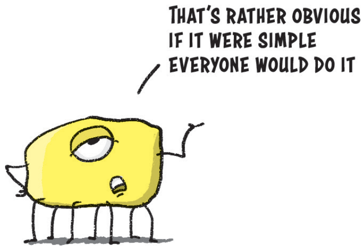
WHY ARE THERE SPECIAL INTERFACES FOR THE TRANSMISSION OF IMAGE DATA?



As camera technology has evolved, so have the interfaces used to extract image data from a camera and transmit it for storage and processing. Early cameras, such as those for early Television (TV) and Closed Circuit Television (CCTV) filming, used an analog interface. This interface enables easy real-time viewing but makes it difficult to capture and store images for subsequent digital post-processing. When cameras began using digital image sensors to capture digital image data, computers had not yet advanced to store or process such large volumes of data. Thus, the digital film had to be converted to an analogue TV signal and fed to monitors and video recorders for storage. Later, special devices were developed to either convert TV signals back into digital information or transfer the digital signals from the digital image sensors (mostly CCD image sensors) for storage on a computer. These boards are called "frame grabbers" (since they 'grab' images for digital storage.) Aside from TV cameras, there were no standard data interfaces at the time. All interfaces were proprietary (see fig. 1 [a] and [b]).

To eliminate the backward step of converting digital image data to an analog TV signal, the Institute of Electrical and Electronics Engineers (IEEE) introduced IEEE 1394 Firewire as a common interface in 1995. Firewire was derived from a former Sony digital video interface originating from consumer applications (fig. 1 [c] and fig. 3 [a]). The Firewire interface made transferring image data from a camera to a computer easy and cost-effective. It allowed for a data bandwidth of approximately 30 MB/s, which sufficed for many applications at the time.

However, as camera technology continued to advance, it became necessary to develop a new digital data interface that surpassed the speed and performance of Firewire. In the late 1990's, National Instruments (NI)

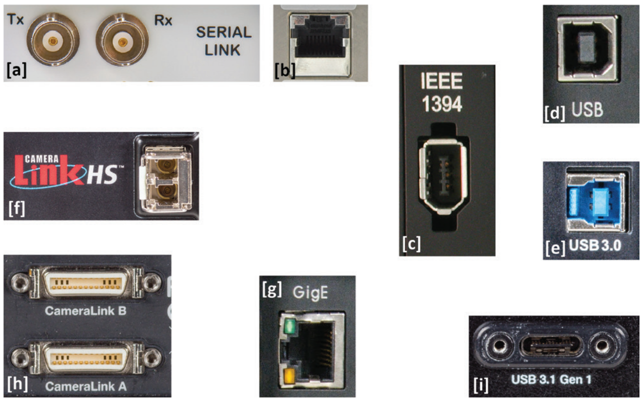


Figure 1: Photos of a variety of image data interface connectors: [a] proprietary highspeed serial data interface based on coaxial cables, [b] proprietary highspeed serial data interface based on LAN cables, [c] IEEE 1394 a "Firewire" interface, [d] USB 2.0 interface (device side), [e] USB 3.0 interface (device side), [f] Camera Link HS interface, [g] Gigabit Ethernet interface, [h] Camera Link Full interface and [i] USB 3.1 Gen 1 interface.

developed a digital interface called Channel Link. This interface was adapted by the Automated Imaging Association (AIA) as an official Vision Standard called Camera Link in October 2000 (fig. 1 [h], fig. 2 middle camera and fig 3. [b]). The Camera Link interface started with a data bandwidth of 100 MB/s and advanced to over 800 MB/s of bandwidth with a later release in 2012. Camera Link's simple hardware reduces camera costs but increases system costs, as it requires the use of special frame grabber boards and demanding high quality transmission cables to operate.

