The New Frontier of MIPI CSI-2 Camera and Imaging Applications:
Leveraging the Power of Machine Vision for Mobile, IoT, Client Devices, Automotive and Beyond

8 January 2020
Haran Thanigasalam
MIPI CWG Chair | Intel Architect
Agenda

• An Introduction to MIPI Alliance
  – Peter Lefkin, Managing Director

• The Big Why
  – Two key discoveries
  – Machine human friction
  – Two pathways

• MIPI Imaging Conduit Solution
  – Multi-phase development
  – What’s done
  – What’s WIP
  – What’s next

• Summary
About MIPI Alliance

Peter Lefkin
Managing Director, MIPI Alliance
MIPI Alliance formed to standardize camera and display interfaces.
MIPI Alliance Member Ecosystem

- Application Processor Developers
- Device OEMs
- Consumer Electronics
  (Cameras, Tablets, PCs/Laptops, Peripherals, Wearables)
- Software Providers
- IP and VIP Providers
- Test Labs
- Test Equipment Companies
- Semiconductor Companies
- Automotive OEMs/ Tier 1 suppliers

AS OF 31 DECEMBER 2019
339 members

Number of countries
27

© 2020 MIPI Alliance, Inc.
MIPI Specifications Leveraged Beyond Mobile

Number of current specifications

48

Fundamentally, usage rights are granted to members royalty free for implementation of MIPI specifications from all MIPI members
The Big Why &
The MIPI Imaging Conduit Solution

Haran Thanigasalam
MIPI CWG Chair | Intel Architect
The Big Why

- Enrich lives by better understanding the world around us
- Knowledge limitations
- Scope of perception
- Challenges with abstraction
- Evolution of intelligence
- Two key discoveries
  1. Individual & Collective Dysfunction
  2. Superior Intelligence
Machine Human Friction

- Future is deeper human machine interaction with connected devices

- Two Pathways:
  1. Making us become more like machines
  2. Making machines become more like us (machine awareness, emotional vision)

MIPI CSI-2 Imaging Conduit

Unified Imaging Conduit for AI Vision Spanning Multiple Platforms

A smart connected device is blessed with cognitive computing that uses AI and perception awareness to sense, learn, reason, and make decisions when interacting with individuals or surrounding situations.

AI Vision

Connected Devices

Perception & Decision Making AI

Human-Device Friction

Internet

Mobile

Computer

© 2020 MIPI Alliance, Inc.
Machine Emotional Cognition & Expression Wheels
Emerging Applications

• Salesforce Dreamforce & Amazon AWS
  – Enable context sensitive AI to present the relevant information
  – Wish List: enable Consumer & Institutional reps using Client products pathway to establish deeper connection with remote customers
  – FFT Avatars & emotional recognition

• Computational Imaging & Emotional Cognition
  – Alleviate machine device friction

• Pathway to Full-Autonomy
  – Beyond visible spectrum awareness
  – Near-Military-Grade Image Sensors
Evolving MIPI Imaging Solution

I. **Mobile** - Pristine photography & video streaming on mobile platforms [CSI-2 v1.x]
   - RES FPS BPP | PORT EXP | SNS SWITCHING

II. **Platforms** - Support broad range of imaging applications beyond photography on multiple platforms [CSI-2 v2.x, v3.x]
   - SCR | VCX | LRTE (PDQ, ALP) | USL | RAW-24 | DPCM | SROI

III. **Awareness** - Develop infrastructure for emotional intelligence and machine awareness for perception and decision making capabilities [CSI-2 v4.x]
   - AOSC | FSAF | ISEC | ADAPL

IV. **Scale** - Open System Cloud Imaging Applications utilizing vision analytics (Schools, Hospitals, Municipalities, States)

V. **WIP**

Complex problems cannot be solved by an individual company
Need for global alliances and liaisons
Two Different CSI Architectures

- MIPI CWG is continuing to evolve and advance CSI-2 imaging conduit targeting multiple platforms:
  - I3C: Ultra-Low-Power AON
  - C/D-PHY: Performance
  - A-PHY: Long Reach

