

Thunderbolt™ 3

The USB-C that does it all.

TECHNOLOGY BRIEF



This document provides an in-depth summary of Thunderbolt 3. A brief overview is [available here](#).

Major trends in the computing industry have necessitated a new form of I/O to address challenges including:

- Continued advances in video and audio media quality (4K content and displays), creating unprecedented amounts of data
- Relentless shrinking of system form factors, leaving 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 flexible performance from a single system to simultaneously meet the needs of desk-bound creators and on-the-go mobile consumers

These seemingly disparate trends have created a growing demand for a convenient, standards-based, multi-function, small form factor, and of course – fast – interface to meet consumers' ever-increasing needs for the latest media, storage, docking, and other capabilities.

Thunderbolt™ 3 gives you exactly that: uncompromised performance of the fastest data, and the highest-quality display technology available in your PC – all over one standard connector.

New demands, new challenges

New display technologies present an amazing visual experience for media of all types. But the latest ultra-high-resolution formats and screens also create a mass of data that needs to be sent from a hard drive, or I/O, to your screen.

Whereas uncompressed 1080p content consumed about 4 Gbps of data, uncompressed 4K consumes nearly 15 Gbps, or 16 million more pixels than HD. Handling this massive increase in data requires additional storage, CPU, and I/O performance.

For a concrete example of how these kinds of data rates can add up in real life, you can see the chart below. Essentially it shows three typical usages that utilize uncompressed display and storage traffic. You can see by combining data and display on a single cable, data rates rise dramatically and necessitates Thunderbolt 3. In the third case (dual 4K + USB 3.1 storage), a scenario can be created which can even exceed 40 Gbps of outbound throughput. In the Thunderbolt case this means that displays get highest priority and their full allotment (see Figure 1).

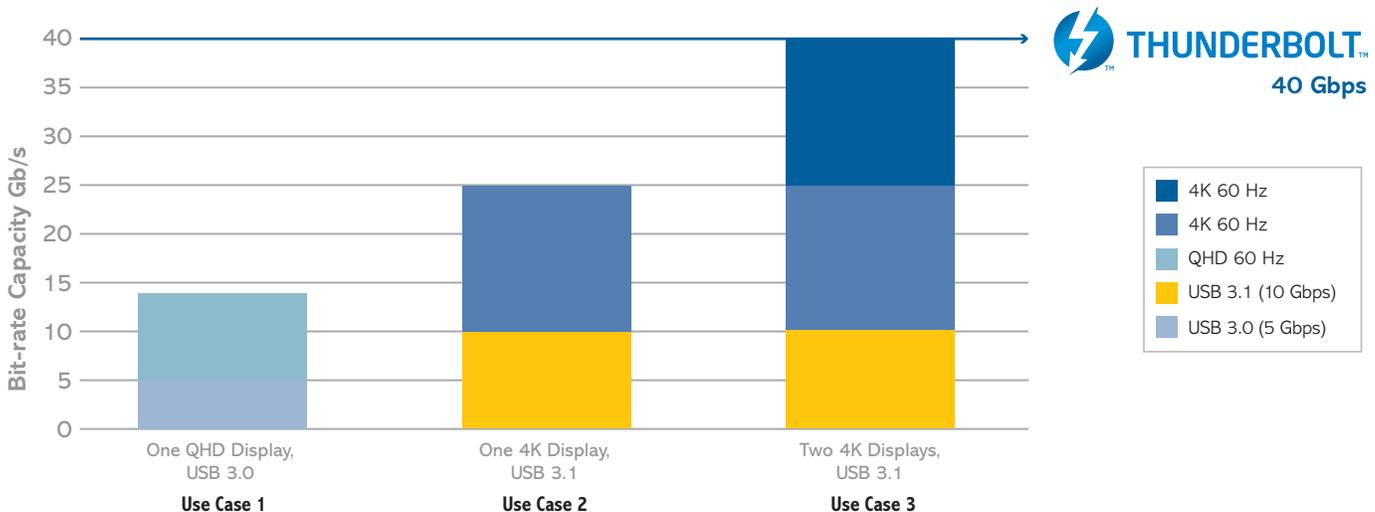


Figure 1. See "What Gets Priority?" section on page 6.