Around the same time, a very successful consumer computer interface was introduced to the market: Universal Serial Bus (USB). Since 2000, USB has been available in Version 2.0 (fig. 1 [d] and fig. 3 [d]), which provides nearly 40 MB/s of bandwidth sufficient for small-resolution cameras. One of the greatest advantages of USB 2.0 is its widespread availability as the main interface for consumer computer peripherals like keyboards, printers, and scanners. Most desktop and notebook computers come with USB as a standard interface. In 2008, USB technology took a major step forward with USB 3.0 (later called USB 3.1 Gen 1, see fig. 1 [e] & [i], fig. 2 right camera and fig. 3 [f]). This latest USB interface supports a data bandwidth of nearly 450 MB/s and an additional delivery of power via cable up to 15 W, enabling high-performance single-cable cameras. New capabilities with USB 3.2 allow for power supplies up to 100 W and a bandwidth of approximately 1800 MB/s.

Figure 2: Same model of an sCMOS camera with three different image data interfaces. From left to right: Camera Link HS, Camera Link (full) and USB 3.0.

Ethernet, one of the IEEE's oldest computer interfaces, is also significant in the history of camera interfaces. The development of Gigabit Ethernet (GigE) in 1999 allowed for a bandwidth of approximately 120 MB/s and leveraged the complete infrastructure of a network. GigE makes it possible to connect several cameras on a single port using Ethernet Switches, with the use of very long cables (up to 100 m in length) extending the scope of application. Ethernet also provides power over cable. In 2006, GigE Vision (see fig. 1 [g] and fig. 3 [e]) became the AIA's standard control and image transmission protocol, replacing manufacturers' proprietary communication protocols. All camera manufacturers eventually supported the use of 10 GigE, GigE with Channel Bonding (increasing bandwidth combining several cables to a virtual transfer channel), NBASE-T (5 G Ethernet). 40 G and 100 G Ethernet followed.

GigE and GigE Vision laid the foundation for a generic camera interface called GenICam in 2006, hosted by the European Machine Vision Association (EMVA). This common control and data transmission protocol was a big step forward to improve compatibility over camera manufacturers' proprietary protocols. The GenICam protocol was compatible with both Ethernet and USB, creating a new standard called USB Vision. Future camera interfaces will also use GenICam. GenICam defines a common method to control cameras and frame grabbers, allowing customers and system integrators to develop applications hardware separately.

Camera Link eventually reached limitations in bandwidth and cable length, and certain applications are not suited to standard interfaces like USB and GigE. This led to the development of new standards: CoaXPress (see fig. 3 [h]) by the Japan Industrial Imaging Association (JIIA) in 2010, and Camera Link HS (see fig. 1 [f], fig. 2 left camera and fig. 3 [c]) by the AIA in 2012.

The main goal of CoaXPress (CXP) is to use a single coax cable for camera control, image data transmission, power supply and camera trigger. The first version provides a bandwidth of approximately 580 MB/s in its fastest form (CXP-6) and 116 MB/s in its slowest form (CXP-1). Additionally this interface is scalable by using several cables with a single camera to increase bandwidth. In version 2.0, CXP-12 will have a bandwidth of 1160 MB/s across a single cable with up to 13 W of power usable by the camera. Depending on the link speed, a minimum cable length of 68 m (CXP-6) is possible. Like Camera Link, CXP requires a special chipset for data transmission (which is only available from Microchip) and high-quality cables rather than cheap coax cables. CXP uses an uncommon computer interface frame grabber.

Camera Link HS (CLHS) succeeds the popular Camera Link interface. It provides a very high bandwidth, superior data reliability and long cable length in an affordable design using off-the-shelf hardware. It uses Ethernet-based hardware (specifically the fiber standard of 10G Ethernet/10GBASE-R). Fiber transmission is highly reliable, with immunity to electromagnetic interference (EMI) and an effect forward error correction protocol to correct bit error bursts of up to 11 bits. There are no limits to cable lengths with fiber cables; over 10 km can be achieved easily and cost-effectively. The first version of CLHS achieved bandwidth of up to 1187 MB/s from a single fiber with a bitrate of 10.3125 GB/s. Like CXP, the interface is scalable to increase the bandwidth of a single camera to up to 8309 MB/s. In version 2.0, the useable bitrate is increased up to 15.9375 GB/s for a total bandwidth of 1834 MB/s for image data over a single fiber cable, and triggering of the camera was also possible.