- CSI-3 is not a next-gen solution, nor superset, nor backwards compatible with CSI-2
What’s Done

PSD

LRTE
(PDQ, ALP)

USL
(ENCAP, REPL, OPT_WIRE)

SROI

DPCM | RAW-24

UNIFIED IMAGING DRIVER
(CCS, DisCo*)
PSD Reduction

CSI-2 over D-PHY PSD emission reduction with scrambling (data lanes)

CSI-2 over C-PHY PSD emission reduction with scrambling (embedded clock and data)
LRTE

- Dramatically Improve Sensor Aggregation
- Optimal Transport Preserving Integrity
- Real-time Perception & Decision Making
- Phase out EOS &IL Impediments
- Asymmetric SP/LP Spacers
LRTE PDQ

i. Increase number of supported sensors by CSI-2 Aggregators (system cost reduction)

ii. Facilitates optimal transport, while preserving CSI-2 packet delimiter integrity

iii. Reduce frame latency for real-time perception & decision making applications

LRTE ALPS (requires PDQ)

 Transitional pathway to phase out (1.2v) EOS impediments

Detailed CSI-2 System Analysis & Benefits of Using LRTE PDQ

System 1: CSI-2 v2.0 over C-PHY v1.2 (3.5 Gbps/lane or 8Gbps/lane)

- 24 Gbps using 3 lanes (requires 9 wires)
- CSI-2 v2.0 supports up to 32 Virtual Channels over C-PHY

Multi Sensor Aggregator with each sensor configured as

- 1920x1200 (2.3MP), 12 BPP, 60 FPS

Image Sensor Packet Transport

- 1920 pixels x 12bps = 23040 bits per Horizontal Row Long Packet (LP)
- 23040 bits / 24Gbps = 0.960 us / LP (CSI-2 Payload; ignoring PH/PF)
- Packet Header + Packet Footer = 336+48= 384 bits
- 23424 bits / 24Gbps = 0.976us / LP_PHF (CSI-2 Payload with PH and PF)

CPU: 2.0 with Legacy C-PHY Packet Delimiters:
- LP Delimiter (SoT/EoT) = ~0.3 us
- Total Time per LP_PHF = 1.276 us
- Packet Delimiter Overhead = 23.5%
- Time per Image Frame = 1.276us x 1200 = 1.53 ms (Ignoring FS/TE)

Stream 60 frames from single image sensor requires: 1.53ms x 60 = 91.87 ms

CI-2 v2.0 with LRTE PDQ:

- Time per Image Frame = 0.976 us x 1200 = 1.171 ms
- Stream 60 frames from single image sensor requires: 1.172ms x 60 = 70.27 ms
- Maximum Supported Image Sensors on an Aggregator = 14
- FLOOR(1/0.0707) = FLOOR[14.23]

Benefits of CSI-2 v2.0 with LRTE PDQ:

- Frame Transport Efficiency Improvement: 23.5%
- Additional Supported Image Sensors on Aggregator: +4 (over the same channel)
- Alternatively, reduce toggle rate / wires

<table>
<thead>
<tr>
<th>Considerations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Legacy PD Hor Row Overhead</td>
<td>23.51%</td>
</tr>
<tr>
<td>Legacy PD Max Supported Sensors</td>
<td>10</td>
</tr>
<tr>
<td>LRTE PDQ Hor Row Overhead</td>
<td>0.20%</td>
</tr>
<tr>
<td>LRTE PDQ Frame Transport Efficiency Impact</td>
<td>23.35%</td>
</tr>
<tr>
<td>(reduce: power / wire / toggle)</td>
<td></td>
</tr>
<tr>
<td>LRTE PDQ Max Sensors Supported</td>
<td>14</td>
</tr>
<tr>
<td>LRTE PDQ Additional Supported Sensors</td>
<td>40.00%</td>
</tr>
</tbody>
</table>
Smart Region of Interest

- Phase 2 Single Frame
- Phase 4 Multi Frame
- ARCH: Edge | Hybrid

DPCM Objective Qualification

• Enable 10-bit compression of RAW-12 video image with better IQ than prior version 12-8-12

