THUNDERBOLT™

TECHNOLOGY BRIEF

Thunderbolt™ 3

More speed. More pixels. More possibilities.

This document is designed to be a slightly more in depth summary of Thunderbolt™ 3, if you want a brief overview, see here.

Major computing industry trends have necessitated a new form of I/O that can deliver on the vision of future computing:

- Continued advances of video and audio media quality (4K content and displays) creating unprecedented amounts of data
- Relentless shrinking of system form factors with less room for multiple, large connectors
- Dramatic growth of processing and storage from new technologies and the march forward of Moore's law
- Demand for the flexible performance from a single system to meet the needs of a desk bound creator and an on-the-go mobile consumer at the same time

These seemingly disparate demands have created a push for a convenient, standards-based, multi-function, small form factor, and of course – fast – interface to meet the demands of media, storage, docking, and future expansion consumer demands.

Thunderbolt 3 is a way to gain uncompromised performance of the fastest data, and the highest quality display technology available in their PC – all over a single standard connector.

With the advent of new display technologies presenting an amazing visual experience for media, the new ultra high resolution formats and screens create an explosion of bits needing to be sent from hard drive, or I/O, to your screen.

Whereas uncompressed 1080p content consumed around 4 Gbps of data, uncompressed 4K consumes nearly 15 Gbps, or 16 million more pixels than HD. Additional storage, CPU, and I/O performance is needed to handle this substantial increase in data (see Figure 1).

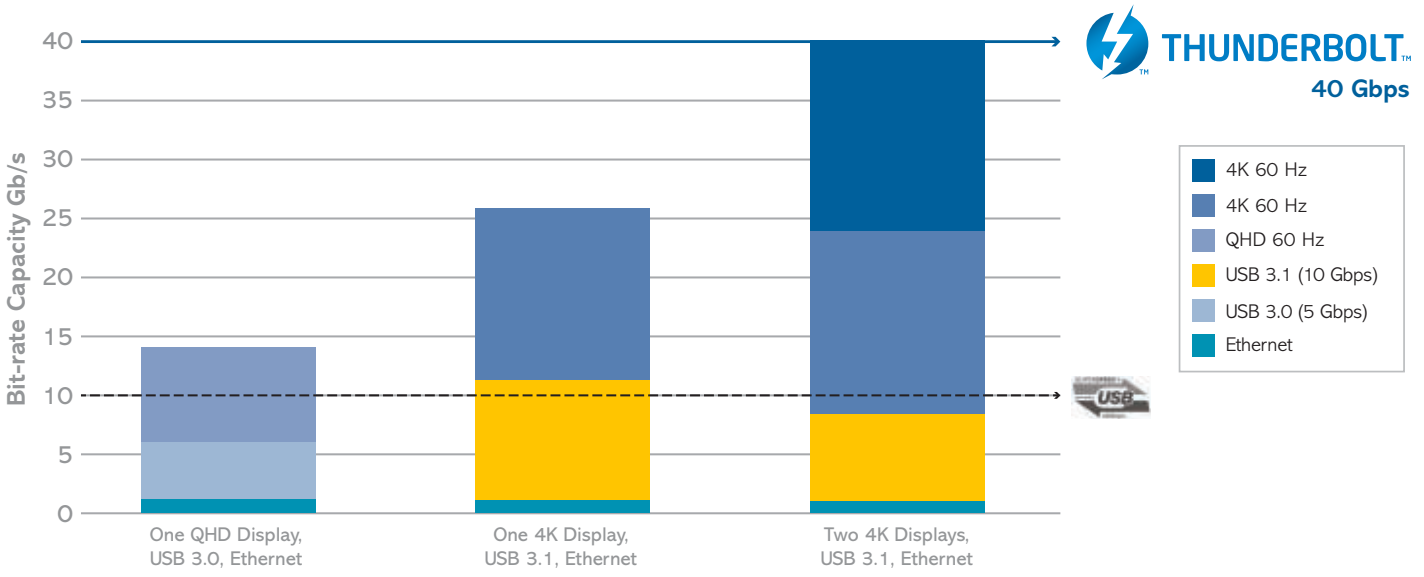

Figure 1. See "What Gets Priority?" section on page 6.