DATA INTERFACES

Like CoaXPress, CLHS requires an uncommon computer interface frame grabber.

A technical question arises: is there a solution for high image data transfer and long cable length without the overhead of a special interface protocol like 10 GigE, CXP or CLHS? The answer lies with the external PCIe (computer bus), and Thunderbolt (fig. 3 [i]), a tunnel for PCIe. In both cases special fiber cables can be used. Some camera manufacturers use both interfaces, and both can use special fiber cables. However, neither is popular, and PCIe requires complex camera hardware.

Of course, there are many other interfaces available, like HD-SDI by SMPTE. However, these interfaces target specific markets and applications and are not classic interfaces for machine vision and scientific cameras.

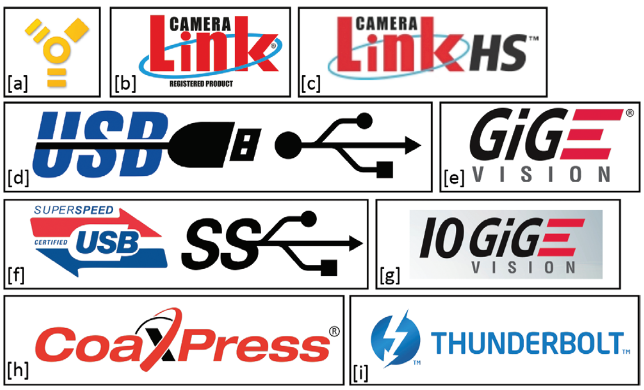


Figure 3: A selection of logos of the different standard image data interfaces: [a] IEEE 1394 “Firewire”, [b] Camera Link, [c] Camera Link HS, [d] USB 2.0, [e] GigE Vision, [f] USB 3.0/3.1 Gen 1, [g] 10 GigE Vision, [h] CoaXPress, [i] Thunderbolt.

Name	Cable Type	Cable Length	Bandwidth (MB/s)
Firewire	Twister Pair/Fiber	4.5 m / 100 m	125
USB 2.0	Twisted Pair	5 m	50
USB 3.1 Gen 1	Twisted Pair	3 m	450
USB 3.1 Gen 2	Twisted Pair	2 m	1100
USB 3.2	Twisted Pair	2 m	2200
GigE	Twister Pair/Fiber	100 m / 10 km	118
10 GigE	Twister Pair/Fiber	100 m / 10 km	1183
CoaXPress	Coax Cable	212 m / 68 m	116 / 580 (single link)
Camera Link HS	Fiber	10 km	1183 (single link)
Thunderbolt	Twisted Pair	3 m	515 (PCIe Gen 2 x2)

Table 1: Data interfaces for image data transfer with maximum cable length and bandwidth

Regarding the hardware, there are similarities between 10 GigE (10 GigE Vision) and Camera Link HS, as both use the 10 Gigabit Ethernet network technology. However, each uses a different protocol and different overhead and integrated features for error correction. Since CLHS doesn’t use the standard network protocol, it has a much leaner protocol overhead compared to 10 GigE Vision, and even the integrated forward error correction for safe image data transmission doesn’t generate any additional overhead.

To conclude, we return to the titular question of this chapter: why are special interfaces necessary? As camera technology moves forward, the amount of image data that must be transferred to computers for storage and processing is continuously increasing in all fields of application. The demand for fast, reliable data transfer increases in turn.

Scientific applications are a prescient example. High-speed cameras can record 36 GB of image data in seconds, but it takes much longer to download that data to a computer. It is common in life science to collect, process and store this volume of data in everyday applications. Special camera interfaces enable reliable streaming data transfer from the camera to the computer, and depending on the application, across larger distances.