Looking forward, MIPI CSI-2 v4.0, currently scheduled for release in early 2020, will add the following critical safety and security features:

- Functional safety to meet ISO-26262-2018 requirements for ASIL-B to ASIL-D (Automotive Safety Integrity Level) specifications.
- Imaging security with end-to-end data protection between camera and ECU.
- Ultra-Low-Power Always-On Sentinel Conduit (AOSC) mapped to a broad range of machine awareness applications.
- Discrete and integrated solutions using A-PHY for long-reach transport.

CSI-2 v4.0 will also enable the advanced, AI-powered vision capabilities necessary to make autonomous and semi-autonomous vehicles safe and practical. For example, interior cameras to detect drowsy or inattentive drivers represent yet another potential use of CSI-2.

MIPI DSI-2: The Display Serial Interface

The DSI interface, later updated to DSI-2, was initially developed in the mid-2000s to service smartphone displays with high resolution and high frame rate, yet low power consumption. Today, the DSI-2 specification is the display protocol utilizing either D-PHY or C-PHY to provide over 6 gigapixels/s of uncompressed image content for modern mobile, IT or IoT displays. As the payload of displays has increased, the carrying capacity of DSI-2 has also grown. This has been achieved through increasing the raw bandwidth of the underlying PHYs and introducing digital image compression or protocol efficiencies that remove video blanking, easily allowing for the attachment of multiple displays in a daisy-chain fashion.

The physical dimensions of automotive displays, their requirements and the number of displays in cars have increased significantly in the past few years. There are displays stretching across the entire front dashboard and large center console displays 18 or more inches across. The display resolutions for expansive panels will be tailored to the dashboard dimensions. In order to ensure high visual quality, economy and repairability, four or more displays may stretch across the front of a car, perhaps 1280 pixels to 4000 pixels each. The instrument cluster may contain multiple smaller displays, each fitting its purpose, such as the speedometer, trip odometer, temperature gauge or car operation and warning lights. When using DSI-2, a console maker can exercise design options to chain different displays in different sizes, with different pixel timing, into one set of signal wires from an automotive link. DSI-2 solved this challenge at its inception by introducing a display command mode. Using the command mode protocol, each command mode display in a console receives data packets timed to its own refresh rate.

As displays become more customized to the form factor of the car, they probably will not follow typical consumer electronics formats. Due to its long and successful history in the custom mobile market, DSI-2 is well-suited to serving specialized displays of different sizes and resolutions.

Visually lossless image compression has future-proofed DSI-2 in terms of data-carrying capacity by incorporating either the VESA VDC-M or VESA DSC standards in its transport layer. These codecs enable up to six times compression of the display payloads and give OEMs a better choice for high picture quality compared with sub-sampling techniques or reducing frame rate. For DSI-2 over A-PHY, plans call for support for both uncompressed and compressed payloads.

The DSI-2 protocol is pin efficient because of the in-band, asymmetric, half-duplex, D-PHY and C-PHY low-power escape mode for upstream communications. DSI-2 can communicate display integrity, status, data integrity and other information with no additional auxiliary channel (side band). The upstream communications in DSI-2 will also remain an important automotive protocol feature in automotive.

Automotive displays also take advantage of DSI-2's ability to support multiple smaller-screen displays that are stitched together in an instrumentation console, as shown in Figure 8.

FIGURE 8

Example of automobile multiscreen dash stitched together as single screen

Source: Stock Graphic

Automotive displays have unique requirements and will use features of DSI-2 not found in smartphones. These include functional safety capabilities, extra link integrity for safety applications and HDCP content protection. In particular, because premium content producers generally allow content to flow over a "standard interface" accessible to the user only if it is "content protected," enabling content protection across the A-PHY link is an important feature for consumers. Without the content protection feature on standard connectors, car repair or upgrades would be either more costly or impossible. Infotainment displays can be found in rear car seats for providing trip information or video entertainment. These displays provide video synchronized with audio played either through the car speaker console or through a headphone connection. The MIPI Alliance has auxiliary audio interface choices, such as SoundWire or SoundWire I3S, that accompany video over DSI-2 with host-synchronized audio programming.

The MIPI Alliance further created a MIPI Touch Framework for the ever-familiar touch capability needed by infotainment and center console displays. As with host-based audio synchronization, the local host processor synchronizes display updates with the touch prompts received through the MIPI Touch protocol and commands defined in an I3C sideband channel.

MIPI D-PHY & C-PHY: The Short-Reach Physical Interfaces for CSI-2 and DSI-2

MIPI Alliance has developed two physical layers (PHYs) for short-reach connections to CSI-2-based cameras and DSI-2-based displays: MIPI D-PHY and C-PHY.

MIPI D-PHY is based on the traditional two-wire differential signaling used in the industry for decades and was standardized and optimized for low power use with the CSI-2 and DSI-2 protocols. Its configuration is nominally four data lanes and one clock-forwarding lane on a 10-wire interface port. Some of the key attributes of D-PHY include a clock-forwarded synchronous link with high performance, high noise immunity and high jitter tolerance, with low-latency transitions between high-speed and low-power modes. For the MIPI "standard channel" definition, the D-PHY v2.1 interface supports up to 4.5 Gbps per lane or 18 Gbps with a four-lane (10-wire) interface port.

MIPI C-PHY was introduced after D-PHY and is based on an embedded-clock three-wire signaling method carrying 2.28 bits per three-wire lane, with a total of nine wires per port. Its multi-bit-per-symbol encoding results in a reduced symbol rate and the promise of higher performance over bandwidth-limited channels. Typically, one camera or one display connects to the nine-wire interface port, and a modern smartphone may support five cameras and two displays. For the MIPI "standard channel" definition, the C-PHY v2.0 interface supports up to 6 Gsps per lane at 2.28 bits per symbol (13.7 Gbps per lane), or 41.1 Gbps with a three-lane (nine-wire) interface port.

The D-PHY and C-PHY interfaces are illustrated in Figure 9 in the CSI-2 camera use case, where the transmitter in the camera sends CSI-2 format data to the receiver in the host application processor.

FIGURE 9

D-PHY and C-PHY lane configurations in the CSI-2 camera use case

Source: MIPI Alliance

The choice between D-PHY and C-PHY can be made by the silicon provider, the module provider, and/or the OEM. For applications that require an embedded-clock PHY or one that operates at a lower symbol rate, C-PHY is the most appropriate choice. For a conventional and simpler clock-forwarding architecture, D-PHY is most appropriate. These PHYs have been created so implementations can be pin-compatible in a dual-mode PHY for maximum design flexibility.

Over the years, the D-PHY/C-PHY roadmaps have been developed to support and anticipate requirements for the camera and display payloads. In 2017, MIPI collected historical data for smartphone camera and display payloads since MIPI's formation in pre-smartphone 2003, and used these to influence its camera and display specifications for 2020, including for the first automotive use cases. This data is shown in Figure 10.