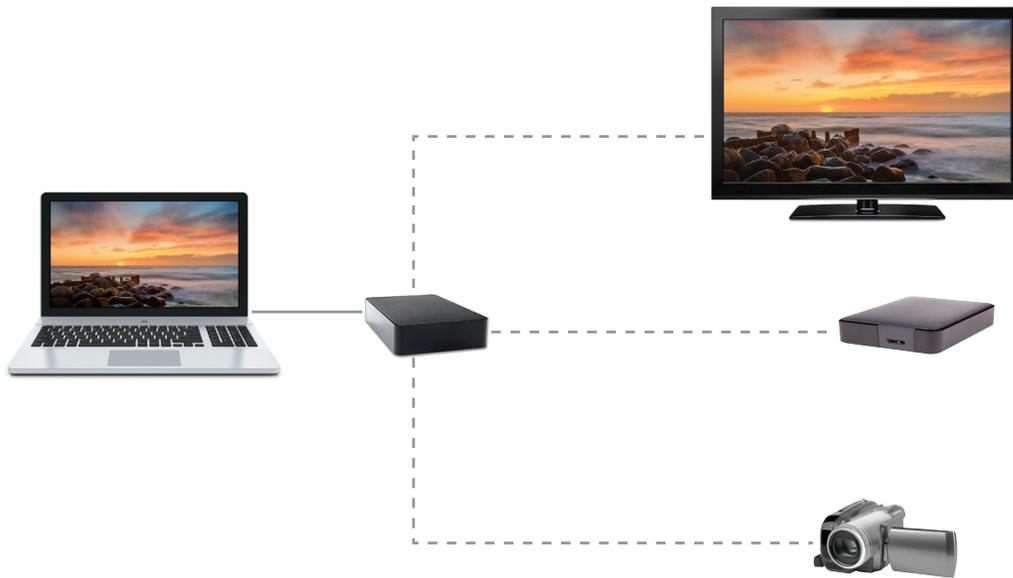


Figure 2.

Another challenge relates to the growing popularity of mobile devices. Consumers appreciate the comfort and convenience of these devices, such as handheld or small notebook computers, and the devices are rapidly becoming powerful enough to handle many demanding tasks once relegated to desk-based systems.

For these portable systems to operate as fully-fledged workhorses at a desk, the systems need to be expandable via some interconnect or dock (see Figure 2).

Especially for those who want premium desktops and workstations, there needs to be a way 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.

One final challenge relates to consumers' desire to be able to play the same 3D intensive games on their notebook as on their desktop.

Intel has a solution to address all these challenges.

The Thunderbolt Vision: One Connector for Everything

Thunderbolt is a sophisticated technology, with a simple vision: the USB-C that does it all.

Intel believes that Thunderbolt is the only connection 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 and more with a single connector through which you can also charge your system.

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

One connector for everything; that is the Thunderbolt vision. All you really need to know is that if you plug your device into a Thunderbolt 3 port, everything just works.

