# Making the 5G Vision a Reality:

# *A 5G Readiness Assessment of MIPI Specifications*

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# 1 Introduction

## 1.1 Purpose

The MIPI Alliance's mission is to develop the world's most comprehensive set of interface specifications for mobile and mobile-influenced products. MIPI Alliance has always been at the forefront of defining state-of-the-art, low-power interfaces to support the key subsystems in advanced mobile platforms. These interfaces are largely invisible to consumers and other end users because they're internal, such as between a device's application processor and its camera and display. But these interfaces play a crucial rule in enabling the applications and experiences that people expect from smartphones, tablets and other mobile devices.

Today, virtually every 4G device uses MIPI interfaces. This white paper describes how existing MIPI specifications are capable of supporting the first generation of 5G smartphones, as well as additional, emerging 5G mobile platforms, including connected/autonomous/semi-autonomous vehicles and Internet of Things (IoT) devices.

This 5G readiness is based on two factors:

- The MIPI specifications discussed in this paper meet all of the industry's bandwidth, performance and feature requirements through 2021 and beyond.
- Several major vendors are already using these MIPI specifications for their first-generation 5G smartphones.

One goal of this paper is to foster industry discussion about how existing MIPI specifications can be enhanced, and new ones developed, to enable the 5G devices, applications and use cases that will emerge over the next decade. To learn more about MIPI in 5G and to become involved, visit **mipi.org**.

## 1.2 Scope

This document focuses on evaluating each relevant MIPI specification from the perspective of applications in the 5G mobile platforms, such as 5G smartphones. It examines the typical 5G mobile system architecture; evaluates key interface attributes such as performance, latency and power; and analyzes each MIPI specification's general readiness to deploy in 5G mobile platforms.

This paper also discusses emerging 5G use cases. However, 5G's implications for some mobile-influenced areas, such as automotive, wearables and IoT devices, are not completely known at this time. They will be evaluated and addressed in future MIPI papers. Please refer to Section 5 References for more information about 5G network technologies, emerging use case examples and industry trends.

## 2 5G Basics and Main Use Cases

**By 2021, mobile data traffic will exceed 48 exabytes (EB) worldwide per month, a sevenfold increase from 2016, according to Cisco's Visual Networking Index (VNI).** One reason is because people are increasingly using smartphones, tablets and other mobile devices to watch videos, post on social media and do other things that once were done on PCs over wired connections. Another reason is the rise of the Internet of Things (IoT), a sprawling category of applications that includes smart utility grids, smart cities, autonomous vehicles, public safety and telemedicine.

**These two trends are why between 2016 and 2021, mobile traffic will have a compound annual growth rate (CAGR) of 46 percent, which will be more than double the CAGR for fixed IP networks, Cisco's VNI predicts.** Fifth-generation (5G) cellular will both accommodate and enable that growth by supporting faster speeds, lower latency and greater scalability than 4G, also known as Long Term Evolution (LTE).

For example, 5G will support peak data rates of 20 Gbps, so it could accelerate the cord-cutting trend by giving consumers a new way to watch streaming video services such as **DIRECTV NOW**—including bandwidth-intensive 4K and 8K. This bandwidth also is ideal for connected car applications, such as the high-definition (HD) maps that autonomous and semi-autonomous vehicles will rely on. **An HD map for a single neighborhood can be as much as 1 TB**, so a vehicle traveling through a metropolitan area would need to download several maps per trip.

Standards work on 5G began in 2012, and **the initial two versions were completed in late 2017 and early 2018**. **AT&T** and **SK Telecom** are among the dozens of mobile operators worldwide trialing 5G and, in some cases, planning to launch commercial service by late 2018. The trials and standards work have progressed so quickly and so well that in early 2018, some analyst firms doubled their 5G forecasts. **CCS Insight, for example, expects roughly 60 million 5G connections worldwide by 2020, 280 million by 2021 and 2.7 billion by 2025**.

### 2.1 Eight Ways 5G is Superior to 4G

Figure 1 compares 5G (also known as International Mobile Telecommunications 2020) with 4G (also known as IMT-Advanced) in eight key areas. As the figure shows, 5G is superior in every category, including ones that consumers and businesses will notice. In fact, almost all user-experience-related metrics, such as throughput, have at least an order of magnitude (10X) improvement with 5G.

Other metrics are less noticeable to end users but just as important. For example, 5G uses spectrum more efficiently, which is key because it's in chronically short supply worldwide. **By 2020, countries in the Americas region, for instance, will need up to 1161 MHz of additional spectrum to meet demand, according to a GSMA-commissioned study**. Even if regulators could free up that amount—which is more than double what most countries have licensed to mobile over the past 40 years—each operator still would have to pay billions of dollars, euros or yuan for the additional licenses. So by using spectrum more efficiently, 5G helps operators both meet demand and manage their overhead cost of delivering services.

Another example is speed though not in terms of data rates. 5G supports connections when the user device is moving at up to 500 km/h. This capability is crucial for connected car applications, as well as vehicles traveling at even higher speeds, such as bullet trains.

### 2.1.1 Data Rates: Gigabit Peaks and Per-User Speeds of 100 Mbps

3GPP Release 15 (Phase 1) defines a peak 5G New Radio (NR) data rate of up to 5 Gbps, while Release 16 will support a peak data rate up to 20 Gbps. In everyday, real-world environments, each user could reasonably expect outdoor speeds of about 100 Mbps and 1 Gbps or more indoors, where 5G would be aggregated with Wi-Fi to create a fatter “pipe.” Figure 2 illustrates how 5G speeds are expected to evolve over the next several years.

The bottom line is that these per-user speeds are sufficient for bandwidth-intensive applications such as HD video. Streaming 4K TV services, 4K telemedicine and 4K video surveillance are examples of how 5G enables applications and use cases that are difficult or impossible with 4G. Another example is enabling fast downloads of HD maps to thousands of connected vehicles in a city simultaneously.

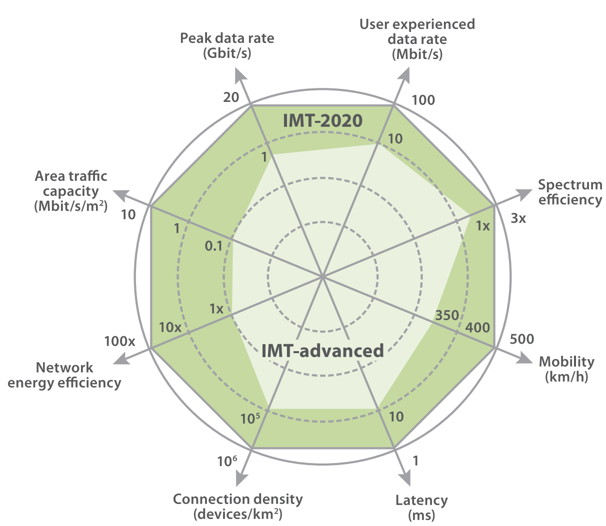



**FIGURE 1**

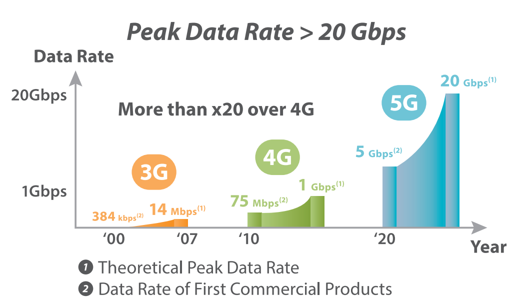
*Comparing 4G (IMT-Advanced) and 5G (IMT-2020) in Eight Key Areas*

Source: Recommendation ITU-R M.2083

**FIGURE 2**

*Expected Peak Data Rates*

Source: Samsung Electronics



### 2.1.2 Ultra-High Device Density for IoT

The initial versions of 5G were developed at the same time IoT started to become a phenomenon. **Over 8 billion IoT devices were in use worldwide in 2017, up 31 percent from 2016, and the total will exceed 20 billion by 2020, Gartner says**. Although many IoT applications are low bandwidth, the sheer number adds up to an enormous traffic load for mobile networks. Unlike 4G, 5G was designed from the ground up to shoulder that load alongside traffic from non-IoT applications, such as smartphones.

For example, 5G supports up to 4 devices/m$^2$ with a throughput of 30 Mbps per device. In a high-density environment, such as a downtown business district or a smart city, 5G supports up to 200,000 devices/km$^2$ with each device getting up to 300 Mbps download speeds and 60 Mbps uploads. 5G also supports 1 million devices/ km$^2$, an emerging use case referred to as massive IoT (mIoT) or massive Machine-Type Communications (mMTC).

### 2.1.3 Ultra-Low Latency

5G has a latency target of 1 msec, which has multiple components and interpretations. In 5G standards, latency is defined as the round-trip time it takes data to traverse the 5G network, where the latency goal is under 4 msec for enhanced mobile broadband (eMBB) applications and 0.5 msec for mission-critical applications.

Figure 3 illustrates these latency targets. To achieve 1 msec end-to-end latency, the combined radio interface and the user interface latency should not exceed 0.5 msec. Meeting these targets enables 5G to support highly delay-sensitive applications such as telemedicine and mission-critical use cases such as public safety. These often are referred to as Ultra-Reliable, Low-Latency Communications (URLLC) applications.