This data illustrates a trend in which display payloads grew by about 10X every 5 years and camera payloads grew by about 5X every 5 years. A typical high-end smartphone display in 2017 supported "4K60" performance, measured by parameters such as 3840x2160-pixel resolution x 30 bpp (bits per pixel) x 60 fps (frames per second), requiring a 15 Gbps interface. At the time, the projected 2020 display would require an increase to "10K120" displays, with an interface supporting about 93 Gbps, largely driven by the AR/VR use case of a display worn close to a person's face with a display for each eye. Figure 10 also identifies the camera use cases, which require about half the interface bandwidth of displays. It also illustrates what was, at the time, the expected first-generation long-reach bandwidth of A-PHY at 20 Gbps. This is discussed later in the paper. The decision ultimately was made to set the bandwidth of A-PHY v1.0 at 16 Gbps.

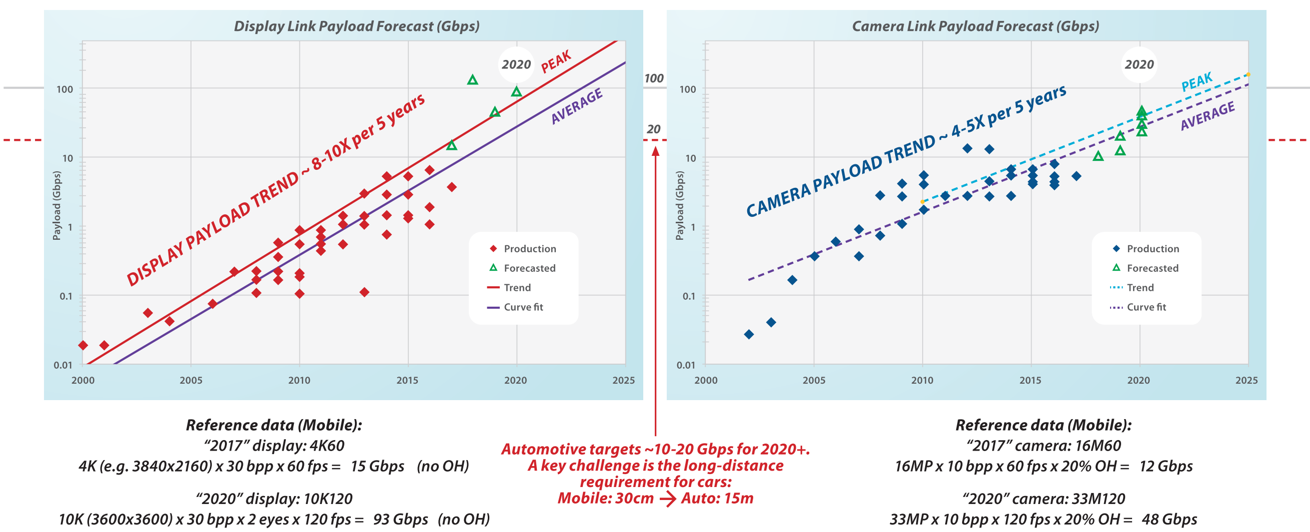


FIGURE 10

Display and camera payload forecast for smartphones and cars in early 2020s

Source: MIPI Alliance

While the short-reach distances of D-PHY/C-PHY in a smartphone do not typically extend beyond approximately 15 cm at the highest performance data rate, they can be readily implemented within the local domain of an automotive module or subsystem, such as within a camera or display module. For longer-reach connections involving meter to multiple-meter CSI-2/DSI-2 connections, such as between domains, system integrators currently must use “bridge solutions” or “bridges” to translate the D-PHY/C-PHY signaling to longer-reach PHYs, often based on low-voltage differential signaling (LVDS) technology. Such bridge solutions are shown in Figure 11 below. Although individual bridge functions are shown in Figure 11, many such bridge functions are combined into a single chip, such as in dual and quad hubs.

These bridge solutions enable long-reach connectivity, but the multitude of different and incompatible solutions in the marketplace cause confusion in the ecosystem, and in particular for the OEMs that must line up multiple camera and display vendors with their preferred LVDS provider(s). A long-reach standard was needed. For this reason, and with a view to the camera and display roadmaps on its horizon, MIPI Alliance started the development of its long-reach A-PHY specification with the promise of a single scalable solution for long-reach connectivity for its CSI-2 and DSI-2 protocols.

Finally, while D-PHY and C-PHY are usually described as “short reach,” as per the “15 cm” in smartphones and tablets, the most recent specification versions of D-PHY and C-PHY have developed modestly longer reaches of 1 m and beyond, with speeds that decrease with the longer reach. These longer reaches will mostly benefit those IoT applications that need beyond “15 cm.” Those applications such as automotive needing the 10–15 m reach may be served by A-PHY.