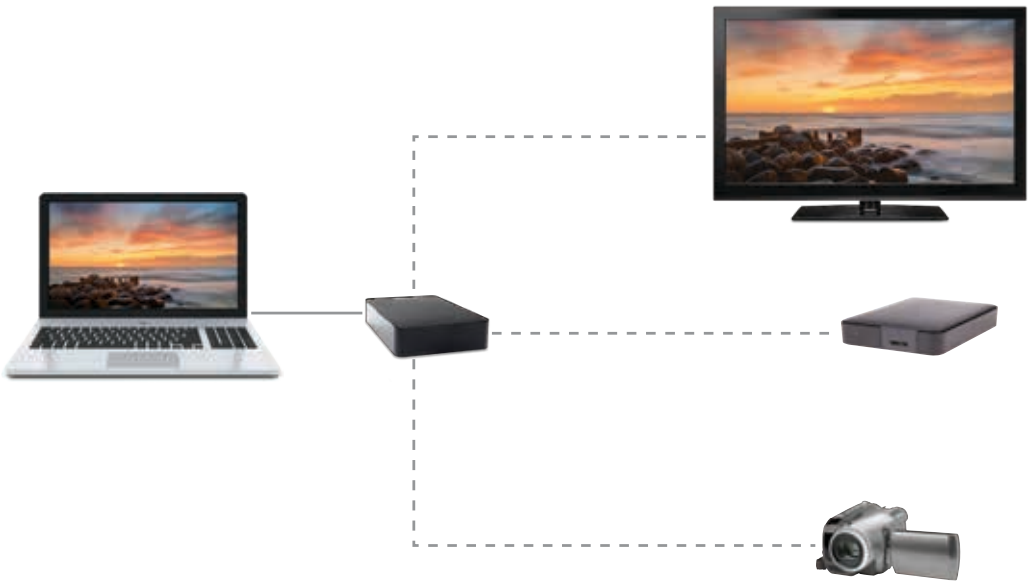

Figure 2.

In addition, many consumers have found the comfort and convenience of devices that are easy to carry around, like handheld or small notebook computers, are becoming powerful enough to be able to handle many of the more demanding tasks once relegated to desk based systems.

A barrier to bridge this vision of a portable system being a fully-fledged work horse at a desk is the expandability of the system via some interconnect or dock (see Figure 2).

In premium desktop and WS markets, there is a yearning for a path to link systems together for faster connection speeds than can be achieved with basic Gigabit performance, but without the complexity and cost of 10 GbE and the accompanied switching hardware.

And of course there is the lack of ability to play the latest 3D intensive games on a notebook that can also be hyper mobile.

However, Intel has a solution.

The Thunderbolt Vision

Thunderbolt is a sophisticated technology, with a simple vision – The connector that just works.

Intel believes Thunderbolt can be the only external connector you need for your PC. Power? Data? Display? External graphics? All of the above simultaneously, with the most bandwidth, through a dynamically allocated link? Yes…

Thunderbolt is the single connector that can deliver on all your connectivity needs, from the mundane to the complex. Connect to a dock and expand to your legacy peripherals, directly cable to a monitor or two, or connect to a single (or series of) high performance dedicated Thunderbolt devices. You can do all this through a single connector which can also charge your system at the same time.

Importantly, Thunderbolt 3 builds on the new USB-C reversible connector and integrates the latest USB 3.1 technology to deliver high performance and high compatibility to the existing standard.

One connector for everything; that is the Thunderbolt vision. A consumer doesn't need to know anything other than if they plug their device into a Thunderbolt 3 port, everything will just work.