• Reduce maximum absolute error of single-bit change in pixel value by a factor of 4.43x

• Qualified 5 degree slanted edge input image with low, medium, and high illumination levels:
  – 12-10-12 virtually indistinguishable from original image
  – MTF frequency response analysis closely tracks the original (HI/MI/LI - LC/MC/HC)

• Benefits include Link BW reduction cost savings

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Per-Lane 4-Lane Bit Rate (Gbps)</th>
<th>12-10-12 DPCM Enables Use of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 bpp</td>
<td>D-PHY</td>
</tr>
<tr>
<td>4Kp60 or 1080p240</td>
<td>1.485</td>
<td>v1.1</td>
</tr>
<tr>
<td>16M (4:3) @ 30 fps</td>
<td>1.45</td>
<td>v1.1</td>
</tr>
<tr>
<td>20M (16:9 crop) @ 30 fps</td>
<td>1.371</td>
<td>v1.1</td>
</tr>
<tr>
<td>32M (4:3) @ 24 fps</td>
<td>2.263</td>
<td>v1.2</td>
</tr>
</tbody>
</table>
Algorithm is King

- Unified Imaging Software Driver
- Enable Image Sensor Capabilities for Vision Compute
- Accelerate Bring up on Reference Platforms

• Advance pathways to realize image sensor self-tuning
CSI-2 CCS

- Vertical Flip | Horizontal Mirroring

- Sub-Sampled Readout | Binning | Digital Crop
### AOSC
- Enable always-on surrounding awareness
- Infrastructure to accommodate rapid evolution of vision inferencing
- Ultra-low-power operations

### FSAF
Mission Critical Imaging Applications: 
- End to End CRC Protection
- Enhanced Frame Structure
- Fault Injection Mode

### A-PHY ADAPL
- Enable native long-reach support for DISCRETE and INTEGRATED image sensors

### ISEC
- Develop provisions for end-to-end imaging conduit security (interface and class)
  - Authentication - trustworthy / genuine sensor module with certificate signing
  - Data signing - data is originating from trusted source devoid of spoofing attack
  - Obfuscation - Data encryption at line rate
- External liaisons with Distributed Management Task Force Security Protocol & Data Model development
  - Authentication
  - Session key exchange
Always On Sentinel Conduit (AOSC)

- Enable always-on surrounding awareness
- Infrastructure to accommodate rapid evolution of vision inferencing
- Ultra-low-power operations

Always On Imaging Applications
SNS Guidance
<2mw @ 3FPS, 8-10BPP, QVGA Monochrome
Select applications may require higher capabilities

Dual-Mode Image Sensor (Cropped | Full-Frame)

APP

Application Processor

Point-To-Point
CSI-2 over I3C

CSI-2 over C/D-PHY
End-to-End Security

- Develop provisions for end-to-end imaging conduit security (interface and class)
  - Authentication - trustworthy / genuine sensor module with certificate signing
  - Data signing - data is originating from trusted source devoid of spoofing attack
  - Obfuscation - Data encryption at line rate

- External liaisons with Distributed Management Task Force Security Protocol & Data Model development
  - Authentication
  - Session key exchange
<table>
<thead>
<tr>
<th><strong>CSI-2 ISEC Considerations</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Device Manufacturing</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Platform Manufacturing</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Platform Refurbishing</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Host Firmware Update</strong></td>
</tr>
<tr>
<td><strong>Model Authentication</strong></td>
</tr>
<tr>
<td><strong>Device Authentication</strong></td>
</tr>
<tr>
<td><strong>Device Session Key Rotation</strong></td>
</tr>
<tr>
<td><strong>Device Firmware Measurement</strong></td>
</tr>
<tr>
<td><strong>Device Firmware Measurement Replay</strong></td>
</tr>
<tr>
<td><strong>Device Firmware Rollback</strong></td>
</tr>
<tr>
<td><strong>Device Data Integrity</strong></td>
</tr>
<tr>
<td><strong>Device Data Confidentiality</strong></td>
</tr>
<tr>
<td><strong>Host Authentication</strong></td>
</tr>
<tr>
<td><strong>Host Command Integrity</strong></td>
</tr>
<tr>
<td><strong>Device Revocation</strong></td>
</tr>
<tr>
<td><strong>Device Tamper Detection</strong></td>
</tr>
</tbody>
</table>
CSI-2 Functional Safety