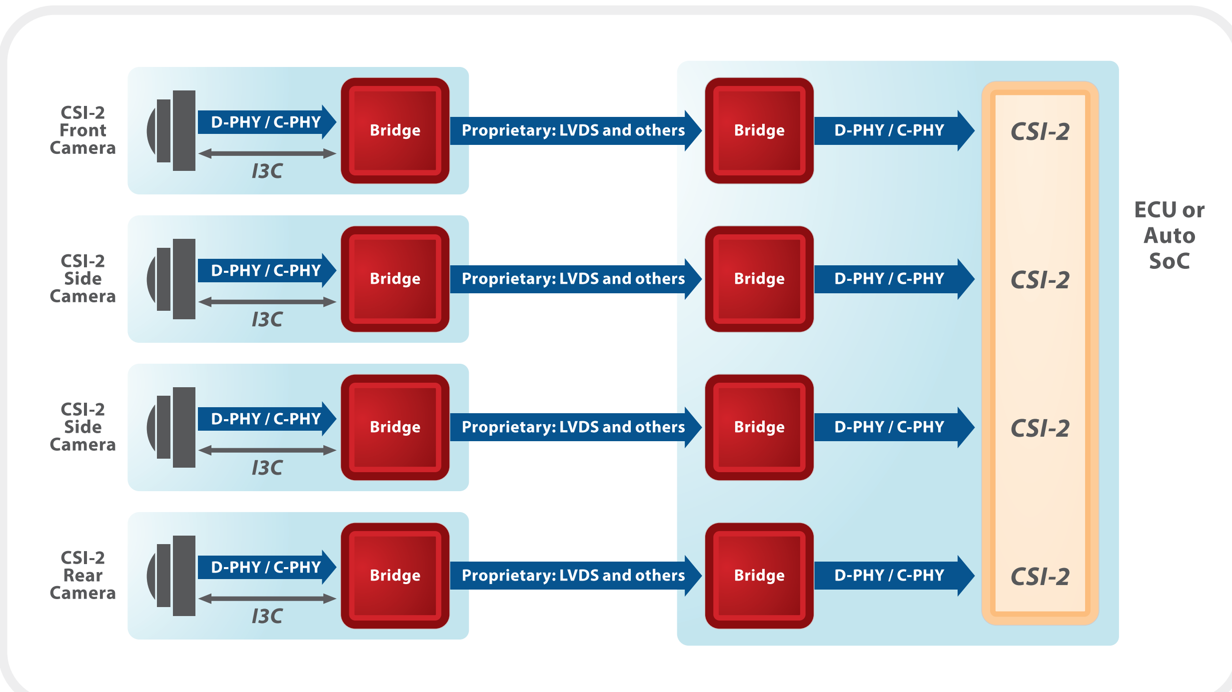


FIGURE 11

Current implementation of bridged D-/C-PHY using proprietary solutions

Source: MIPI Alliance

MIPI I3C: The Next-Generation Control Bus

MIPI I3C was developed as a performance, power and pin-count improvement on the decades-old and broadly used I²C interface, with the additional goal of displacing the SPI and UART interfaces whenever possible. While initially targeted as the interface for the many sensors in smartphones, I3C has gradually gained very broad functionality and serves as a general-purpose low-speed control bus or messaging interface. Over time, I3C also has gained broad acceptance in other markets, including automotive, as discussed below.

As shown in Table 2, I3C maintains compatibility with the two-wire multi-drop I²C interface but adds new functionality, including in-band interrupts, in-band command codes, dynamic addressing, and support for multiple classes of devices, including main and secondary master.

Two-wire communication interface, clock (SCL) and data (SOA)	
Number of gates	< 2000
Bandwidth	33 Mbps
Features	• In-band interrupts • In-band command codes • Dynamic addressing • Multi-master / multi-drop • Port-join support • Backward compatible with I²C

TABLE 2
MIPI I3C standardized interface at a glance

Source: MIPI Alliance

I3C uses an I²C-like interface with an open-drain data line (SDA) and a push-pull clock line (SCL), where the open-drain SDA line allows a slave device to take control of the interface to initiate an in-band interrupt, and the push-pull SCL line is driven by the master to clock the communication bus at frequencies up to 12.5 MHz. The ability of a peripheral device to gain the attention of the controlling master on the SDA line without using a dedicated signal line per device, as required in the I²C and SPI interfaces, is important. It results in cost savings of many pins and reduced complexity in the number of interfaces, PCBs and connectors.

The I3C master can dynamically assign 7-bit addresses to all MIPI I3C devices while supporting the static addresses of legacy I²C devices, ensuring full backward compatibility with I²C.

Operationally, a set of common command codes (CCCs) has been defined for the most often used operations, such as enabling and disabling events, managing MIPI I3C-specific features including dynamic addressing and timing control and others. These CCCs can be broadcast (sent to all devices) or directed at a specific device on the bus.

The I3C interface represents a shift in power performance while providing greater than an order of magnitude improvement in speed compared with I²C. It offers four data transfer modes that, on the maximum base clock of 12.5 MHz, provide a raw bitrate of 12.5 Mbps in the baseline SDR (standard data rate) default mode and 25 Mbps, 27.5 Mbps and 39.5 Mbps, respectively, in the HDR (high data rate) modes. Excluding transaction control bytes, the effective data rates achieved in each mode are 11.1 Mbps, 20 Mbps, 23.5 Mbps and 33.3 Mbps, respectively. These rates are protected by I3C's basic error detection mechanisms. Figure 12 illustrates the energy consumption per bit of the various MIPI I3C modes compared with I²C (left), and the corresponding raw bitrates for each (right), demonstrating that MIPI I3C is a more power-efficient interface even in its I²C-compatible mode.

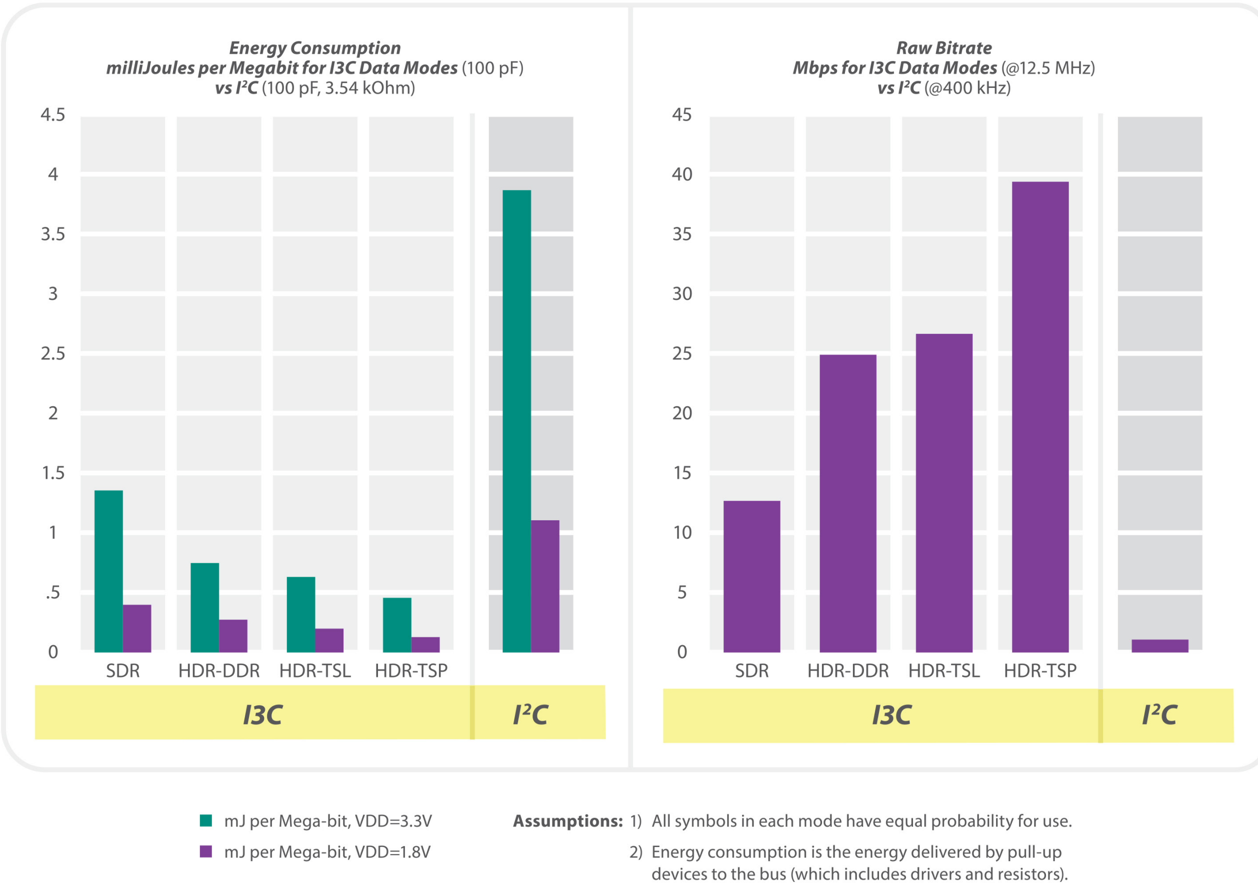


FIGURE 12

MIPI I3C vs I²C: Energy consumption and raw bitrate

Source: MIPI Alliance

In smartphones, sensor peripherals such as accelerometers, gyroscopes, magnetometer compasses, proximity and ambient light sensors, and other components connect to the central application processor. In automotive, there is a different and even larger variety of sensors, including engine speed, pressure, temperature and seat and window controls.