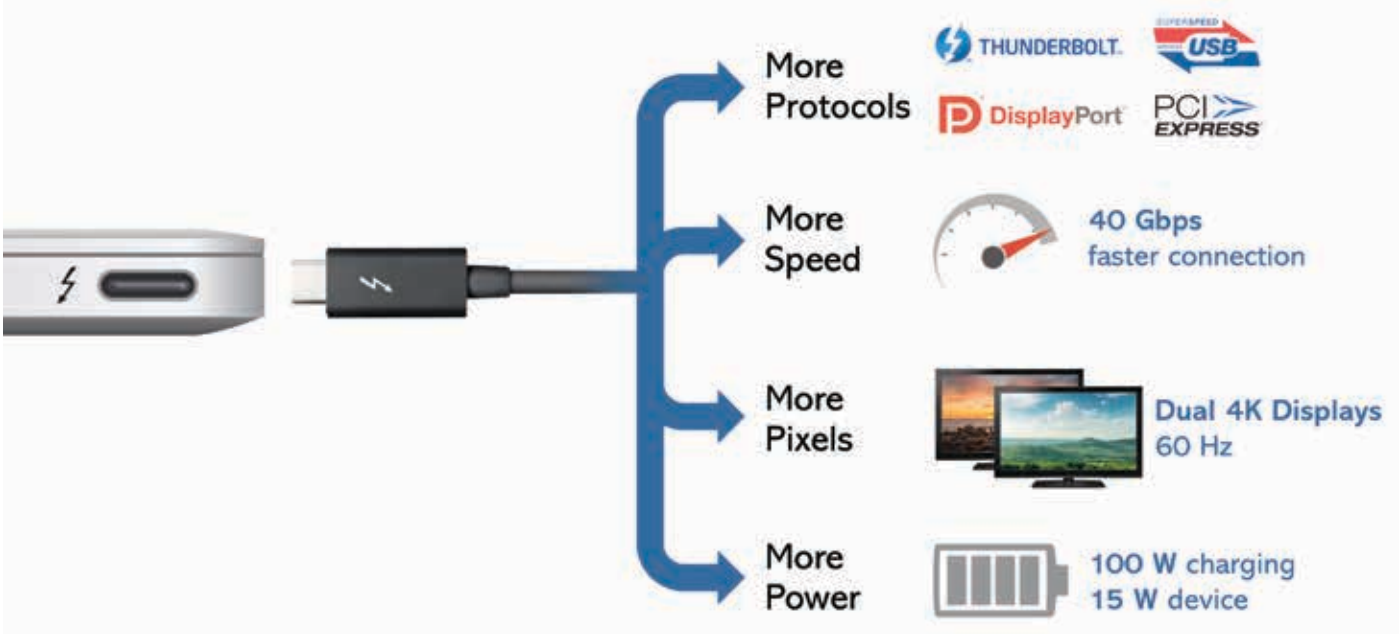

Figure 3.

How Thunderbolt 3 Works

Fundamentally, Thunderbolt is a tunneling architecture designed to take a few underlying protocols, and combine them onto a single interface, so that the total speed and performance of the link can be shared between the underlying usages of these protocols – whether they are data, display, or something else.

At the physical interface level, Intel's Thunderbolt 3 silicon builds in a few important features:

- A physical interface (PHY) layer that can dynamically switch it's operating mode to drive either:
  - USB 2.0, 3.0, and 3.1
  - DisplayPort 1.1 and 1.2a
  - Thunderbolt at 20 and 40 Gbps
- In the Thunderbolt mode, Thunderbolt 3 port has the ability to support at least one or two (4 lane) DisplayPort interface(s), and up to 4 lanes of PCI Express Gen 3

Different Connection Modes

With Thunderbolt 3 having dynamic detection of the capabilities of the cables and devices that are plugged in, there are several modes that can be detected and activated, in a way generally transparent to the consumer.

USB Only Mode

If a USB device is plugged in, a USB host controller inside the Thunderbolt 3 enabled system is activated, and the Thunderbolt 3 silicon PHY drives USB (2.0, 3.0, or 3.1) signals to the USB-C port. In this mode, a Thunderbolt 3 port behaves exactly like a typical USB-C 3.1 enabled connector.

DisplayPort Only Mode

If a DisplayPort display or adapter is plugged in, the Thunderbolt 3 enabled system will detect this, and switch the pins driving the USB-C connector to the DisplayPort alternate mode. Thunderbolt 3 silicon will then act as a router to send raw DisplayPort traffic from the graphics engine within the system out over the USB-C connector pins and pass that DisplayPort link directly to the display or adapter.

In this mode, a Thunderbolt 3 enabled USB-C port will support a single four lane (4 x 5.4 Gbps, or HBR2) link of DisplayPort. These four links run across the two pairs of high speed wires in the USB-C connector and cable. This kind of DisplayPort link can support a single, uncompressed display, at 4K resolution at 60 Hz.