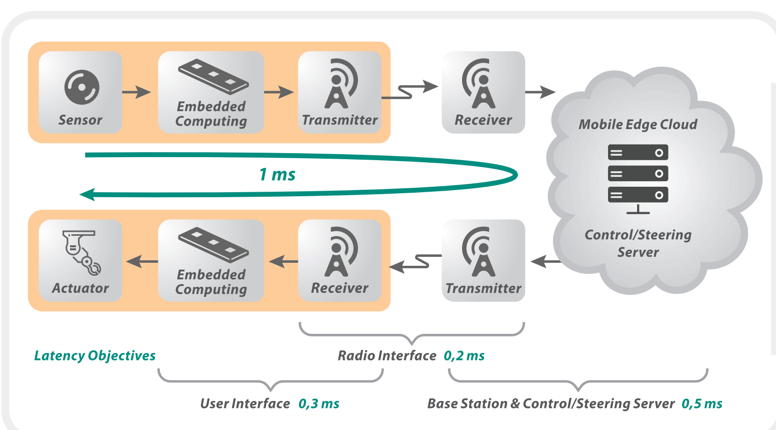



FIGURE 3
*Latency Budget for an Example Tactile Internet System*

Source: I. Riedel, G. Fettweis

## 2.2 5G Enables New Use Cases for Mobile, Automotive and More

### 2.2.1 5G Application Areas

Although capabilities such as ultra-low latency and ultra-high device density make 5G ideal for IoT applications, the new standard will spend its first few years powering smartphones. That focus is largely because the smartphone market is enormous and because consumers typically replace their device roughly every two years. Another reason is that as Figure 4 shows, smartphones will continue to drive the majority of mobile data traffic through at least 2022, and 5G gives operators new, much-needed capabilities for keeping up with that demand. Finally, most IoT applications are highly price-sensitive, and it will take several years for 5G to ride down the cost curve to the point that its modules are competitive with 4G versions.

As 5G smartphone adoption ramps up beginning in 2019, it will help drive the buildout of 5G networks, setting the stage for IoT applications to begin migrating to 5G sometime after 2020. Even in developed countries, 5G will take several years to achieve geographic coverage on par with 4G. But consumers, businesses and government agencies can begin buying and using 5G devices because the technology is backward-compatible with 4G. So when users are in areas where 5G hasn't been deployed yet, their devices can still use **LTE, which many operators will continue to expand and enhance through at least 2022**.

*Smartphones will continue to drive the majority of mobile data traffic through at least 2022, and 5G gives operators new, much needed capabilities for keeping up with that demand.*

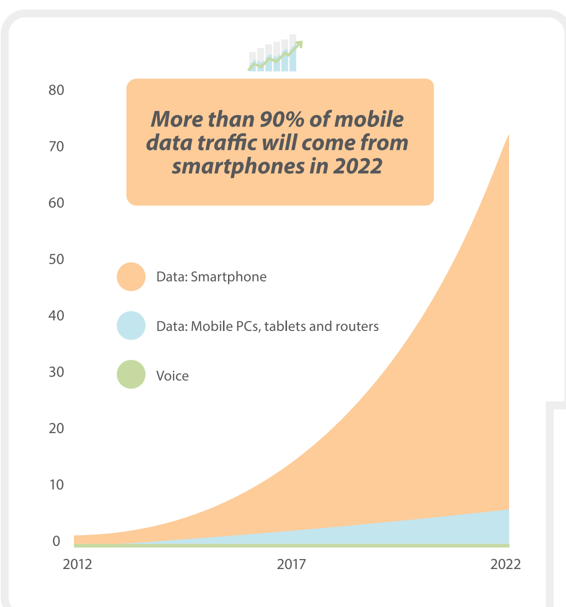



**FIGURE 4**
*Global Mobile Voice and Data (Exabytes/Month) 2012 to 2022*

Source: Ericsson Mobility Report, June 2017

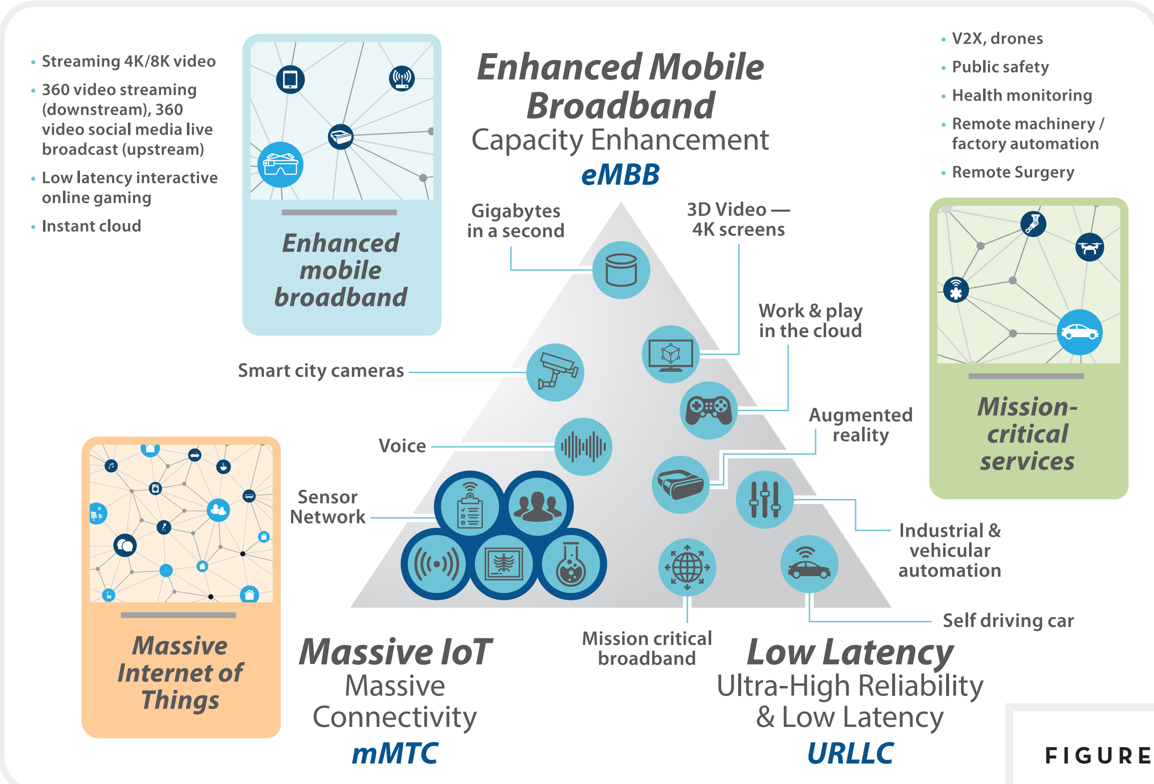



FIGURE 5

*5G Use Cases*

ETRI graphic, from
ITU-R IMT 2020 requirements

Figure 5 provides a representative sampling of near- and long-term applications that 5G will enable. These can be grouped into three categories: eMBB, mIoT/ mMTC and URLLC.

## 2.2.2 Enhanced Mobile Broadband (eMBB)

Most eMBB applications and use cases center around people and involve video, such as 3D, 4K, augmented and virtual reality (AR/VR), and often combinations of those technologies. For example, multiple gamers in different parts of the world could use 5G-powered VR headsets to play against one another in immersive environments, or 5G-powered AR glasses that leverage the real world as part of a multi-player game. Another example is fans at a football game watching replays in 4K 3D on their smartphones, as a live feed from the player's perspective generated by a camera mounted in the quarterback's helmet.

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### 2.2.3 Massive Machine-Type Communications (mMTC)

This application area is mainly for a very large number of connected devices typically transmitting a relatively low volume of non-latency-sensitive data. The devices are expected to be low cost and support a very long battery life—at least 10 years.

Energy efficiency is key for enabling IoT applications—such as smart grid monitoring and control—where it would be time consuming and cost prohibitive to replace batteries on tens or hundreds of thousands of devices in the field every few years. Low cost, meanwhile, makes large-scale deployments financially viable and in turn ensures that the business or organization is able to collect enough data to make informed decisions.

### 2.2.4 Ultra-Reliable, Low-Latency Communications (URLLC)

These applications have very strict requirements for throughput, latency and availability. Some involve humans, such as telemedicine and autonomous vehicles—two use cases that highlight the life-and-death aspects of throughput, latency and availability. Other applications center entirely around machines, vehicles and sensors, such as real-time traffic management systems that use artificial intelligence.

## 2.3 MIPI Alliance: Enabling 3G, 4G and Now 5G

**MIPI Alliance was founded in 2003**, right as 3G networks and devices were making their commercial debut in Europe and other parts of the world. Over the past 15 years, MIPI Alliance has played a fundamental role in enabling the applications and services that use 3G and 4G. For example, the first MIPI interface provided connectivity between application processors and cameras and displays, thus enabling the first camera phones and virtually every one since.

For example, **over four years ago, MIPI Alliance released specifications that support 4K displays and high-performance cameras** for applications such as smartphones and **connected vehicles**. At the time, 4K displays were rare, as were mobile networks capable of delivering video of that quality. So these specifications also are an example of how the MIPI Alliance has a long history of anticipating the marketplace's needs years in advance so systems designers have the necessary interfaces for developing tomorrow's solutions when they're ready.