The automotive sensors, such as pressure, air flow, temperature and crash detection often are widely distributed around a car. These sensors require long-distance connections where digital sensor interfaces SENT and PSI5 are used. Other groups of sensors are often localized within a module and can consist of several to dozens of sensor connections. Today these sensors may be connected via SPI or I²C within a module. I3C's virtues of higher performance, lower latency, lower energy per bit, lower pin count through in-band interrupts and the flexible multi-drop configuration across multiple sensors make it as highly valued in automotive as it is in smartphones.

Figure 13 below shows an example of a module-based architecture where the physical sensor and a set of slaves is located within an ECU. Figure 14 shows an example of the preferred simplified architecture for the use of MIPI I3C in an automotive module.

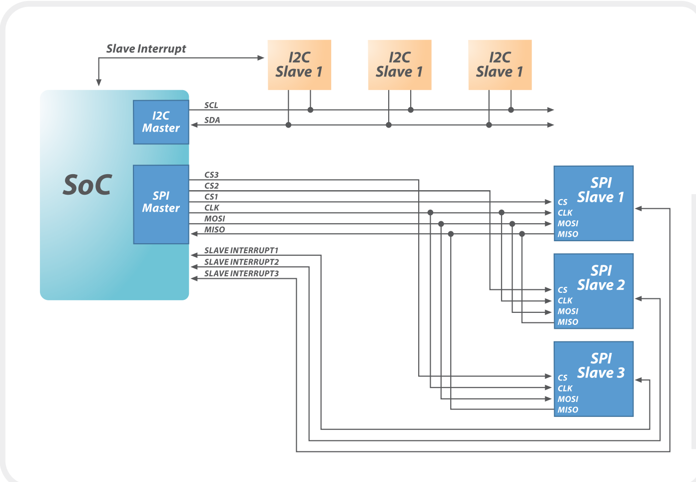


FIGURE 13

Sensor module example using IMU and ECU

Source: MIPI Alliance

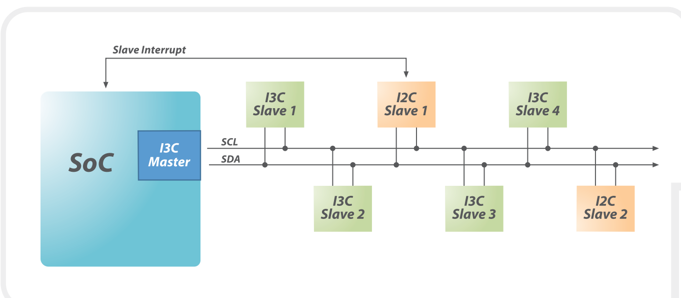


FIGURE 14

Sensor module architecture using MIPI I3C

Source: MIPI Alliance

In this architecture, MIPI I3C is an ideal interface for reliable and low-cost connectivity between the module's sensor and slaves inside an ECU. For automotive applications such as imaging that require sensor data rates much higher than that of MIPI I3C, MIPI I3C can be used for control and management of the sensor. The faster MIPI CSI-2 interface can be used to transport the high-speed data via D-PHY/C-PHY over short distances or A-PHY over long distances. In this case, the two MIPI interfaces work collaboratively to provide a reliable and well-managed camera and control functionality.

MIPI RFFE: Wiring the Front End

MIPI RFFE is a dedicated control interface for the RF front-end module (FEM) or subsystem of a smartphone, consisting of power amplifiers, antenna tuners, filters, low-noise amplifiers (LNAs) and switches that connect to the modem baseband and/or the RF integrated circuit (RFIC) transceiver. The RFFE control interface has essentially replaced generations of proprietary and less capable (often point-to-point) interfaces to front-end components, thus simplifying the design, configuration and integration of an increasingly complex RF front end consisting of multiple aggregations of RF bands and channel combinations. Automakers and suppliers will continue to leverage these advancements.

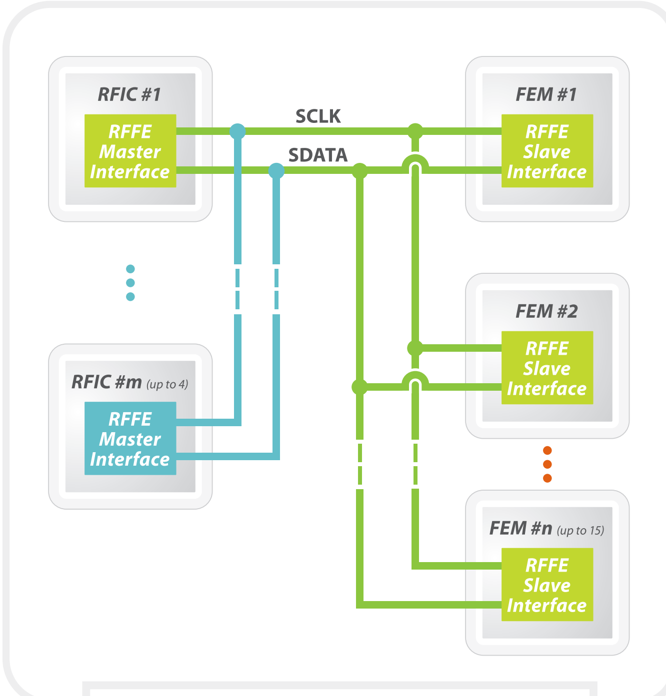


FIGURE 15
MIPI RFFE multi-master control of front-end module (FEM) peripherals

Source: MIPI Alliance

RFFE consists of a two-wire SDATA and SCLK bus interface, which is deployed as a multi-point, multi-master topology as shown in Figure 15, where RFICs control FEMs consisting of the discrete components identified above (tuner, filter, etc.).