• End to End CRC Protection
• Enhanced Frame Structure
• Fault Injection Mode
Importance of Machine (Emotional) Awareness

I. RES | FPS | BPP | CCI (CSI-2 v1.x)
II. VCX | PSD | LRTE | DPCM (CSI-2 v2.x)
III. USL | SROI | RAW-24 (CSI-2 v3.0)

I. AOSC | FSAF | ISEC | A-PHY (CSI-2 v4.0)
CSI-2 v4.0 Imaging Conduit

- **Always On Sentinel Controller (AOSC)**
  - Optimal infrastructure for VDSP: ultra-low power, simple, always on CSI-2 transport mechanism using I3C I/O
  - Target Platforms: Mobile, IoT & Client, Autonomous

- **Functional Safety (FSAF)**
  - Develop safety provisions for mission critical decision making applications on autonomous platforms with areas of interest may include Message Counter (MC), SourceID, End-To-End CRC/MC protection, Enumeration of Rows & Columns.
  - The solution shall also meet the needs of Automotive ISO-26262: 2018 requirements for ASIL-B to ASIL-D.
  - Target Platforms: IoT, Autonomous (ADAS)

- **Imaging Security (ISEC)**
  - Develop provisions for end-to-end imaging conduit authentication & data protection required for privacy.
  - Establish liaisons with DMTF
  - Target Platforms: Mobile, IoT & Client, Autonomous

- **Adaptation Layer (ADAPL) for A-PHY**
  - Support integrated and discrete solutions couple to CSI-2 over C/D-PHY
  - Long-reach SerDes solution for imaging applications.
  - Target Platforms: Autonomous (ADAS)

- **Time Synchronization Provision (TSP)**
  - Explore development of time synchronization including 1) Transport and 2) Enablement
  - Target Platforms: Mobile, IoT & Client, Autonomous

- **Multi-Sensor Support (MSS)**
  - Explore supporting two or more C/D-PHY image sensors coupled to single RX port on Application Processor
  - Target Platforms: Mobile, IoT (AR / Wearable Headgears), Client, Autonomous

- **Radar and LiDar Enhanced Support**
  - Explore enhanced provisions to transport RAW data from Radar and LiDAR image sensors for ADAS

- **Unified Imaging SW Driver | Self Tuning**
  - Continue to advance CCS aligned with CSI-2
  - Develop DisCo for Imaging v1.0 with SWWG

- **Alleviate Product Interoperability Risk**
  - Continue to advance ETE CTS for CSI-2 (X-Matrix)
Problem Definition (Use Cases) | Timing (Execution Vs Perfection)

Phase I (Mobile)

Phase II (Platforms)

Phase III (Awareness)

Phase IV (Scale)

MIPI CWG

Innovation

Growth

Maturity
What’s Next – Computer Vision Systems

Open System Cloud Imaging Applications
Vision Analytics | 3D Perception | Training model (self, supervised) | Deep Learning | Object Classification
PHYs & I/Os

Natively Supported
- I3C: Ultra-Low-Power
- D-PHY: Performance
- C-PHY: Performance
- A-PHY: Long Reach

Potential Exploration / Evaluation for cloud connectivity
Closed System PHYs

- Closed System Mid-Range solutions targeting Q2 2019 development
- Closed System Long-Range solution targeting Q1 2020 development
- Exploring possibilities for Open System developments
CSI-2 Over C/D-PHYs (2 Lanes)