Systems designers use these and other MIPI specifications extensively for their 3G and 4G devices, so there's no learning curve to implement them in their 5G solutions. That's a prime example of how MIPI Alliance will help systems designers get their 5G products to market quickly and cost effectively. In fact, as of summer 2018 at least four major vendors were already using MIPI interface specifications for their initial 5G smartphones.

Another reason why MIPI specifications are ready to meet the first wave of 5G deployments is because they have a foundation in four "pillars" (Figure 6) that will be as valuable tomorrow as they are today:

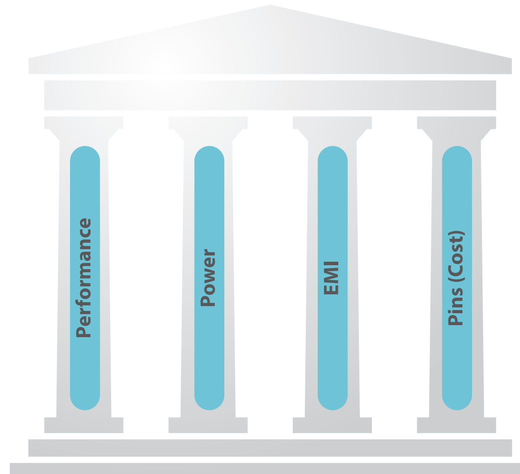



FIGURE 6

*The Four "Pillars" - Key Attributes of MIPI Specifications*

Source: MIPI Alliance

- **High performance.** MIPI interfaces provide high speed and low transmission latency between components such as application processors and cameras. By using MIPI specifications, systems designers don't have to worry that interfaces will become bottlenecks that undermine the user experience. High performance is particularly important for 5G devices because users will expect them to be significantly faster and more responsive than 4G and 3G models.

- **Low pin counts.** High performance is one way that MIPI specifications are designed to minimize pin counts. For example, high performance in the MIPI PHYs, and efficient protocols in the low-speed MIPI I3C and VGI interfaces, minimize pin count in both APs and peripherals. Fewer pins enable smaller devices and fewer interconnections on chips, printed circuit board (PCB) traces and connectors. Less complexity also reduces device costs, giving them a bigger addressable sales market—especially in the highly price-sensitive IoT space. From a competitive perspective, these savings also are valuable for smartphones and other consumer devices because for the first few years, 5G will carry a price premium simply because it hasn't spent a decade riding down the cost curve like 4G has.

- **Low power.** MIPI specifications are designed to be highly energy-efficient, which is key for providing the long battery lives that people want from their smartphones and wearables. For example, MIPI interfaces reduce EMI through a combination of factors including low voltage swings on the high-speed PHYs (C-PHY, D-PHY, M-PHY), accommodation of the 1.2V level in all low-speed CMOS interfaces (such as RFFE and I3C), where levels are currently at 1.8V, and critically supporting slew rate control on these specifications. MIPI's commitment to low power also complements features in the 5G standards that are designed to maximize battery life—potentially beyond a decade in the case of some IoT applications such as remote sensors.

- **Low electromagnetic interference (EMI).** The smaller the device, the less space there is between components. That close proximity means a higher risk of EMI, which can undermine a device's performance and reliability. MIPI specifications are designed to meet stringent requirements for EMI, which has been a key concern for 3G and 4G. EMI is an even bigger concern with 5G simply because it uses far more spectrum bands than 3G and 4G, and far more Tx/Rx paths, so there are more opportunities for interference.

# 3 MIPI Specifications are 5G Ready

This section reviews the MIPI interface specifications that a typical high-end 4G LTE smartphone currently uses (Note: MIPI has **other specifications**, but only those most applicable to 5G readiness are discussed in this paper). In mid-2018, several major vendors had begun using MIPI specifications for their initial 5G smartphones. This section also discusses the MIPI Alliance roadmap for providing additional features to further enhance the performance and user experience to meet the next phase of 5G requirements.

## 3.1 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.

Figure 7 is a high-level system diagram of an example 5G smartphone. This section explores where MIPI interfaces fit into this design.

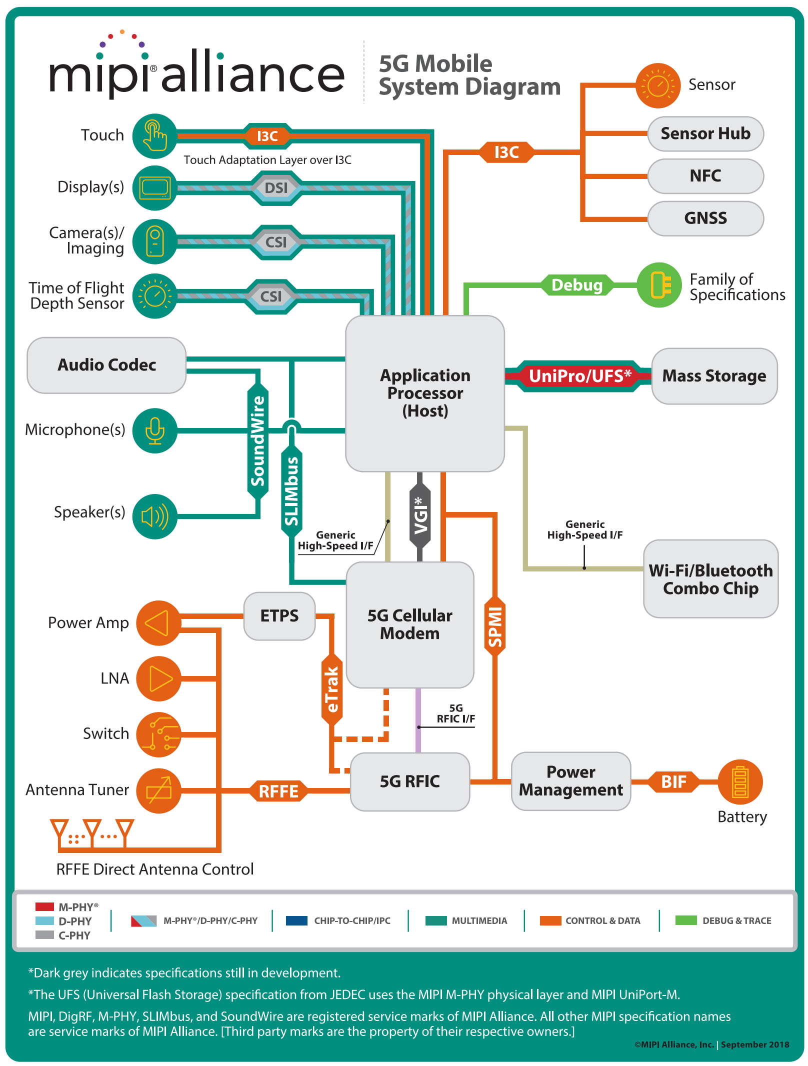



**FIGURE 7**
*5G Mobile System Diagram*

Source: MIPI Alliance

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.

Table 1 summarizes the MIPI specifications, whose features, advantages, 5G phase 1 readiness and future roadmap plans are discussed later in this section.

| ***Application Area*** | ***MIPI Specification/Interface*** |
|---|---|
| ***Audio*** | SLIMbus |
| | SoundWire |
| ***Camera and Imaging*** | CSI-2 (Camera Serial Interface) |
| ***Display*** | DSI-2 (Display Serial Itnterface) |
| ***Physical Layers*** | D-PHY, C-PHY for camera and display |
| | M-PHY for UniPro/UFS |
| ***Control and Data*** | RFFE (RF Front-end Control Interface) |
| | I3C (Improved Inter Integrated Circuit) |
| | VGI (Virtual GPIO Interface) |
| ***Storage*** | UniPro for support of UFS flash storage |
| ***Debug*** | Full family of Debug specifications |

### 3.1.1 MIPI SLIMbus and SoundWire: Rich, Immersive Audio and Lifelike Calls

The MIPI Audio Working Group defines two specifications: MIPI SLIMbus and MIPI SoundWire. These interfaces simplify the integration of multiple audio components in a wide range of platforms, including smartphones, PCs, connected vehicles, wearables and IoT devices.

MIPI SLIMbus is designed primarily for transporting audio between larger components. Figure 8 illustrates examples such as modems and application processors interfacing with peripherals such as Bluetooth, FM and audio subsystems/codecs.

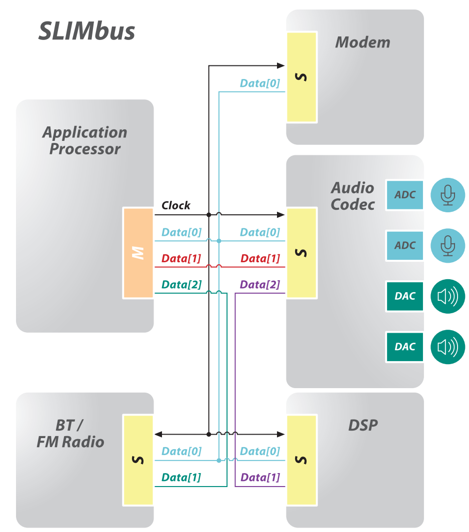



FIGURE 8
*Example of SLIMbus Implementation*

Source: MIPI Alliance

SLIMbus v2.0 is a two-wire, multi-drop, TDM interface that supports multi-master and multiple devices. It employs CMOS I/O running in single data rate (SDR) up to 28MHz, with fixed frame size, support master and clock hand-over capabilities for low-power operation. SLIMbus v2.0 also supports multiple multi-channel, high-quality audio streams, phase coherence to enable stereophonic sound, microphone arrays and other compelling features. It also supports scalable bandwidth up to eight lanes per device for a peak aggregated bandwidth of up to 224Mbps.