In preparation for the increasingly complex 5G cellular designs, the RFFE specification has added capabilities to improve flexibility in controlling the front end. One feature of RFFE v2.1, known as Master Context Transfer (MCT), enables rapid transfer of information between masters so control information can be quickly transferred to an alternate master. Another new capability in MIPI RFFE v2.1 is the masked write command sequence, which enables a transceiver's software to control individual aspects of programmable content in a front-end device. This feature addresses increasing hardware complexity by giving software developers more flexibility in how they apply configuration changes. MIPI RFFE v2.1 also extends the trace lengths of RFFE buses, up to 45 cm from the standard 15 cm. This enhancement reflects how cellular, Wi-Fi and other wireless technologies are increasingly used in more than just smartphones. A longer bus gives system designers more flexibility for devices such as laptops, where the antenna may be up in a corner of the lid and the transceiver may be underneath the keyboard.

As the requirements of 5G RF front-ends continue to evolve, the RFFE Working Group is developing RFFE v3.0, incorporating many new features focused on those needs. In particular, RFFE v3.0 will address devices that operate in the traditional sub-6 GHz cellular bands, where many of the earlier deployments of 5G are expected to be concentrated. MIPI RFFE v3.0 will also seek to improve throughput and latency to help ensure devices utilizing RFFE can provide the high-performance RF capabilities at the core of critical consumer and business features. In one example, the Timed Trigger feature planned for RFFE v3.0 configures a device such as a low noise amplifier (LNA) to quickly switch among or be triggered by different frequency bands, with fine time coordination, to allow for reception of data from several bands essentially at the same time. Timed triggers allow for synchronized transmission and reception on different bands, whereas slower, non-synchronized command implementations cannot do this effectively.

As the automotive industry prepares cars to be essentially “smartphones on wheels,” with full 5G cellular connectivity, it is expected that RFFE will continue to be used in front-end control applications within a module. Future versions beyond RFFE v3.0 also are expected.

MIPI SoundWire: Wiring for Audio Performance

While visual information plays a critical and growing role in vehicle operation and the in-car experience, audio is also important. MIPI SoundWire consolidates key attributes of mobile and PC industry audio interfaces that have migrated to automotive. It supports fully digital, multi-stream, multi-channel audio with advanced capabilities over a two-wire multi-drop interface. The existing SoundWire specification is designed for systems that deliver audio and control data over a wire length of up to 50 cm, so it’s best suited to audio endpoints within that distance from the SoC, such as in the infotainment center or next to displays.

In a car where the driver is on a hands-free conference call, the front passenger is watching news and children in the back are watching cartoons, it might be useful to have “directional speakers” to create personal audio zones with less interference to others in the car. This is available with the proper audio algorithms operating over MIPI SoundWire, which enables playback with continuous monitoring of interference so the audio algorithm can adjust sound levels and directions in real time.

In keeping with the move toward pin-count reduction, MIPI SoundWire includes embedded command and control, which eliminates the need for other interfaces such as I^2C or SPI. To help decrease power consumption, it includes clock-stop modes to save power during idle periods.

At the time of writing, MIPI is developing an evolution of SoundWire known as SoundWire I3S using a differential PHY. The benefits of the differential PHY include operation over longer distances to support larger devices or modules, such as in automotive, and to lower the EMI emission relative to single-ended interfaces based on SoundWire when a connection is placed near sensitive receiving devices such as antennas.

Storage Solutions: MIPI UniPro and MIPI M-PHY in UFS

As the capabilities of ADAS and ADS expand, the need for storage with higher performance and lower power consumption will grow. Universal Flash Storage (UFS), a JEDEC Solid State Technology Association specification, has emerged as an ideal standard for data storage in vehicles. UFS is already widely used for storage in smartphones and tablets, digital cameras and other consumer electronics, bringing higher data transfer speed and increased reliability to flash memory storage.

Infotainment and navigation are the major drivers for high-performance in-vehicle data storage. Given that advanced connected cars can collect more than 1 GByte of data per second, transmitting all that data to cloud servers and back is generally ineffective and inefficient, so a storage and compute subsystem at the edge, on board the vehicle, solves the processing challenge. These systems will become even more important with the transition from ADAS to semi-autonomous and autonomous driving, especially with the use of HD maps across all cities visited on a journey.

As shown in Figure 16, a UFS host device connects to the UFS storage device via the M-PHY interface. M-PHY is a differential signaling interface operating over discrete gears of operation and up to four lanes. M-PHY can also operate without the discrete reference clock and reset signals as shown in Figure 16, which is the desired UFS configuration. UFS 3.0 operates at M-PHY Gear 4, for 11.6 Gbps per lane, or 23.2 Gbps per direction, with up to two lanes. UniPro is the transport protocol for UFS storage. One of the UniPro v1.8 features that most benefits automotive applications is its ability to continuously monitor the symbol error rate of forward and reverse links, as well as receiver performance, enabling it to "retrain" the communication channel dynamically. This feature updates link settings if needed to ensure a link delivers the same reliability and quality of service (QoS) at higher data speeds—both of which are crucial to automotive, as systems are subject to highly variable and sometimes extreme temperature conditions.

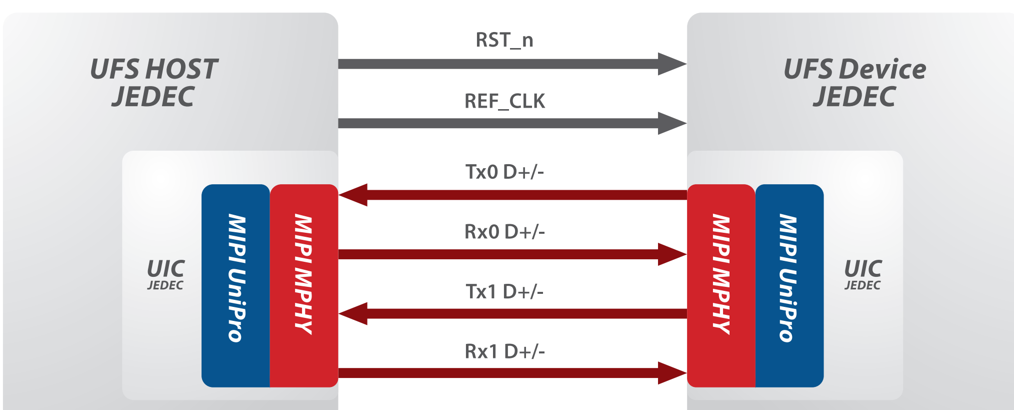


FIGURE 16

JEDEC UFS using MIPI M-PHY and MIPI UniPro

Source: MIPI Alliance

A-PHY: Solving the Long-Reach Challenge in the Stringent Automotive Environment

MIPI Alliance is collaborating with leading automotive companies to develop the first generation of A-PHY, a standardized and robust long-reach automotive interface for camera/imaging and display systems using the near-ubiquitous MIPI camera and display protocols. A-PHY is being developed as an asymmetric data link in a point-to-point topology, with high-speed unidirectional data, embedded bidirectional control data, and optional power delivery going over a single cable. It will support both coaxial cables up to 15 m and shielded differential pair (SDP) cables, each with up to four inline connectors. A-PHY will allow the automotive industry to more fully realize the benefits of implementing MIPI specifications for a multitude of automotive use cases. It is also expected that A-PHY will find other long-reach applications beyond automotive, such as IoT and industrial applications.