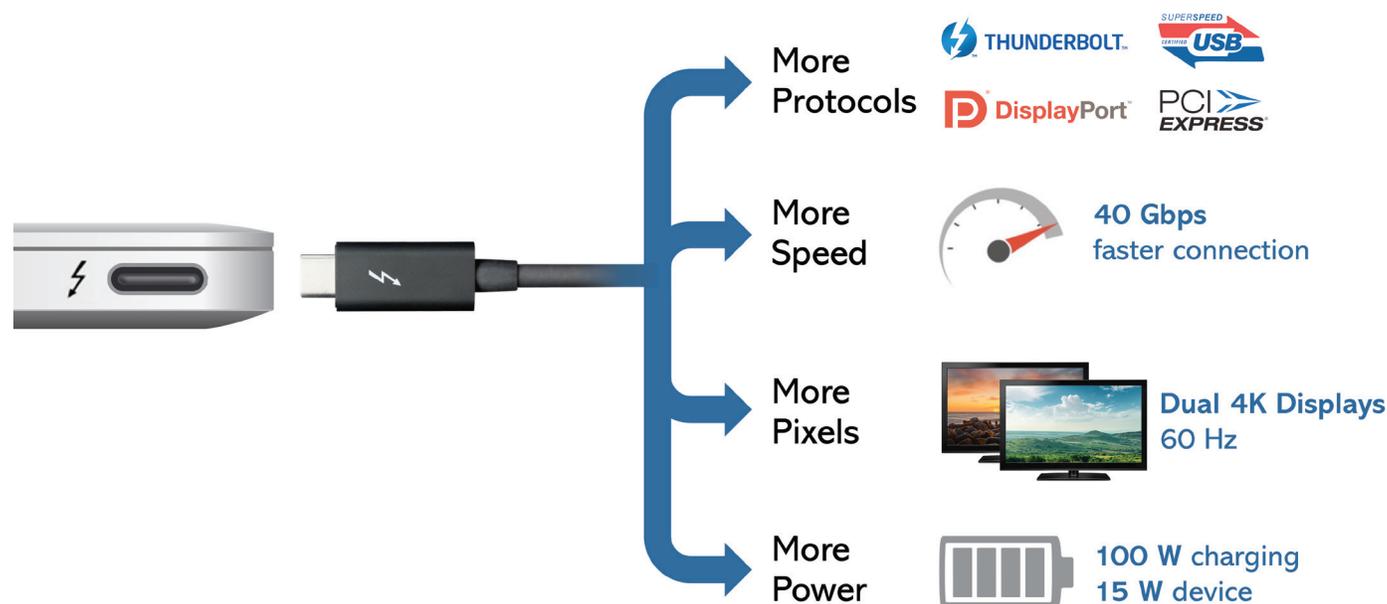


Figure 3.

How Thunderbolt 3 Works

Fundamentally, Thunderbolt is a tunneling architecture designed to take a few underlying protocols and combine them onto a single interface. That way, 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 its operating mode to drive either:
 - USB 2.0, 3.0, and 3.1
 - DisplayPort* 1.1 and 1.2a
 - Thunderbolt at 20 Gbps and 40 Gbps
- In the Thunderbolt mode, the Thunderbolt 3 port has the ability to support at least one or two (4-lane) DisplayPort interface(s), and up to four lanes of PCI Express Gen 3.

Different Connection Modes

Thunderbolt 3 dynamically detects the capabilities of the cables and devices that are plugged in. Several modes can be detected and activated, in a way that is generally transparent.

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, the 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 Mixed Mode

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

With two lanes of DisplayPort 1.2a, resolutions at Quad HD (QHD) can be achieved, or 2560 x 1600 at 60 Hz.

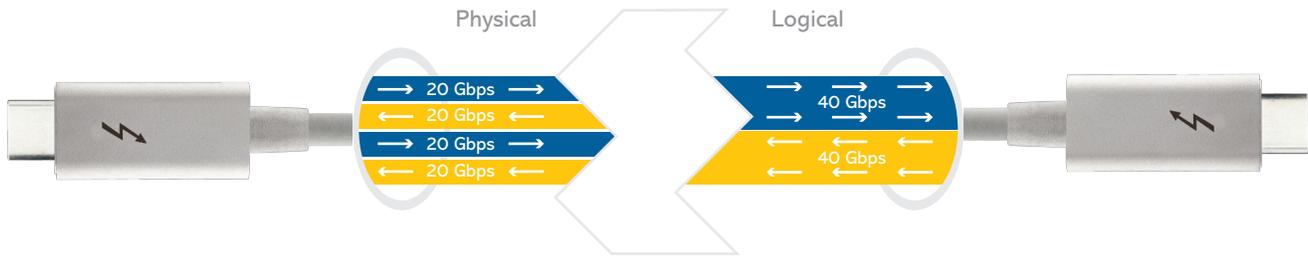


Figure 4.

Thunderbolt 3 Mode

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

Additionally, to fill this Thunderbolt link, the silicon extracts and routes up to four lanes of PCI Express Gen 3 (4 x 8 Gbps) and up to two (four-lane) full 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 six 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 allows two or more hosts to be connected directly (or on separate ends of a Thunderbolt chain) via Thunderbolt. In this case, Thunderbolt has software that 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 that the Thunderbolt silicon has in each host system.