DisplayPort and USB Mulit-Function Mode

In this alternate mode of operation, one of the high speed connector pin pairs of signals will be dedicated to DisplayPort (now 2 lanes at 5.4 Gbps) and one to USB 3.1 This allows for a basic connectivity for data and display devices such as docking stations or data and display dongles.

With two lanes of DisplayPort 1.2a, resolutions Quad HD (QHD) can be achieved, or 2560 x1600 at 60 Hz.

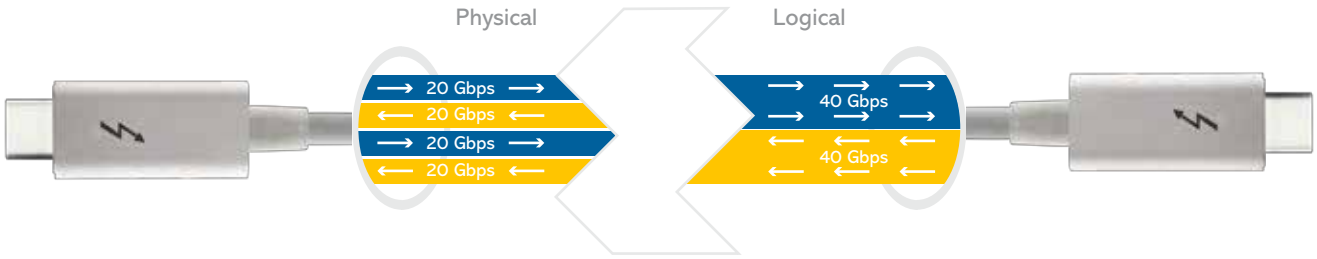

Figure 4.

Thunderbolt 3 Mode

If a cable and device supporting Thunderbolt are plugged in, the Thunderbolt silicon activates its highest capability mode and configures four high-speed links at either 10 Gbps or 20 Gbps (depending on cable and device support) to support the Thunderbolt transport. This provides bidirectional data rates of 20 or 40 Gbps (Figure 4 illustrates the 40 Gbps case).

Additionally, to fill this Thunderbolt link, the silicon extracts and routes up to 4 lanes of PCI Express Gen 3 (4 x 8 Gbps) and up to two full (4 lane) links of DisplayPort out over the Thunderbolt cable and connector to the device(s) attached downstream from the host system.

The first device in the Thunderbolt link has a few options of how it can use this underlying PCI Express and DisplayPort traffic:

- Consume the data from PCI Express by connecting it to PCI Express enabled devices such as networking, storage, cameras, DSP or FPGA adapters, or perhaps some new custom product
- Consume the DisplayPort links by exposing them to a display panel, or a display connector(s)
- Pass the unused PCI Express or DisplayPort data capabilities down to another Thunderbolt device(s) via a second, daisy chained Thunderbolt 3 port
- Some or all of the above

If the Thunderbolt device has two Thunderbolt ports, the dynamic mode configuration described above will be configured on the downstream or second port of the device when another cable and device are plugged in to it. Each mode will still be supported on this downstream connector, and data and display traffic will be provided as demanded to that downstream port.

If each consecutive device is a Thunderbolt device, up to 6 devices in a chain can be supported. At any time if a USB or DisplayPort device is plugged directly into the USB-C connector downstream from any device, then the Thunderbolt daisy chain is terminated at that point.

Thunderbolt Networking Mode

An additional, powerful capability of Thunderbolt also allows the connection of two or more hosts directly (or on separate ends of a Thunderbolt chain) via Thunderbolt. In this case, Thunderbolt has software which creates an IP networking link between these systems (see Figure 5).

This networking mode allows for the Thunderbolt interface to act as a virtual Ethernet adapter and transfer traffic over the PCI Express interface the Thunderbolt silicon has in each host system.