A key application for A-PHY is to support the camera and imaging sensors and other surround sensors, including lidar and radar, for ADS and ADAS. A-PHY will also support the increasingly large and high-resolution infotainment displays in the center console and passenger seats, as well as other display applications, such as digital rearview mirrors and rear-seat displays.

Before A-PHY becomes available, current automotive solutions that connect cameras to ECUs, and ECUs to displays, generally all use the MIPI CSI-2/DSI-2 protocols but are unable to use the MIPI D-PHY/C-PHY interfaces due to their limited reach. As a result, integrators must rely on "bridge" solutions to convert D-PHY/C-PHY to and from a proprietary long-reach PHY to recreate the native D-PHY/C-PHY interfaces that most automotive suppliers use today. This configuration is shown in Figure 11.

A key issue in today's implementations is that there is no single standard for this long-reach PHY, resulting in a level of complexity and confusion in the automotive ecosystem. Further, the use of a bridge transmitter chip (TX) followed by a bridge receiver chip (RX) requires these two additional chips, which adds cost, weight, power consumption and potential points of failure. The goal of A-PHY is to create a single standardized solution for long-reach automotive that directly and efficiently carries the MIPI CSI-2 and DSI-2 protocols. This has two benefits:

1. In the short term, bridge chip providers can focus on the single long-reach PHY standard A-PHY to reduce complexity and cost in the ecosystem. See Figure 17.
2. In the long-term, the endpoints, such as cameras, SoCs and displays, can natively support the integrated A-PHY and eliminate the bridge chips. See Figure 18.

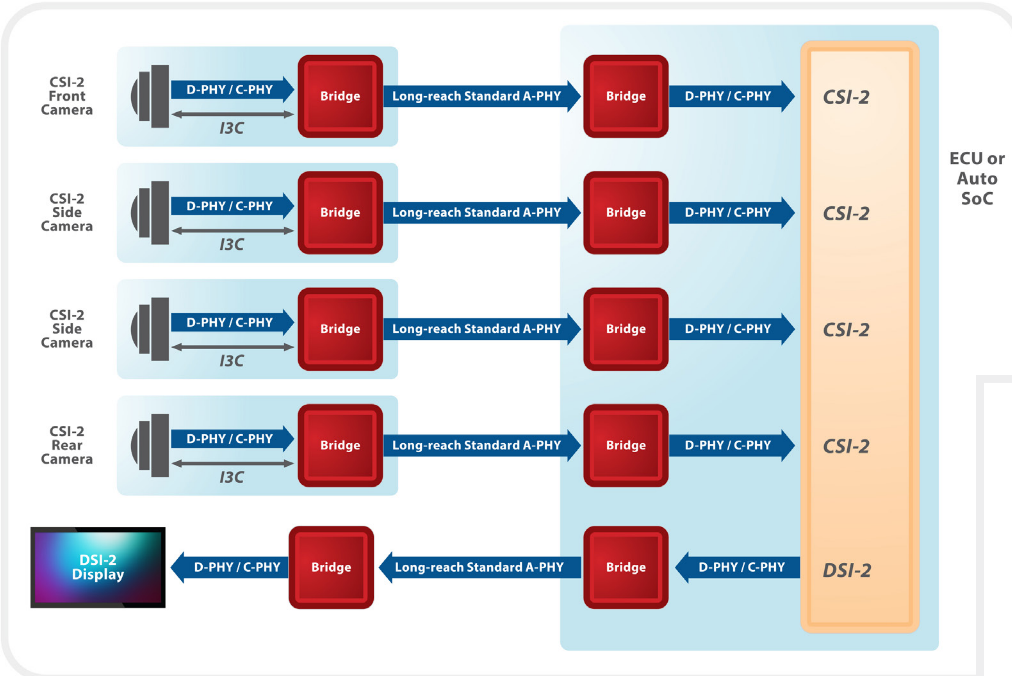


FIGURE 17
Bridge chip solutions for automotive long reach to benefit from a single MIPI A-PHY specification

Source: MIPI Alliance

Figure 18 illustrates the simplest direct connection between an A-PHY-equipped image sensor and an A-PHY-equipped ECU or automotive chip. Elimination of the bridge chips at each endpoint will reduce cost, cable weight, power consumption and latency, and improve reliability.

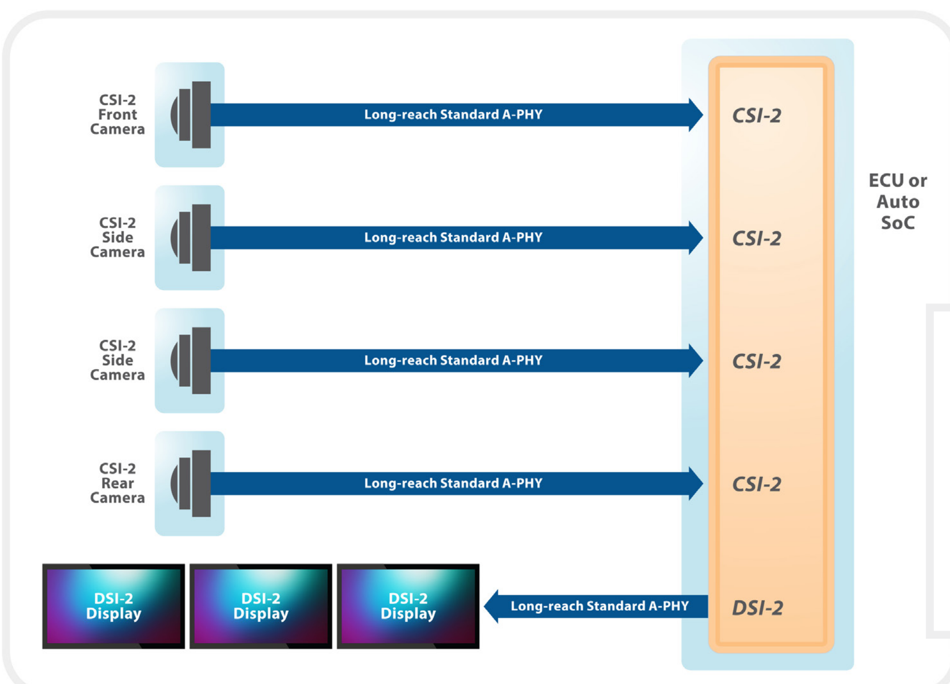


FIGURE 18
Native MIPI A-PHY integration in the endpoint devices, eliminating bridge chips

Source: MIPI Alliance

A-PHY v1.0 will support up to 16 Gbps data rate over distances up to 15 m, with a roadmap vision to support 48 Gbps and beyond for camera, display and other use cases, such as multiple cameras or display links that are aggregated into a higher-speed link. When complete, A-PHY will serve a broad spectrum of long-reach, high-speed connectivity needs.