Thunderbolt™ Networking: 10 GbE+
Faster than 10 GbE for free

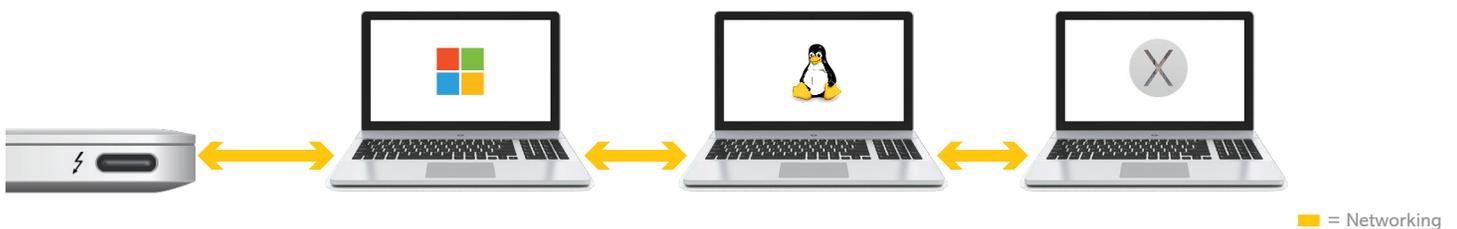


Figure 5.

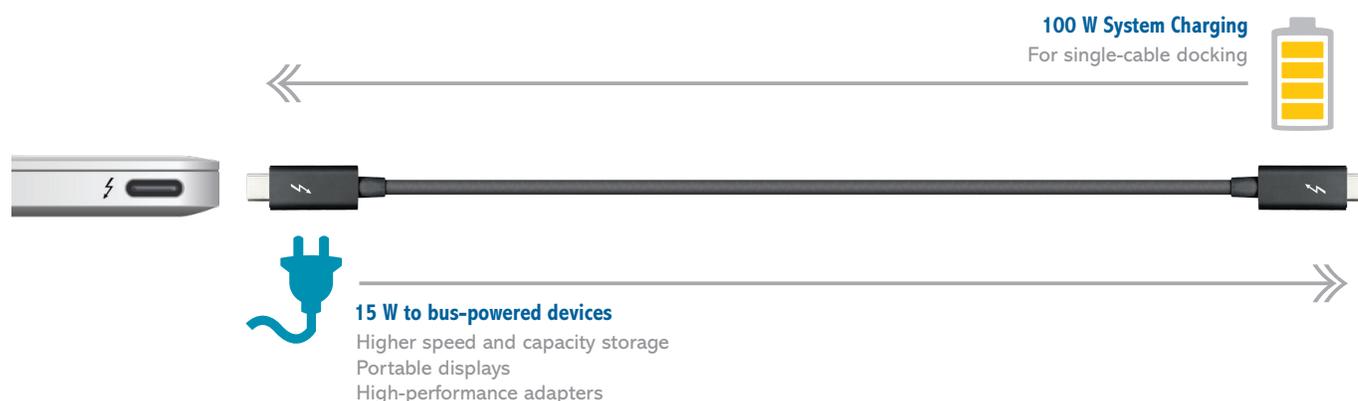


Figure 6.

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 100W, via the USB-PD specification.

In this way, the Thunderbolt 3-enabled USB-C connector can support charging, display, data – or all three – 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). Thunderbolt 3 also guarantees the ability of the host system to send 15W 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. Also, just as a two-port Thunderbolt device supports the same capabilities on its downstream port as the Thunderbolt host, the same holds true for power delivery.

How Thunderbolt 3 Allocates Bandwidth

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

The Basics

A Thunderbolt 3 port requires that each connector be provided with at least:

- The equivalent of two lanes of PCI Express Gen 3 data
- 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. It takes four lanes of PCI Express Gen 3 as an input and two 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. And 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 roughly at 32 Gbps (4 x 8 Gbps). Two links of (four-lane) DisplayPort 1.2 consume 2 x (4 x 5.4 Gbps) or 43.2 Gbps. For both these numbers, the underlying protocol uses some data to provide encoding overhead that is not carried over the Thunderbolt 3 link, which reduces the consumed bandwidth by roughly 20% (DisplayPort) or 5% (PCI Express Gen 3). Regardless, adding both together results in a figure 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.