**CSI-2 Imaging over D-PHY**
- Image Sensor
- D-PHY TX (6-pins)
- D-PHY RX (6-pins)
- Application Processor

**CSI-2 Imaging over C-PHY**
- Image Sensor
- C-PHY TX (6-pins)
- C-PHY RX (6-pins)
- Application Processor

**Pin compatible**

1x Effective Pixel BW

2.3x Effective Pixel BW

---

Insertions:
- 1x Effective Pixel BW
- 2.3x Effective Pixel BW

---

Note: The diagram shows the connection between Image Sensor, D-PHY TX/RX, C-PHY TX/RX, and Application Processor, highlighting the data and clock signals between them. The I2C Compatible 2-wire Camera Control is also illustrated.
Unified Serial Link

- Builds on LRTE
- Wire Reduction
- Encapsulation
- Replay Protection
- Long reach
Latest CSI-2 v3.0 over C/D-PHY Port BW

- CSI-2 v3.0 C/D-PHY BW capabilities per lane
  - C-PHY v2.0: Standard Channel 6 GSps / Lane = 6 x 2.28 Gbps / 3 wires, Short Channel 8 GSps / Lane
  - D-PHY v2.5: Standard Channel 4.5 Gbps / Lane = 4.5 Gbps using 4 wires, Short Channel 6.5 Gbps / Lane
  - D-PHY v3.0 will provide higher BW—trending spec completion Q1 2020

CSI-2 v3.0 over C/D-PHY Imaging Conduit Effective (Usable) BW Solutions:

- 9 Wire CSI-2 over C-PHY: 41.1 Gbps [Standard Channel] (3 x 6 x 2.28)
- 10 Wire CSI-2 over D-PHY: 18.0 Gbps [Standard Channel] (4 x 4.5)
CSI-2 over C-PHY - 2.3x Effective BW

- 3 terminated conductors
- CSI-2 policy: symbol transition each state for trivial CDR
- Theoretical BW gain: $\log_2^5$
- As implemented for CSI-2 = 16/7
CSI-2 over A-PHY

- Discrete & Integrated
- NRZ: Low Cost: NRZ (8b/10b)
- PAM: Scalable Performance: PAM-X (i.e. PAM-4)
- O: Optional | M: Mandatory
- Cable Topologies (Image Sensor PCB → Processor ECU PCB)
  - 50 Ohm Coax | 15 m | 4 inline connectors
  - 100 Ohm SDP | 10 m | 4 inline connectors

**NRZ**

- G1 (2 Gbps)
- G2 (4 Gbps)
- G3 (8 Gbps)
- G4 (12 Gbps)
- G5 (16 Gbps)

**PAM**

- 32/48/100 Gbps

- M
- M
- M
Platform Considerations

CSI-2 v4.0 supports multiple features over 4 modes of transport

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00 to 0x07</td>
<td>Synchronization/Short Packet Data Types</td>
</tr>
<tr>
<td>0x08 to 0x0F</td>
<td>Generic/Short Packet Data Types</td>
</tr>
<tr>
<td>0x10 to 0x17</td>
<td>Generic/Long Packet Data Types</td>
</tr>
<tr>
<td>0x18 to 0x1F</td>
<td>YUV Data</td>
</tr>
<tr>
<td>0x20 to 0x2F</td>
<td>RGB Data</td>
</tr>
<tr>
<td>0x27 to 0x2F</td>
<td>RAW Data</td>
</tr>
<tr>
<td>0x30 to 0x37</td>
<td>User-Defined Byte-based Data</td>
</tr>
<tr>
<td>0x38</td>
<td>USL Commands (See Section 8.12)</td>
</tr>
<tr>
<td>0x39 to 0x3F</td>
<td>Reserved for future use</td>
</tr>
<tr>
<td>0x3F</td>
<td>For CSI-2 over G-PHY: Reserved for future use</td>
</tr>
<tr>
<td></td>
<td>For CSI-2 over D-PHY: Unavailable (0x3F is used for LRTE EPO Spacer)</td>
</tr>
</tbody>
</table>

STD – Unidirectional C/D-PHY, CCI over I2C / I3C / SPI, GPIOs
USL – Encapsulation using bidirectional C/D PHY
AOSC – Encapsulation using bidirectional I3C
APHY – Integrated and Discrete SerDes transport

ARCH: Mobile | Client | IoT | Autonomous
CENTRAL
EDGE / DISTRIBUTED
HYBRID

SNS MODULE
IRX
VCM
GYRO
ACC
EPROM
LED
LASER
...