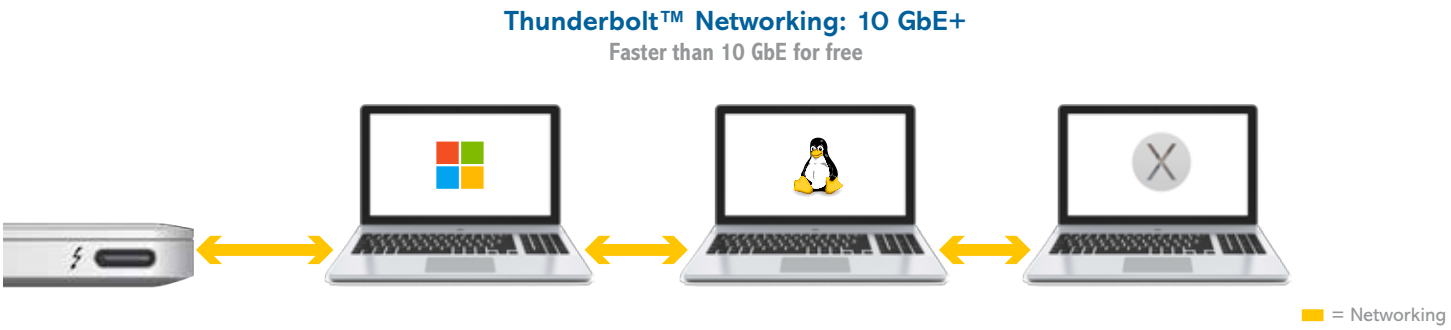

Figure 5.

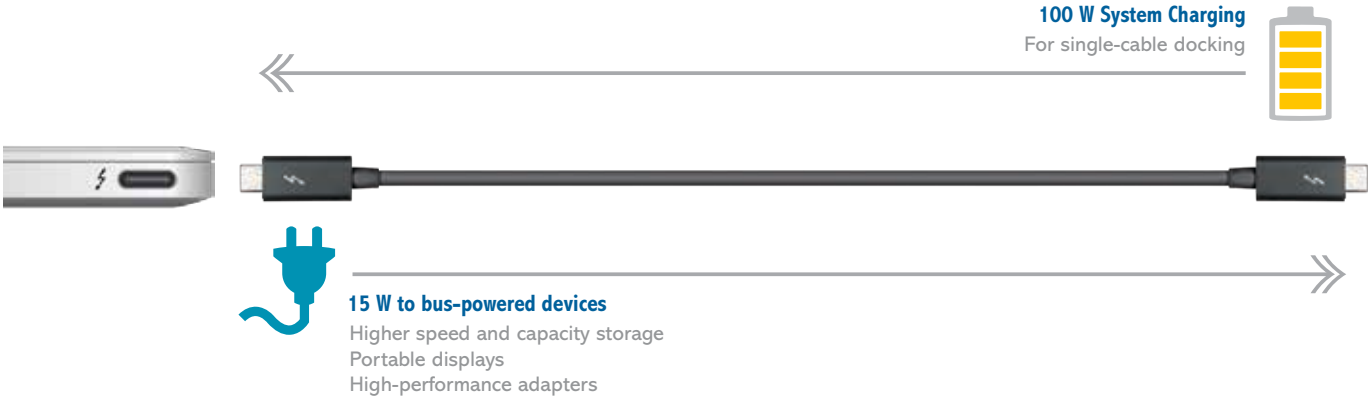

Figure 6.

Power Delivery and Charging

In each of the modes listed above, the Thunderbolt 3 system (if designed to support this by the system manufacturer) can also request to charge over the connector from a device or adapter designed for delivering power to the system, up to 100 W, via the USB-PD specification.

In this way, it is possible for the Thunderbolt 3 enabled USB-C connector to support charging, display, data, or all of them at the same time in various configurations.

Separately, but related, every USB-C port enabled with Thunderbolt 3 supports the basic USB 2.0 and USB 3.0/3.1 power delivery modes (power sent from the system to a device). In addition to this, Thunderbolt 3 provides the ability of the host system to send 15 W of power on at least one port if a Thunderbolt 3 device that requires bus power is connected (see Figure 6).[1]

This power delivery allows Thunderbolt devices to support additional performance and capabilities given this extra power. Also, just like a two port Thunderbolt device supports the same capabilities on its downstream port as the Thunderbolt host, this also holds true for power delivery.

How Thunderbolt 3 Allocates Bandwidth

There are some interesting intricacies of how a Thunderbolt host assigns its underlying data and display resources once a device or series of devices are connected and demanding display and data.