MIPI SoundWire is a complementary specification to MIPI SLIMbus. Introduced in 2014, SoundWire consolidates the key attributes in mobile and PC industry audio interfaces and provides a common, scalable architecture that can be used to enable comprehensive audio features in multiple types of devices across market segments.

MIPI SoundWire is a unified interface designed primarily for small audio peripherals. It is optimized for low-complexity, low-gate-count designs to support the use of cost-sensitive audio components such as digital microphones, digital speakers and advanced amplifiers in mobile handsets. In addition, it can optimize speaker protection, microphone power and performance, noise cancellation and "always-listening" audio input.

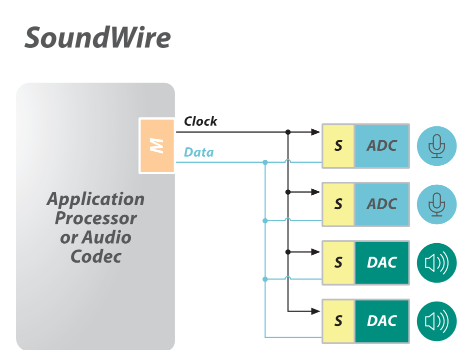



FIGURE 9
*SoundWire Typical Use Case*

Source: MIPI Alliance

SoundWire shares many SLIMbus features. SoundWire v1.1 also employs CMOS I/O and supports up to 11 slave devices, multi-channel audio, PDM format and in-band control/interrupts/wake. However, it runs in double data rate (DDR) mode up to 12.288MHz (up to 24.576 Mbps), and supports configurable frame size and enhanced low latency protocol. Optional multi-lane extensions up to eight data lanes are available to support high-end audio applications. For example, eight-channel 192 KHz 24-bit audio requires 8 * 24 * 192000 = 36.864 Mbps, which would require two or more lanes, while it may operate at a lower frequency to optimize for power accordingly.

Figure 9 shows an example of an application processor directly connecting to multiple digital microphones and speakers over SoundWire. This is a typical use case.

MIPI SoundWire and MIPI SLIMBus can operate collaboratively in a system through bridging solutions, enabling a flexible yet sophisticated audio system for mobile or mobile-influenced platforms. Figure 10 shows an example.

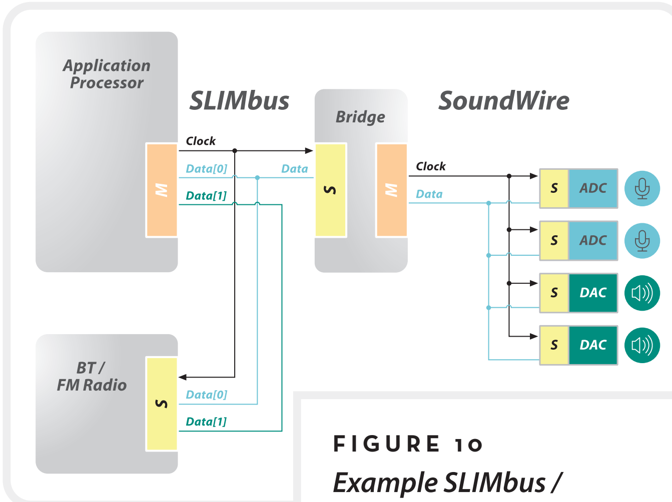



FIGURE 10
*Example SLIMbus / SoundWire Bridging Solution*

Source: MIPI Alliance

**IN BRIEF:**

*MIPI SLIMbus and SoundWire are ready to support the first generation of 5G smartphones. SLIMbus is a mature specification with mature audio components, and deployed in advanced smartphones and mobile-influenced platforms. SoundWire is rapidly gaining momentum as an enabler for digital microphones and speakers in high-end smartphone platforms. Both SLIMbus and SoundWire are expected to be deployed in the first wave of 5G smartphones that come to market between late 2018 and late 2019.*

### 3.1.2 MIPI CSI-2: 4K and 8K Video with High Frame Rates and High Color Depth

MIPI CSI-2 is the primary camera interface in virtually all 4G LTE smartphones and is already being used in the first wave of 5G smartphones. MIPI CSI-2 specifications support flexible mobile design with multi-cameras, depth/time-of-flight (ToF) and face-detection sensors. Today's high-end and mainstream 4G smartphones support up to two rear-facing sensors, and a few models have three. Tomorrow's 5G devices will have two-sensor with Tele+Wide, Color+Mono, Main+Depth sensors, or the aforementioned two-sensor + Eye / Face detection / ToF sensor in three-camera configurations. All of these implementations can be supported by MIPI CSI-2 coupled with MIPI D-PHY or C-PHY physical layers.

CSI-2 v2.1 over C-PHY v1.2 delivers up to 8.0 Gbps (3.5 Giga symbols per second, or Gsps) with embedded clock and data over three wires per lane, and supports lane expansion (up to 24 Gbps with three C-PHY lanes using nine wires). CSI-2 also supports D-PHY v2.1 delivering up to 4.5 Gbps with forwarded clock and data over four wires and supports data lane expansion (up to 18 Gbps using 10 wires).

The main camera in 4G smartphones is currently 12-16MP, with some models as high as 40MP. With 4K/30fps video capture now common, 4K/120fps and 8K/30fps video capture are likely to become available around 2021. CSI-2 v2.1 can already support these high resolutions and frame rate combinations, even with high-color depth RAW20 (8K x 30fps x 20 bit/RAW pixel = 20 Gbps). They also are well within the capabilities of the next-generation CSI-2 and C-PHY/D-PHY data rates.

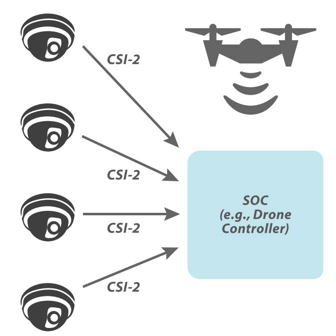



**FIGURE 11**

***Multi-Camera Drone Application***

Source: MIPI Alliance

But CSI-2 is more than simply resolution, frame rate and bandwidth. The MIPI Camera Working Group continues to drive advanced features to enhance emerging 5G use cases such as AI/machine vision, AR/VR and connected vehicles. These advanced features include:

- Latency reduction transport efficiency (LRTE) to reduce transport latency, facilitate real-time perception, processing and decision-making; and optimize transport efficiency to reduce the number of wires, toggle rate and power.
- Eye tracking (AVRET), camera-to-camera sync, camera-display sync for AV/VR applications.
- Smart regions of interest (SRoI) to enable distributed- and hybrid-vision architectures.
- USL (Unified Serial Link) to help facilitate native long-reach support for IoT product platforms.
- RAW 12-10-12 compression/decompression reduces bandwidth while delivering superior signal-to-noise ratio (SNR) images devoid of compression artifacts for mission-critical vision applications.
- RAW-16, RAW-20 and RAW-24 color depth for superior image quality that vastly improves intra-scene high dynamic range (HDR) and SNR for high quality imaging and can bring "advanced vision" capabilities to autonomous vehicles and AI systems.
- Enhanced CCI (Camera Control Interface) and CCS (Camera Command Set) supporting I2C FM+ and MIPI I3C SDR and HDR_DDR modes for higher throughput, lower latency camera control.
- Scrambling and SSC (spread spectrum clocking—MIPI D-PHY only) to reduce power spectral density (PSD) emissions and minimize radio interference.

## Beyond Smartphones: Drones, IoT, Automotive and More

MIPI CSI-2 supports a wide array of low-cost and high-quality image sensors at different resolutions, frame rates, quality and color depths. This combination of selection and capabilities makes it a popular choice for what's sometimes referred to as "mobile++" devices. Examples include AR/VR headsets, drones (Figure 11) and IoT endpoints.