APP
ISP
CVE
GFX

CSI-2 v4.0

A-PHY SerDes

CSI-2 v1.3
SCR EN
RAW 12

CSI-2 v3.0
SROI EN
USL EN

CSI-2 v2.1
SCR EN
DPCM EN

CSI-2 v4.0

STD
USL
AOSC
ADAPL

RAW
DPCM
SCR
LRTE
SROI
FSAF
ISEC

PHY
DISCRETE
INTEGRATED
Recent activities:

- Automotive white paper released late 2019
- A-PHY to support broadest spectrum of speed needs using two profiles
- Auto-related features included in CSI-2 v3.0, as well as next camera and display specifications
- Now identifying requirements for A-PHY v2.0

Download the white paper: https://mipi.org/mipi-white-paper-driving-wires-automotive
MIPI CSI-2’s Newest Frontier: Machine Awareness

Written by: Haran Thanigasalam, Chair of the MIPI Camera Working Group
27 September 2019

One of the challenges we humans have is that our ability to perceive things around us and to make sense of the world relies on abstractions based upon mental constructs. It’s a limited capability. And what we have come to realize is that enabling machines to become aware of our surroundings and act on behalf of our well-being and work for us will dramatically enrich our lives. But this machine intelligence remains limited, too, in no small part because it is blind. Giving sight to machines will enable vision for real-time perception and decision making.

mipi.org/blog

In the blog:

• Information on new features and specification releases
• Use cases and applications of MIPI specifications
• Q&As with working group chairs and other experts
• Latest MIPI Alliance news
• Highlights and key takeaways from webinars and MIPI DevCon presentations
• Details of MIPI participation in industry events
Summary

- Resolve problems that cannot be solved by single company

- Advance CSI-2 imaging conduit infrastructure to facilitate machine awareness through sight on multiple platforms
  - Mobile | Client | IoT | Automotive | Drones

- Democratize benefits of AI vision through standardization

- Together we go further
  - Camera WG: CSI-2 | CCS | CTS
  - PHY WG: A/C/D-PHYs
  - SWG: I3C
  - SWWG: DisCo for Imaging
  - Liaisons
Thank you!

www.mipi.org
Backup Material
**Virtual Channel Expansion**

**System Considerations**

- Proliferation of Image Sensors Require CSI-2 Aggregators and VC Expansion
- System is limited to 16 or lower VCs:  
  - Supported by CSI-2 over C/D-PHY
- System requires more than 16 VCs:  
  - Supported by CSI-2 over C-PHY

**CSI-2 Virtual Channels** uniquely designate frames (RAW, JPG, IR) and Metadata captured by each image sensor

**CSI-2 Image Sensors**

- Ultrasonic
- Cameras (HDR & IR)
- Radars

---

URL
Imaging System Platforms

**Mobile**
- Target Platform: Smart Phones, Tablets
- Target Imaging Application: Pristine still photography I streaming video

**Client & IoT**
- Target Platforms: Content Creation (AIO, Notebooks, Hub)
- Target Imaging Application: Comprehensive E2E imaging conduit to enable machine awareness

**Autonomous**
- Target Platform: Automotive, Drones, Medical, Factory
- Target Imaging Application: Real time perception and decision making

IP Reuse / Engineering
Evolving CSI-2 Architecture for Automotive

CSI-2 Aggregators may benefit from Virtual Channel Expansion and LRTE PDQ

CSI-2 streaming data from aggregated image sensors for near real-time perception and decision making platform solutions

- Long Range Radar
- UltraSonic
- Video Camera / LiDAR
Deep Neural Networks

Myriad X Hybrid Arch Deep Neural Network
8 Cameras using 16 MIPI Lanes - 700 MP/s
Drone Collision Avoidance (DJI SPARK)