To accomplish these objectives, A-PHY is being developed with two profiles or modes of operation:

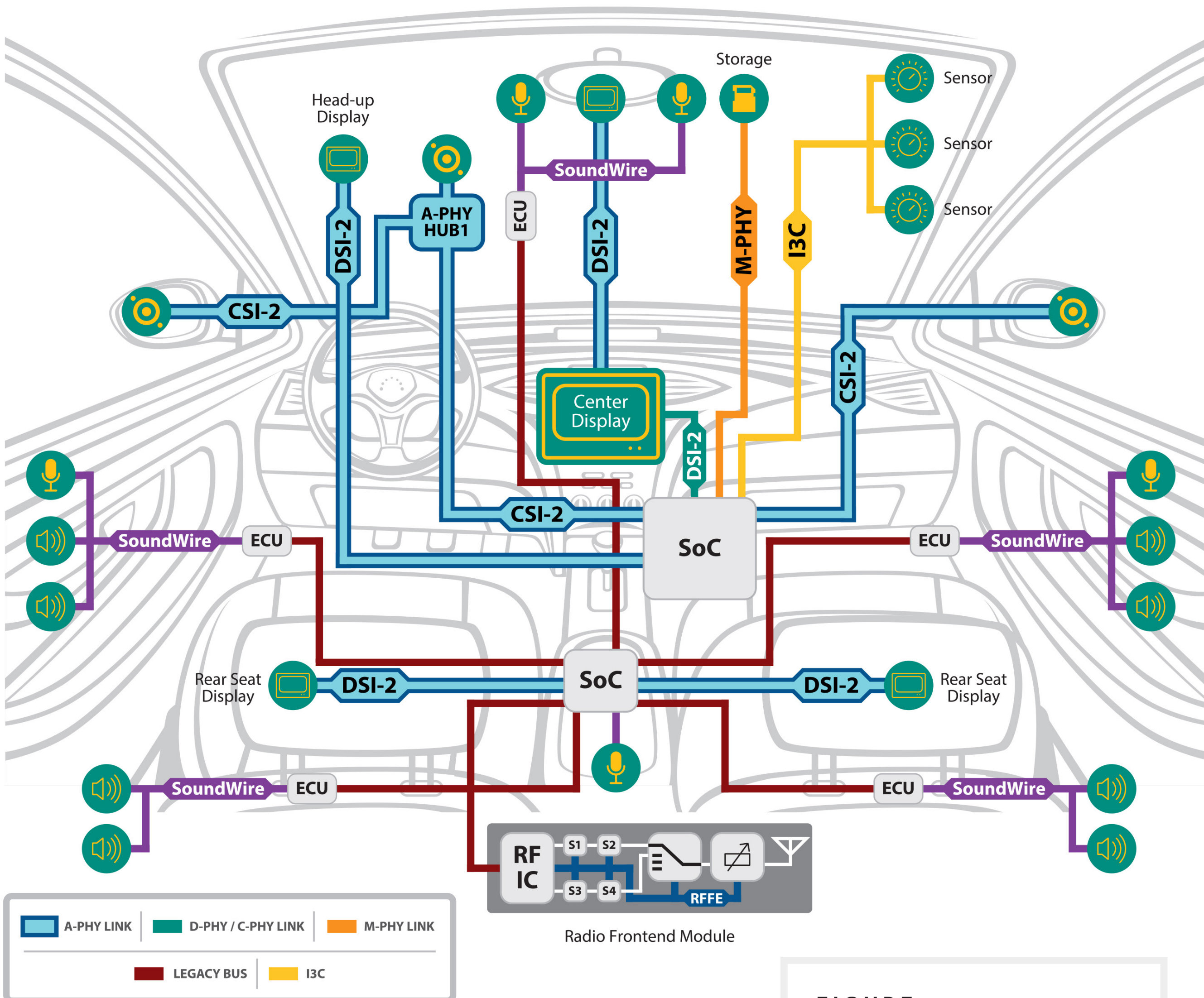
- Profile 1 will be based on NRZ-8b10b encoding and focused toward lower speed applications to meet the desire for a lowest-cost, low-design-complexity solution that simplifies implementation and speeds time to market. Its expected upper speed may be about 8 Gbps at 15 m.
- Profile 2 can be used for all speeds and provides A-PHY with a clear roadmap to increased speeds for those automotive performance-critical applications that require it. This profile will be based on a robust PHY-level retransmission scheme (RTS) with narrowband interference cancellation (NBIC).

The two profiles will have at least one common speed gear to ensure interoperability, while providing the automotive ecosystem with implementation choices spanning performance, cost and complexity.

A-PHY will perform the role in automotive that C-PHY and D-PHY play in mobile today, providing the high-speed connectivity to sensors and cameras in the vehicle where the flow of data is primarily from the sensor or camera to a central high-performance processor in an ECU. A-PHY will also be applied to display connectivity, which demands ever-increasing video resolutions to support next-generation in-vehicle infotainment applications, including the use of displays to replace internal and rearview mirrors.

Figure 19 illustrates the reuse of MIPI protocols over short distances using the mobile implementations, and over longer distances using A-PHY.

Automotive Infotainment System Diagram



Radio Frontend Module

FIGURE 19
Automotive system diagram with optimized MIPI asymmetric architecture

Source: MIPI Alliance

A-PHY Key Technical Advantages

Key technical advantages of A-PHY include:

- **Asymmetric-optimized architecture.** A-PHY is designed from scratch for high-speed asymmetric-only transmission from cameras/sensors to ECU, and ECU to display, while providing concurrent low-speed bidirectional traffic for command and control. The optimized asymmetric architecture allows for design simplification and lower cost than other/symmetric architectures.
- **Mobile protocol reuse.** After successful deployment in billions of smartphones and IoT devices, the MIPI protocols are well-proven for direct leverage into automotive.
- **Hardware-only protocol layers.** As in mobile applications using D-PHY/C-PHY layering, A-PHY is tightly coupled with the CSI-2/DSI-2 protocol layers, thus essentially operating with hardware-only protocol layers without software intervention. This architecture is contrasted to other interfaces that are designed with more flexibility and utilize software layers to accomplish this flexibility.
- **Optimized architecture for wiring, cost and weight.** Due to A-PHY's optimized asymmetric architecture and hardware protocol layering, A-PHY implementations meet optimized cabling wiring, cost and weight requirements. This is increasingly important as the number of electronic components and their interface cabling increases on the road to autonomy.
- **Flexible link-layer support of other protocols.** MIPI Alliance expects to work with other organizations that are leveraging their native protocols into automotive. This includes VESA, which is adapting its DisplayPort protocol specification for automotive use. To accommodate these developing specifications, A-PHY includes a generic Data Link Layer that accommodates different protocol adaptation layers, with a plan to support VESA's Vehicular DisplayPort protocol.
- **High EMC Immunity.** MIPI has invested significantly to analyze and measure the harsh automotive channel and has concluded that an architecture based on a Narrowband Interference Canceller (NBIC) and Retransmission Scheme (RTS) provides the most robust performance, particularly for the applications requiring the higher data rates at longer distances.