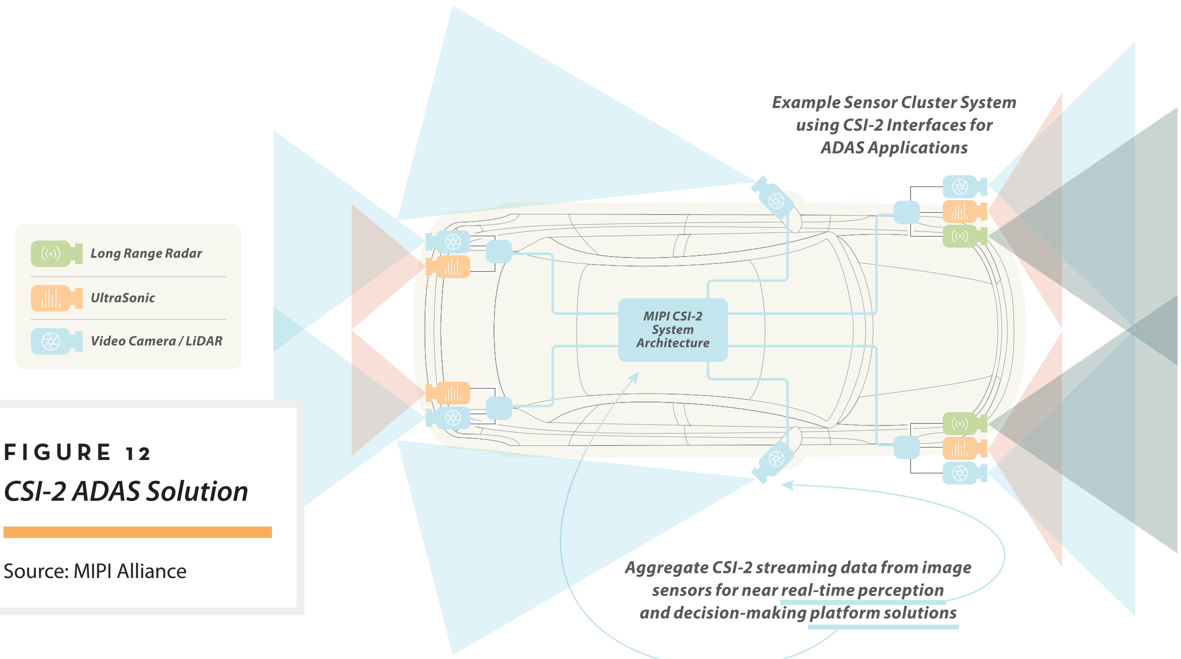



**FIGURE 12**
*CSI-2 ADAS Solution*

Source: MIPI Alliance

Automotive OEMs and their suppliers frequently use MIPI CSI-2 for applications that require unified end-to-end imaging and near-real-time processing and decision making (Figure 12). The MIPI Camera Working Group is currently planning an optimized MIPI camera solution to support the stringent automotive environment and certain IoT use cases:

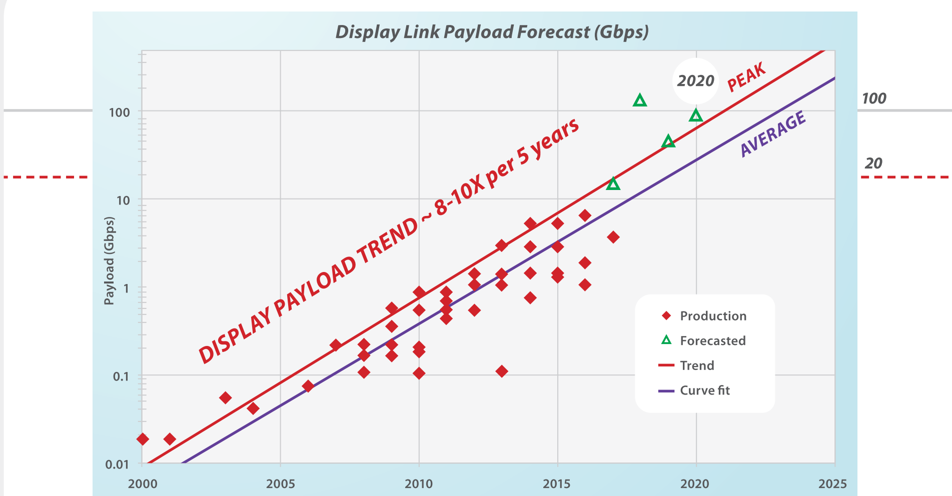
- Native support for a long-reach channel mapped to automotive or IoT platforms, (e.g., drones).
- Unified Serial Link (USL) with guaranteed transport for mission critical (e.g., autonomous vehicle) applications
- Synchronizing image sensors for advanced vision applications
- Provision for end-to-end security (e.g., Interleaved AES-256)

IN BRIEF:

*The MIPI CSI-2 specification is the interface of choice for 4G applications ranging from smartphones to drones to connected vehicles. This preference is continuing into 5G, where CSI-2 is already enabling the first wave of 5G devices, starting with smartphones. The CSI-2 specification for the 2021 market will contain the state-of-art bandwidth/resolution and features, with support for multi-camera, depth sensing, LRTE, USL, AVRET, SRoI, RAW-16/-20/-24, Enhanced CCI with I2C_FM+ and I3C support. All of these features will substantially enhance mobile user experiences with 5G mobile devices.*

### 3.1.3 MIPI DSI-2: 4K and Beyond Displays for Smartphones and AR/VR Headsets

Smartphone display resolution and pixels per inch (PPI) have continually increased over the years, a trend that will continue for the foreseeable future. This trend increases display bandwidth and power consumption. As Figure 13 illustrates, display payload bandwidth has increased at a rate of 8-10 times every five years.




***Reference data (Mobile):***
*"2017" display: 4K60*
*4K (e.g. 3840x2160) x 30 bpp x 60 fps = 15 Gbps (no OH)*

*"2020" display: 10K120*
*10K (3600x3600) x 30 bpp x 2 eyes x 120 fps = 93 Gbps (no OH)*

**FIGURE 13**
*Display Payload Forecasts*

Source: MIPI Alliance

To address this trend, the MIPI Display Working Group collaborated with VESA's Display Stream Compression (DSC) Task Group. MIPI DSI v1.2 adopted the VESA DSC standard in 2014 to provide up to 4:1, 8 bpp visually lossless compression. MIPI Alliance and VESA have continued their collaboration. For example, in May 2018, DSI-2 v1.1 adopted the latest VESA VDC-M standard, which delivers up to 5:1, 6 bpp visually lossless compression. DSI-2 v1.1 over MIPI C-PHY v1.2 delivers up to 8.0 Gbps (3.5 Gsps) with embedded clock and data over three wires per lane, and supports lane expansion (up to 24 Gbps with three C-PHY lanes using nine wires). This is equivalent to 8.0 Gbps x 3 C-PHY lanes x 5 = 120 Gbps effective bandwidth per DSI link with 3 C-PHY v1.2 lanes. DSI-2 v1.1 also supports D-PHY v2.1 delivering up to 4.5 Gbps with forwarded clock and data over four wires and supports data lane expansion (up to 18 Gbps using 10 wires).

Smartphone display resolutions are not expected to exceed 4K or 5K resolution (800 and 1000 PPI at 5.5" screen size, respectively), while tablet and laptop resolutions are not expected to exceed 8K or 10K resolution (572 and 715 PPI at up to 15.4" screen size, respectively) even beyond 2021. The main reasons are that it is both technically difficult to achieve this high resolution, and it would have limited or no visual quality improvement at such high PPI, according to many studies. These resolutions and bandwidths are already supported by DSI-2 v1.1, which meets and exceeds the state-of-the-art requirements beyond 2021. At the same time, DSI-2 also effectively reduces the physical bandwidth while enabling device designs that cost less, are smaller due to fewer wires and have longer battery lives.

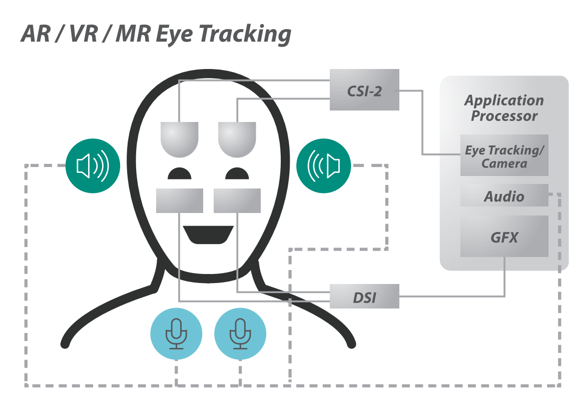
MIPI DSI-2 is also the de facto choice in many AR/VR display devices, such as head-mounted displays (HMDs) and glasses. 5G will enable better and richer AR/VR user experiences, which will require better HMD displays. Researchers are working to reduce so-called "VR sickness," potentially by adding some form of head- and/or eye-tracking sensors, display and audio synchronization and other tricks to avoid sensory conflicts to the human brain. MIPI specifications are ready today to enable these features, illustrated in Figure 14, that help address VR sickness.

The MIPI Display Working Group will continue to investigate the implications of 5G and potential enhancements, such as a high-bandwidth, low-latency return channel to support and enrich emerging 5G use cases.

**FIGURE 14**

***Potential Role of MIPI Specifications in Addressing VR Sickness***

Source: MIPI Alliance



**IN BRIEF:**

***MIPI DSI-2 currently is the world's most widely used interface for 4G smartphones and other devices with displays that have ever-higher resolution and PPI requirements. The MIPI Display Working Group continues to enhance DSI-2's capabilities to meet emerging market requirements, such as by collaborating with VESA's Display Stream Compression (DSC) Task Group to provide up to 5:1, 6 bpp visually lossless compression. These and other initiatives also ensure that DSI-2 is ideally suited to enable 5G smartphones, AR/VR HMDs and other devices with more advanced requirements.***

### 3.1.4 MIPI D-/C-/M-/A-PHY: High-Bandwidth, Power-Efficient Physical Layer Connections for Various Application Layers

MIPI offers a family of three high-performance and cost-optimized physical layer specifications: D-PHY℠, M-PHY and C-PHY℠. MIPI D-PHY is already the predominant PHY layer deployed today, coupling with CSI-2 and DSI-2 in virtually all 4G LTE smartphones. Meanwhile, M-PHY paired with MIPI UniPro/JEDEC UFS are the high-performance mobile storage interfaces of choice in today's LTE devices and in the first wave of 5G smartphones. With the latest MIPI CSI-2 and DSI-2 specifications and industry support, it is expected that C-PHY adoption will ramp up quickly as well.