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 established (via either a downstream Thunderbolt display, or via a downstream dongle to DisplayPort), the Thunderbolt silicon checks the maximum data rate that 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 transmits only the display traffic as demanded, so even though a DisplayPort 1.2 interface is used, if the screen resolution is set to 1080p, for example, only about 4 Gbps of the Thunderbolt link is used for display. If it is a 4K display, perhaps 14 Gbps will be consumed.

If a display is plugged in that exceeds the maximum number of displays available from the Thunderbolt silicon, the display is lit up, and the first display in the chain is deactivated. PCI Express traffic on the Thunderbolt interface is then allowed to consume the remainder of the link.

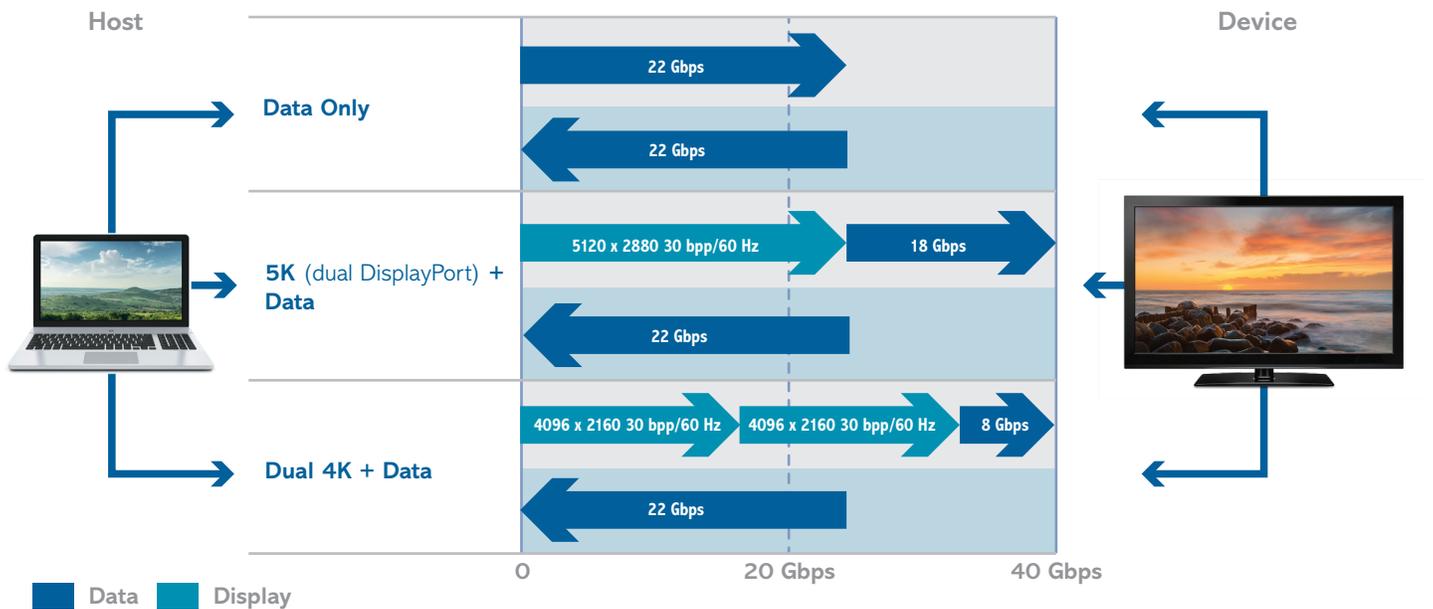


Figure 7.

PCI Express, and data traffic in general, is more variable than display traffic, in which a fixed resolution and color depth is equal to a fixed bandwidth. PCI Express devices will therefore 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. If the Thunderbolt link is using a PCI Express device to ingest traffic to the host system, that PCI Express bandwidth will be largely unaffected by outbound display traffic (outside of some flow control impacts).

Conclusion

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 data and twice the video bandwidth of any other cable, while also supplying power.

Thunderbolt 3 is 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.



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.

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