Other key A-PHY attributes include the following:

- **Complementary coexistence with automotive Ethernet.** Recognizing that IEEE 802.3ch Ethernet is an emerging network backbone for symmetric control and coordination of information among control elements in a car, A-PHY and automotive Ethernet will coexist in many implementations. Figure 20 illustrates the concurrent use of asymmetric and symmetric data flows and interfaces.

- **Support for two common cable types and power over data line.** As required by the automotive industry, A-PHY will accommodate two cable types: a single-ended coax interface (Coax) and a shielded differential or parallel pair (SDP, SPP) that also includes shielded twisted pair (STP). The choice of cable type is dictated by specific OEM requirements or preference, hence both are supported. A-PHY also supports power over data line to eliminate the need for separate power cabling.
- **Daisy-chaining and stream duplication features.** Daisy-chaining enables the connection of multiple cameras or displays via a single link to/from an ECU. Stream duplication can be exploited for redundancy, such as in functional safety applications.

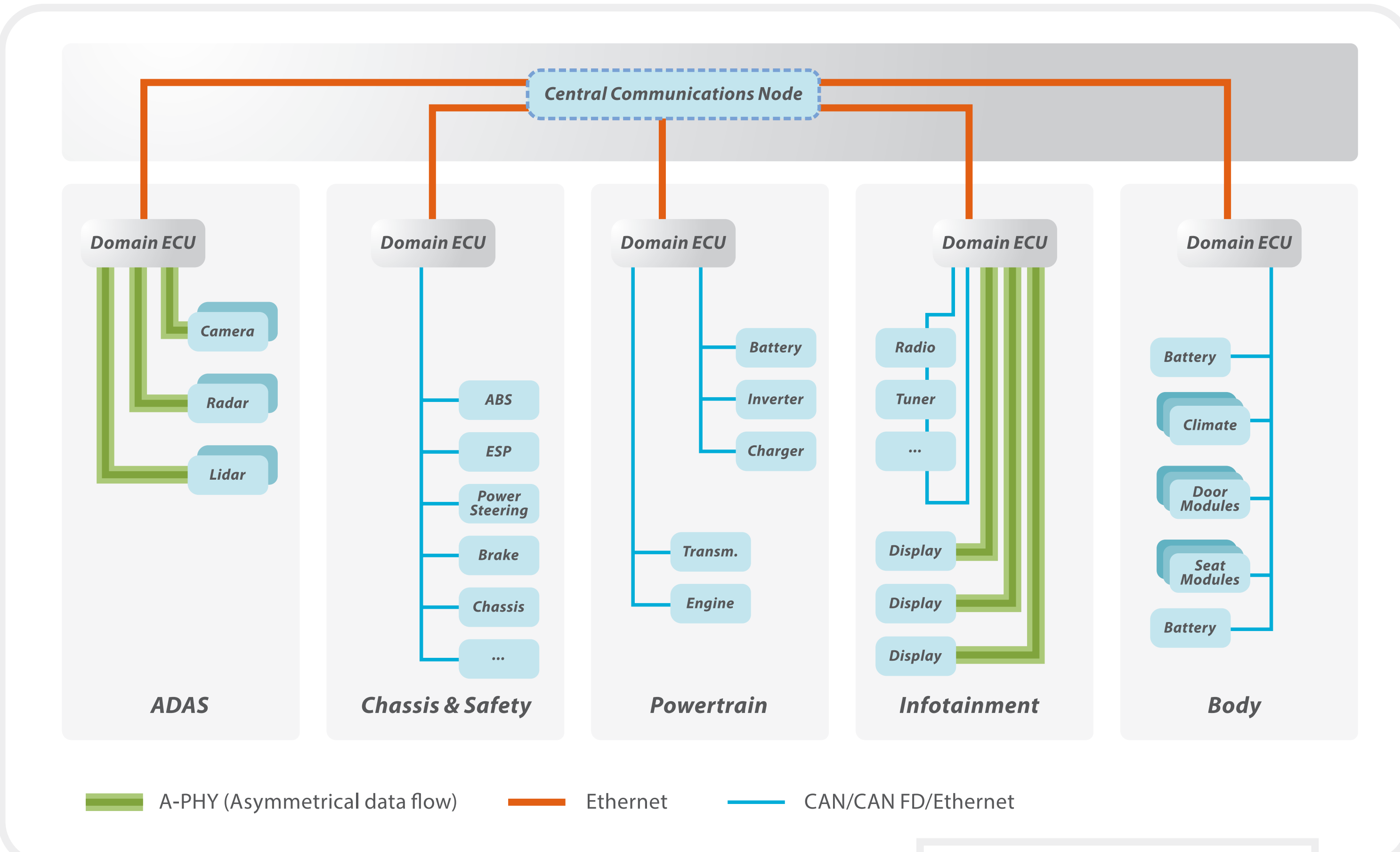


FIGURE 20
Symmetric and asymmetric automotive data flows

Source: MIPI Alliance

Conclusions

Virtually all MIPI Alliance interfaces will continue to be leveraged in mobile-influenced spheres including automotive, although most are limited to short-range connectivity within "modules" or "subsystems" with dimensions comparable to mobile smartphones or tablets. While the Alliance is supplementing its mobile protocols to satisfy automotive requirements such as functional safety to further increase the leverage of its protocols, it is also developing the long-range A-PHY with initial focus on the CSI-2 and DSI-2 protocols used for autonomous driving and advanced infotainment.

A-PHY v1.0 will support up to 16 Gbps data rate over distances up to 15 meters, with a roadmap to support 48 Gbps and beyond, while maintaining backward compatibility with earlier versions. The A-PHY v1.0 specification is expected to be released to developers in early 2020, with a draft specification available to MIPI Alliance Contributor members in late 2019.

By developing a unified A-PHY specification for long-reach asymmetric point-to-point communications in the automobile, it is expected that, as MIPI Alliance contributed to the early mobile phones in the mid-2000s, A-PHY implementations in the automotive ecosystem will lower costs through economies of scale, reduce time to market, and accelerate the road to autonomous driving. The A-PHY specification, consistent with all MIPI specifications, will be available to MIPI members on a royalty-free basis.

mipi® alliance

Driving the Wires of Automotive

MIPI specifications in automotive and the A-PHY solution

October 2019