MIPI D-PHY is the most widely deployed low power physical layer in the mobile industry. Optimized for MIPI CSI-2 camera and DSI/DSI-2 display protocols, D-PHY delivers high performance, low power and low EMI, making it compatible with sophisticated RF subsystems in mobile devices. D-PHY v2.1 supports up to 4.5 Gbps/lane and supports data lane expansion up to an aggregated data rate of 18 Gbps using 10 wires utilizing 4 data lanes plus one clock lane.

MIPI C-PHY provides high-throughput performance over bandwidth-limited channels to connect displays and cameras to an application processor. C-PHY accomplishes this by departing from the conventional differential signaling technique on a two-wire lane by use of a three-phase symbol encoding achieving ~2.28 bits/symbol over a three-wire lane. Each lane includes an embedded clock. C-PHY v1.2 supports up to 3.5 Gsps/lane with an equivalent of 8 Gbps/lane, and can achieve a peak bandwidth of 24 Gbps over three lanes.

MIPI M-PHY is a performance-driven and versatile physical layer targeting multimedia, high performance storage and chip-to-chip interconnect use cases. It uses a differential signaling with an embedded clock, supports two transmission modes with different bit signaling and clocking schemes, as well as multiple high-speed gears, offering configuration choices for run-time optimization between performance and power. M-PHY v4.1 supports 11.6 Gbps/lane, with an aggregated bandwidth of 46.4 Gbps over four lanes.

M-PHY is mostly used in combination with the MIPI UniPro protocol, which supports JEDEC's Universal Flash Storage (UFS). as a reliable, high-performance transport, low-power, and low-latency link. UFS v2.1 is already the predominant mobile storage found in high-performance 4G smartphones and will also be deployed in first-generation 5G smartphones. Meanwhile, UFS v3.0 will continue to enable state-of-the-art mobile storage for the flagship devices in the 5G era by fully utilizing M-PHY v4.1 performance capabilities. MIPI M-PHY is also the PHY of choice for the MIPI CSI-3, MIPI DigRF, MIPI LLI and MIPI UniPro protocols.

The MIPI PHY family of specifications are 5G ready. Refer to Section 3.1.2, 3.1.3 and 3.1.8 to learn more about how current D-PHY v2.1, C-PHY v1.2 and M-PHY v4.1 specifications already exceed the industry's 2021+ performance and bandwidth requirements.

The MIPI PHY Working Group continues to drive the next-generation PHY specifications to meet 2024+ 5G needs, to suit new 5G use cases and to target "beyond mobile" applications such as IoT and automotive. Upcoming C-PHY v2.0 and D-PHY v3.0 specifications target data rates up to 6 Gsps/lane and 14 Gbps/data lane, respectively. They also aim to support IoT use cases with much longer channels than in mobile form-factor devices, while preserving the benefit of MIPI PHYs to offer a low power, low latency, and low EMI solution. Also a new M-PHY specification is under discussion, which would target a data rate of about 23 Gbps/lane along with latency reductions to become even more power efficient. An increased efficiency may also be achieved through an advanced encoding scheme.

MIPI is also addressing automobile use cases for surround sensor as well as display applications. As MIPI protocols are widely employed by camera sensors and displays, it is desirable, that MIPI also offers a solution for an automobile link, to connect such devices to a central processing unit. With development of the MIPI A-PHY℠ physical layer specification already underway to meet 12-24 Gbps, requirements gathering has begun to support higher speeds including over 48 Gbps for display and other use cases. When complete, these specifications will serve a broad spectrum of the automotive industry's future connectivity needs into the 5G era.

MIPI A-PHY v1.0 is expected to be available to developers in late 2019. The specification will optimize wiring, cost and weight requirements, as high-speed data, control data and optional power share the same physical wiring. The asymmetric nature of the MIPI A-PHY link, its point-to-point topology and its reuse of generations of mobile protocols promise overall lower complexity, power consumption and system costs for developers and automotive OEMs. It's anticipated that the first vehicles using A-PHY components will be in production in 2024. In addition to automotive uses, the configuration of the specification will be well suited for applications such as IoT and industrial.

**5G IN BRIEF:**

***MIPI D-PHY, M-PHY and C-PHY are the de facto standards for high-performance, cost-optimized physical layer specifications in 4G device , as well as the first wave of smartphones. They deftly balance the marketplace's bandwidth, latency and power requirements for applications such as displays and cameras, while providing OEMs with choices. Forthcoming enhancements to MIPI's existing PHYs and the new MIPI A-PHY will enable generations of MIPI mobile protocols to be adapted to automotive, IoT and other emerging use cases.***

## 3.1.5 MIPI RFFE: Flexible Front Ends to Support Dozens of 5G Bands and MIMO Antennas

The MIPI RFFE specifications are the industry standard and dominant control backbone for RF front-end devices in smartphones.

MIPI RFFE specifies a two-wire, point-to-multipoint (multi-drop) control bus to control a variety of RF front-end devices, as illustrated in Figure 15. Examples include power amplifiers (PAs), low-noise amplifiers (LNAs), filters, switches, power management modules (PMUs, PMICs) and antenna tuners, to mention only a few. The interface also supports 1.8V and 1.2V IO voltage (VIO).

Since the initial RFFE v1.0 release, in order to meet the demanding and increasingly complex RF front-end subsystems, MIPI has introduced many new features in RFFE v2.0 to support LTE and LTE-A requirements, including:

- A multi-master feature to support MIMO, carrier aggregation and the monitoring of alternate bands.
- An increase of bus frequency from 26 MHz to 52 MHz, doubling the throughput from RFFE v1.x.
- Due to the variety and large number of devices using RFFE, the Extended Product ID was added along with the additional USID programming procedure.

The MIPI RFFE Working Group is actively driving the specification updates and roadmap to meet 5G NR requirements. As Figure 16 summarizes, the latest release, RFFE v2.1, introduced additional features:

- Multiple message types: master context commands and a new masked write command sequence for read-modify-write (RMW) needs.
- Flexible bus configuration: extended manufacturer ID bit field, extended triggers, updated bus load values and additional trace length timing tables for various bus driver implementations.
- Longer reach (or trace lengths) to accommodate buses needing further bus reach in some applications.
- Additional reserved register space for future features.

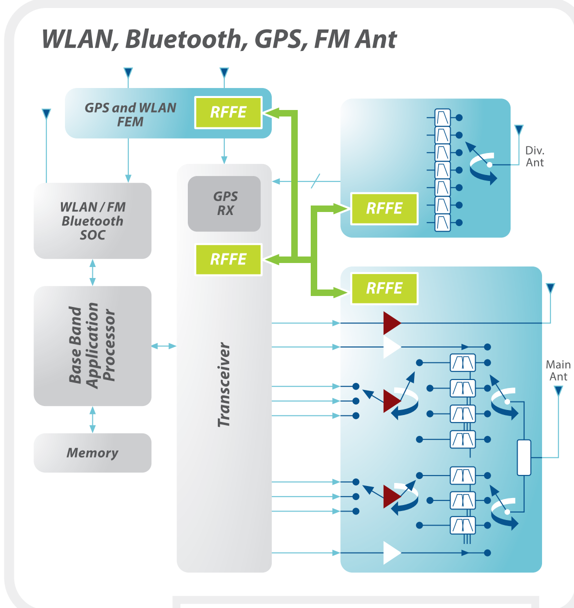



**FIGURE 15**
*Example of an RFFE System Configuration*

Source: MIPI Alliance

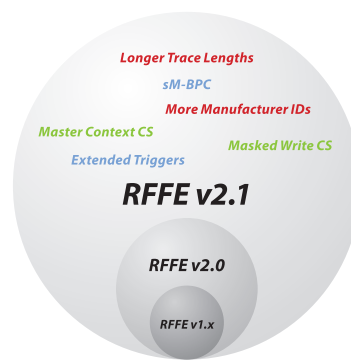



**FIGURE 16**
*MIPI RFFE v2.1 Features*

Source: MIPI Alliance

RFFE v2.1 is designed to perform well with 5G NR radio FR1 (sub-6 GHz) bands and will see deployment in first-generation 5G smartphones.

The MIPI RFFE Working Group continues to investigate requirements for a next-generation RFFE to support 5G NR FR2 (24.25 GHz to 56 GHz) bands and requirements for 5G NR Phase 2, also known as 3GPP Release 16. Future RFFE specifications plan to address enhancing capabilities such as higher data rates, more Tx/Rx paths, shorter configuration time (target <= 1µS) to meet shorter transient time and more flexible programmability, among others.

**IN BRIEF:**

*The MIPI RFFE specifications are the industry standard and dominant control backbone for a wide variety of RF front-end devices, including PAs, LNAs, filters, switches, PMUs, PMICs and antenna tuners. These specifications are continually enhanced to support emerging use cases and marketplace requirements, such as MIMO, carrier aggregation and the monitoring of alternate bands for LTE-A smartphones. Work has already begun on the development of a next-generation RFFE to support 5G massive MIMO and 5G NR FR2 requirements in millimeter Wave (24.25 GHz to 56 GHz) bands.*

### 3.1.6 MIPI VGI: Consolidating Sideband GPIOs and Low-Speed Messaging Interfaces

The Virtual GPIO Interface (VGI), illustrated in Figure 17, is a MIPI specification under development as of fall 2018. It is focused on consolidating sideband GPIOs and low-speed messaging interfaces (e.g., UART, SPI) over a two- or three-wire full-duplex point-to-point interface to bring packaging and system-level I/O pin reduction while meeting sideband signaling and messaging needs.