How it Works

A Thunderbolt 3 port supports up to the following:

- Each connector must be provided with at least the equivalent of two lanes of PCI Express Gen 3 data
- Each connector must be provided at least one full DisplayPort 1.2a (four lane) interface

Starting with Intel systems based on the 100 Series chipset, Thunderbolt 3 is delivered via a series of discrete silicon devices that have varying capabilities. The dual port sku supports two Thunderbolt 3 connectors, and takes 4 lanes of PCI Express Gen 3 as an input, and 2 full (four lane) links of DisplayPort 1.2a.

The single port sku supports a single Thunderbolt 3 connector.

In general, if a system has a single Thunderbolt 3 port, the connectivity behind that port could be as high as four lanes of PCI Express Gen 3 with dual DisplayPort links. It could also be as little as two lanes of PCI Express Gen 3, with a single DisplayPort link.

In each case, the Thunderbolt interface itself doesn't change, it is still 40 Gbps; however, the underlying source data and display may be more limited.

What Gets Priority?

Note that there are many cases where the underlying PCI Express and DisplayPort traffic will not consume the full 40 Gbps Thunderbolt 3 interface, but you will also note that in some of the configurations described, the amount of data and display together from these underlying protocols will consume more than 40 Gbps.

As a reminder, four lanes of PCI Express Gen 3 operate at (4 x 8 Gbps) 32 Gbps roughly. Thunderbolt 3 uses PCIe x4 gen 3 data rate with 128kB header sizes. For a single Thunderbolt chip with two ports, the x4 PCIe interface data rate is shared across the ports. Two links of (4 lane) DisplayPort 1.2 consume 2x (4 x 5.4 Gbps) or 43.2 Gbps. For both of these numbers, the underlying protocol uses some data to provide encoding overhead which is not carried over the Thunderbolt 3 link reducing the consumed bandwidth by roughly 20 percent (DisplayPort) or 1.5 percent (PCI Express Gen 3). But regardless, adding both together gets you above 40 Gbps.

Because a Thunderbolt 3 chip can support either one or two connectors, there is the need to provide more capability than can be used on a single connector. Many Thunderbolt 3 usages are around single connector consolidation, but there are also many consumers who want huge expansion with different devices on each port.

So if a consumer stresses a specific Thunderbolt port, and attempts to use dual simultaneous displays at high resolution and additional PCI Express data, the Thunderbolt 3 silicon will prioritize the display traffic first and throttle the (PCI Express) data traffic. When each DisplayPort 1.2 link is establish (via either a downstream Thunderbolt display, or via a downstream dongle to DisplayPort), the Thunderbolt silicon checks the maximum data rate that the link can demand, and ensures there is enough Thunderbolt link bandwidth available.

For DisplayPort 1.2, the maximum bandwidth on the Thunderbolt interface is about 17 Gbps of data, so for a 20 Gbps Thunderbolt link, a single DisplayPort 1.2 interface can be used, and for a 40 Gbps Thunderbolt link, two DisplayPort interfaces can be connected (see Figure 7).

After the link is established, Thunderbolt only transmits the display traffic as demanded, so even though about 17 Gbps of available data bandwidth is needed to setup a DisplayPort 1.2 connection, if the screen resolution is set to 1080p, only ~4 Gbps of the Thunderbolt link is used for display. If it is a 4K display, perhaps 14 Gbps will be consumed depending on the exact pixel count, color depth, and refresh rate.

If a display is plugged in exceeding the maximum number of displays available from the Thunderbolt silicon, the display is lit up, and the first display in the chain is deactivated.