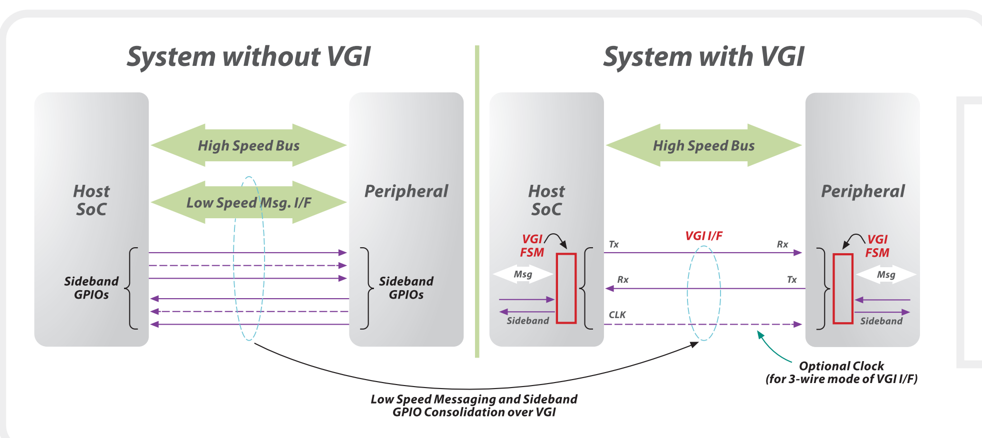



**FIGURE 17**
*MIPI VGI Conceptual Diagram*

Source: MIPI Alliance

The following key features will be supported in VGI 1.0:

- Bi-directional virtual GPIO state information exchange
- Transmission latency within the permissible limits
- Wide range of clock frequency support (from sleep clock to higher frequency (78 MHz)
- Dynamically switchable clock gears
- Ability to detect physical interface failure under corner case conditions, such as power failure, or a watchdog timer bite that renders the SoC unable to communicate via standard bus-based communication
- Minimal to no software required for driving the interface
- For lower transmission latency, a third wire providing clock is permitted, making it a three-wire VGI interface
- Minimum impact on power and die area
- Two-wire mode default signaling scheme: PWM with data rates up to 4 Mbps
- Two-wire mode alternate signaling scheme: UART-NRZ with data rates up to 4 Mbps
- Three-wire mode synchronous mode signaling scheme: Synchronous mode with clock rate up to 78 MHz

VGI v1.0 will support both 1.2V and 1.8V I/O operations. At 4 Mbps operation, it will be able to support trace or physical wire length of up to 90cm. At 78 MHz operation, the VGI interface length will be limited to 10 cm. Under all interface conditions, no termination will be required.

Some 5G IoT devices will require a large number of I/O pins without compromising real-time performance requirements. These devices could also use VGI as the main interface between the application processor and I/O expander. Thanks to these features, VGI is expected to be an interface of choice between low-speed modems and a host controller in 5G IoT devices.

5G **IN BRIEF:**

***The Virtual GPIO Interface (VGI) is a MIPI specification under development that will consolidate sideband GPIOs and low-speed messaging interfaces such as UART and SPI over a two- or three-wire full-duplex point-to-point interface. This architecture will enable packaging and system-level I/O pin reduction while meeting sideband signaling and messaging needs. MIPI VGI is designed to support 5G use cases such as low-to-mid-speed IoT applications.***

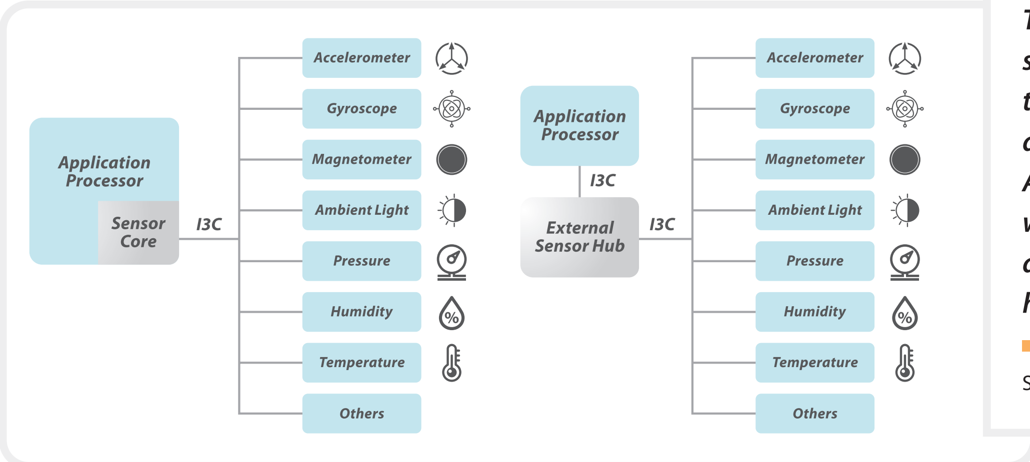



**FIGURE 18**

*Two common types of sensor hub architectures for mobile, wearables and IoT devices: Application processor with sensor hub (left) and external sensor hub (right).*

Source: MIPI Alliance

### 3.1.7 MIPI I3C: Multi-Sensor Support and Ubiquitous, Legacy Low-Speed Interface Convergence

MIPI I3C is a relatively new two-wire interface initially developed for connected sensors, hubs and application processors, as illustrated in Figure 18. It is poised to be deployed in the 5G smart devices coming in 2019.

MIPI I3C features circuit simplicity, maximum effective data rate of greater than 33Mbps with a 12.5MHz clock, in-band interrupt capability, dynamic address assignment, hot join support, common command codes and timing control while maintaining backward compatibility with I²C and attaining proven industry interoperability. These features put MIPI I3C well on its way to becoming the dominant interface for advanced and highly accurate sensors, and converge previous market fragmentation between I²C, UART, SPI and other legacy low-speed interfaces. These are all welcomed capabilities with respect to 5G readiness.

MIPI I3C is leveraged by other specification efforts inside and outside of MIPI, including CCI for CSI-2 v2.1, MIPI Touch TCS/ALI3C and Debug for I3C specifications. Additionally, the MIPI Sensor Working Group is working to advance I3C further with v1.1, expected in late 2018. New features such as grouped addressing, comprehensive flow control, advanced error handling and multi-lane for speed support promise to ensure I3C continues to be the ubiquitous low-speed interface of choice for connected and smart devices.

**IN BRIEF:**

*The MIPI I3C two-wire interface is ideal for advanced, highly accurate sensors, hubs and application processors in 5G smartphones and other devices. Its key features include circuit simplicity, a maximum effective data rate of greater than 33 Mbps with a 12.5 MHz clock, in-band interrupt capability, dynamic address assignment, hot join support, common command codes and timing control. MIPI I3C v1.1, expected in late 2018, will add features such as grouped addressing, comprehensive flow control, advanced error handling and multi-lane for speed.*

### 3.1.8 MIPI UniPro and M-PHY: Eliminating Memory Access Bottlenecks

MIPI UniPro and M-PHY enable lower energy/bit than other mobile storage interfaces in active mode, while the faster data transfer also shortens the active mode duration and reduces the total system power.

JEDEC's UFS 2.1 and UFS 3.0, which is based on MIPI UniPro v1.6 coupled with M-PHY v3.1 and UniPro v1.8 with M-PHY v4.1 respectively, deliver unprecedented aggregated transport bandwidth of 11.6 Gbps and 23.2 Gbps per direction, respectively. These enable faster boot, smoother scroll, faster web browsing and switching tabs, faster multimedia and higher gaming performance.

MIPI UniPro is ready for a variety of 5G applications, starting with smartphones. The UFS v2.1 specification is already the predominant mobile storage in standard high-performance 4G LTE smartphones and is expected to drive wider adoption in the mainstream and value segments with its substantial performance and power benefits. At the same time, UFS v3.0 is powering the next generation flagship smartphones in the era of 5G. Figure 19 illustrates this performance evolution.

It should also be clear that 5G will have no direct implications on mobile storage performance. It is expected that application developers will continue to leverage 5G's high data rate and low latency to push the limit of eMBB and create 5G use cases that will benefit from faster storage performance. Current UFS v3.0 specifications, with a peak transfer rate of 2.9 GBytes per second, would have enough headroom for flash device manufacturers to build high-performance UFS chips or cards to fuel future advanced 5G use cases.

Nevertheless, with the increasingly complex 5G platform, the size of firmware, OS and applications are expected to increase and will take longer time to load. The MIPI UniPro Working Group will continue to evaluate how to further enhance the performance and capabilities to enable the next generation of 5G platforms.