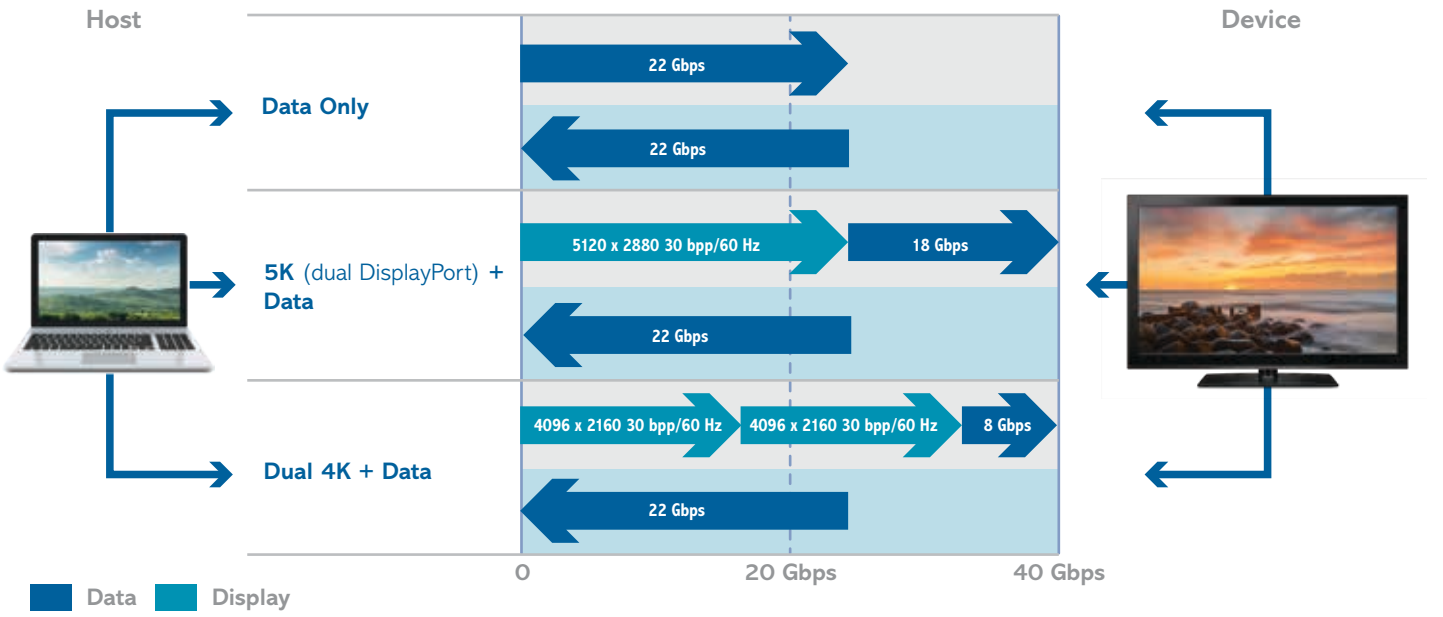

Figure 7.

It is important to note that the PCI Express traffic on the Thunderbolt interface is then allowed to consume the entire remainder of the link. Unlike display traffic in which a fixed resolution and color depth is equal to a fixed bandwidth, PCI Express and data traffic in general are more variable in nature. So PCI Express devices will continue to function with a variable rate of bandwidth, but certain performance levels may not be achieved if two high resolution displays are being used on the same port.

However, it is key to understand that the Thunderbolt interface is bidirectional, while display traffic is mostly outbound from the host system. So if the Thunderbolt link is using a PCI Express device to route traffic to the host system, that PCI Express bandwidth is mostly unaffected by outbound display traffic (outside of some flow control impacts).

A Few Final Words

Thunderbolt 3 is an amazingly powerful technology. It is enabling a new commanding set of experiences with unparalleled speed and simplicity, while building on top of the standards based USB-C connector.

Thunderbolt™ 3 brings Thunderbolt to USB-C at speeds up to 40 Gbps, creating one compact port that does it all. Delivering the fastest, most versatile connection to any dock, display, or data device. For the first time, one computer port connects to Thunderbolt devices, every display, and billions of USB devices. A single cable now provides four times the link speed and twice the video bandwidth of any other cable, while also supplying power. It's unrivaled for new uses, such as 4K video, single-cable docks with charging, external graphics, and built-in 10 GbE networking. Simply put, Thunderbolt 3 delivers the best USB-C experience.

It just works.

THUNDERBOLT™

To learn more visit **https://thunderbolttechnology.net/**

1. On some tablets, 15W power delivery won't be provided.

Intel technologies' features and benefits depend on system configuration and may require enabled hardware, software or service activation. Performance varies depending on system configuration. No computer system can be absolutely secure. Check with your system manufacturer or retailer or learn more at intel.com.

As compared to other PC I/O connection technologies including eSATA, USB, and IEEE 1394 Firewire*. Performance will vary depending on the specific hardware and software used. Must use a Thunderbolt-enabled device.