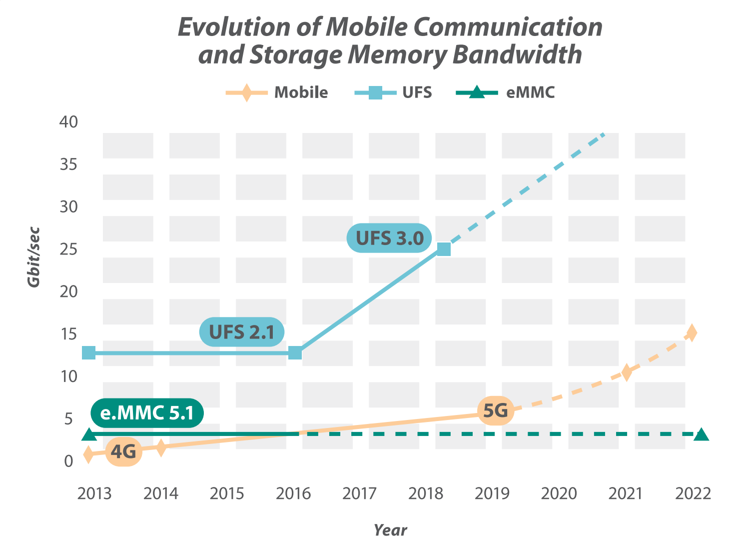



FIGURE 19
*Evolution of Mobile Communication and Storage Memory Bandwidth*

Source: JEDEC

5G **IN BRIEF:**

*MIPI UniPro and M-PHY are designed to meet marketplace requirements for storage access that's both fast and power-efficient. MIPI UniPro supports a variety of 5G applications, starting with smartphones. The UFS v2.1 and v3.0 specifications are the de facto standard for high-performance 4G LTE smartphones and ideally suited to support their 5G counterparts.*

### 3.1.9 MIPI Debug: Tools for Ensuring Robust Performance

The MIPI Debug family of specifications enables a debug framework and architecture for the SoCs used on 5G-enabled platforms. These specifications include debug subsystems for access and control, instrumentation and visibility, and different physical and network interfaces. The MIPI Debug family of specifications focuses on:

- Minimizing the pin cost and increasing the performance of the basic debug interface for mobile devices.
- Deploying debug connectors that are physically robust and have the performance required for the high bandwidth demands of 5G devices.
- Developing generic trace protocols that allow many different on chip trace sources and 5G applications to share a single trace data flow to the debug tools.
- Maximizing debug visibility in fielded systems by reusing some of the functional interfaces and/or connectors for debug.
- Utilizing the high bandwidth functional interfaces being deployed on 5G systems as a transport for debug.

More information about how the MIPI Debug family of specifications can be used to enable a debug solution can be found in the **MIPI Architecture Overview for Debug white paper**.

*The MIPI Debug family of specifications enables a debug framework and architecture for the SoCs used on 5G-enabled platforms.*

### 3.1.10 Summary

Table 2 provides an overview of how MIPI specifications are ready for use today in 5G devices such as smartphones.

| Application Area | MIPI Specification/ Interface | Readiness Details / Future Plans / 5G Enhancements | Mobile 5G Readiness |
|---|---|---|---|
| **Audio** | SLIMbus | SLIMbus v2.0 is poised to be deployed in 5G-enabled smartphones in 2019. | 5G Ready |
| | SoundWire | SoundWire v1.1/1.2 already exceeds state-of-the-art audio requirements. The upcoming SoundWire specification plans to lower EMI and extend reach farther. | 5G Ready |
| **Camera and Imaging** | CSI-2 (Camera Serial Interface) | BW/resolution exceeds state-of-the-art requirements beyond 2021. Advanced features include multi-camera, depth sensing, LRTE, USL, AVRET, SmartROI, GLD, RAW 16/20/24, enhanced CCI with $I^2C$_FM+ and I3C. | 5G Ready |
| **Display** | DSI-2 (Display Serial Itnterface) | BW/resolution exceeds state-of-the-art requirements beyond 2021. As a key 5G use case, AR/VR is an area of focus for MIPI. | 5G Ready |
| **Physical Layers** | D-PHY, C-PHY for camera and display | C/D/M-PHY delivers bandwidth beyond 2021 needs for camera, display and UniPro. | 5G Ready |
| | M-PHY for UniPro/UFS | | |
| **Control and Data** | RFFE (RF Front-end Control Interface) | Now that RFFE v2.1 has been released, the RFFE Working Group is evaluating requirements to enhance the 5G NR subsystem. | 5G Ready |
| | I3C (Improved Inter Integrated Circuit) | I3C is poised to become the dominant next-generation control interface for 5G mobile (as well as other industry use cases and server control I/F). The Sensor Working Group will evaluate 5G reliability and security require-ments after the late-2018 release of v1.1. | In development |
| | VGI (Virtual GPIO Interface) | Version 1.0, targeted for release next year, will enable substantial pin savings for 5G mobile. The three-wire VGI (up to 76.8Mbps Full Duplex) will suit the interface of low-to-mid IoT 5G modems. | 5G Ready |
| **Storage** | UniPro for support of UFS flash storage | UniPro-based UFS is the primary storage interface in high-end smartphones and upcoming 5G mobile. | 5G Ready |
| **Debug** | Family of specifications | The family of debug specifications can be deployed on SoCs enabling 5G. This includes access, control and visibility sub-systems on the SoC, as well as transports for control and data using the network over TCP or UDP. | 5G Ready |

## 4 Conclusion: Making the 5G Vision a Reality

Today, if a device has a 4G radio, it uses MIPI interfaces. That's true not only for smartphones and tablets, but also for connected cars, AR/VR headsets and IoT devices such as smart refrigerators. This multi-industry adoption has set the stage for MIPI specifications to remain the de facto standard for tomorrow's 5G devices.

Tomorrow is now here, with mobile operators such as AT&T and Verizon launching their first 5G networks in 2018. Current MIPI specifications meet the 5G bandwidth, performance and feature requirements through 2021 and beyond for smartphones and other devices. In summer 2018, several major vendors were already using MIPI specifications for their first-generation 5G smartphones.

This adoption is one example of how MIPI is playing a key role in enabling the 5G vision held by operators, device vendors, application developers and their customers. Consumers and business users expect 5G smartphones to provide a noticeably better experience than their 4G predecessors, such as faster retrieval of stored data, images or videos, higher camera resolutions, and rich, immersive audio. MIPI specifications enable operators, vendors and other companies to not only meet those expectations, but exceed them in ways that create market-differentiation opportunities.

*Although current MIPI specifications meet all of the expected 5G bandwidth, performance and feature requirements through 2021 and beyond for smartphones and many other devices, several initiatives are well underway to ensure those specifications anticipate and meet post-2021 market requirements.*

MIPI Alliance and its 300-plus member companies aren't content to rest on those laurels. Although current MIPI specifications meet all of the expected 5G bandwidth, performance and feature requirements through 2021 and beyond for smartphones and many other devices, several initiatives are well underway to ensure those specifications anticipate and meet post-2021 market requirements. One example is the MIPI RFFE Working Group, which continues to work with partners and mobile operators to investigate requirements to meet 5G NR FR2 (24.25 GHz to 56 GHz) bands and 5G NR Phase 2 requirements, including higher data rates, more Tx/Rx paths, and shorter configuration times to ensure RFFE remains the dominant and RF front-end control interface of choice for all 5G devices. MIPI's Display Working Group, Camera Working Group, and PHY Working Group are also preparing display and camera interfaces, and physical layer interfaces, to support the 10s of Gbps payload speeds needed to support these 5G requirements—today, tomorrow and beyond.

# 5 References


"3GPP 5G Core Network Status." 3GPP Webinar, Nov. 2017. Retrieved from **https://www.brighttalk.com/webcast/15727/291037**

"5G Network Transformation." *5G Americas White Paper,* 5G Americas, Dec. 2017. Retrieved from **http://www.5gamericas.org/files/3815/1310/3919/5G_Network_Transformation_Final.pdf**

"5G RAN status report - After RAN#77." 3GPP Webinar, Sept. 2017. Retrieved from **https://www.brighttalk.com/webcast/15727/280315**

"5G Services & Use Cases." *5G Americas White Paper,* 5G Americas- 5G Services and Use Cases, Nov. 2017. Retrieved from **www.5gamericas.org/files/9615/1217/2471/5G_Service_and_Use_Cases__FINAL.pdf**

"IEEE 5G and Beyond Technology Roadmap White Paper." IEEE, Oct. 2017. Retrieved from **https://5g.ieee.org/images/files/pdf/ieee-5g-roadmap-white-paper.pdf**

"LTE to 5G: The Global Impact of Wireless Innovation." 5G Americas/Rysavy Research White Paper, Rysavy Research/5G Americas, Aug. 2018. Retrieved from **www.5gamericas.org/files/4915/3479/4684/2018_5G_Americas_Rysavy_LTE_to_5G-_The_Global_Impact_of_Wireless_Innovation_final.pdf**

"NGNM 5G White Paper." NGMN Alliance, Feb. 2015. Retrieved from **https://www.ngmn.org/fileadmin/ngmn/content/downloads/Technical/2015/NGMN_5G_White_Paper_V1_0.pdf**

"The Global Race to 5G." *CTIA White Paper,* CTIA, April 2018. Retrieved from **https://www.ctia.org/news/race-to-5g-report**

"Wireless Technology Evolution Towards 5G: 3GPP Release 13 to Release 15 and Beyond." 5G Americas, Feb. 2017. Retrieved from **www.5gamericas.org/files/3214/8833/1313/3GPP_Rel_13_15_Final_to_Upload_2.28.17_AB.pdf**