



Technology Brief

Thunderbolt™ 5

What is Thunderbolt™ Technology?

Thunderbolt technology is a best-in-class, high-speed data transfer and connectivity solution built on a strong foundation of open industry standards and protocols, as illustrated in Figure 1. It works through a USB-C connector by utilizing USB 2, USB 3, USB4, DisplayPort, and PCIe protocols to provide best-in-class capabilities for connecting monitors, docks, storage, eGFX, and other accessories. By adhering to the robust requirements of these standards, Thunderbolt ensures a strong baseline of features that deliver leading performance,¹ unrivaled simplicity, and reliable connectivity.

Intel is the steward of the Thunderbolt technology specification, with support built into Intel platforms. In addition, Intel validates and certifies all products bearing the Thunderbolt logo to ensure they meet exacting connectivity specifications that deliver a true, end-to-end, optimized solution for users. Plug it in and it just works.

Released in 2020, Thunderbolt 4 established itself as the leading USB-C connection in the industry by offering 40 Gbps throughput and other powerful features. Available in a broad range of systems and accessories, it has helped change how users think about connecting hardware and devices simply and reliably.

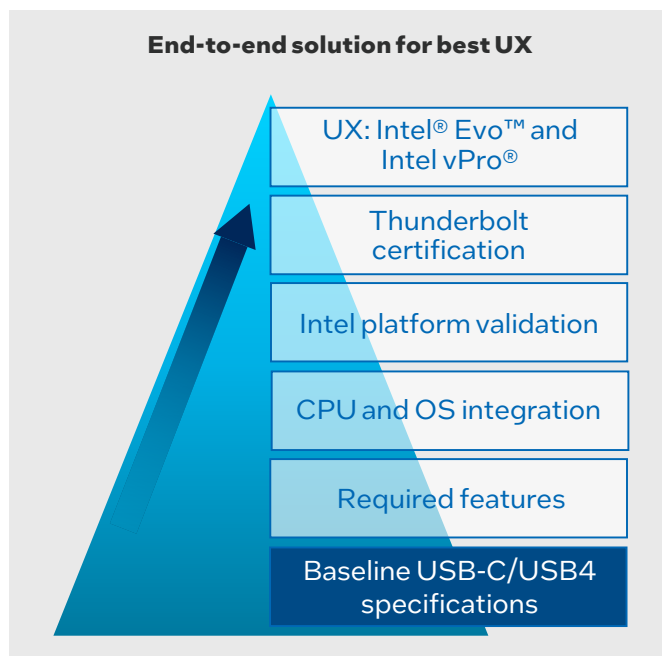


Figure 1. Thunderbolt expands USB-C/USB

Introducing Thunderbolt 5

Now, Thunderbolt 5 is pushing the boundaries of connectivity even further, leveraging the latest USB4 v2 and DisplayPort 2.1 standards to boost performance while maintaining outstanding simplicity and reliability. In this brief, we'll look at the features and benefits of Thunderbolt 5, why it's important, and how it will affect the future.

Thunderbolt 5 addresses increasing demands for display performance, data transfer speeds, and power delivery in modern computing systems. As technology evolves and user requirements expand, Thunderbolt is keeping pace, providing a seamless and powerful user experience.

Thunderbolt 5 helps maximize performance in a number of ways:

- New Bandwidth Boost capabilities enable transmit bandwidth at up to 120 Gbps, unleashing the power of high-performance systems by maximizing display performance up to 3x over Thunderbolt 4.²
- Users benefit from 2x performance for data transfer, storage, and networking.³
- The introduction of the latest PAM-3 signaling technology enables support for 80/120 Gbps over the same Thunderbolt passive cables, connectors, and PC boards that previously supported up to 40 Gbps.

Thunderbolt 5 Advances

Thunderbolt 5 provides users with all the capabilities and convenience of previous versions, plus advances to meet both today's and tomorrow's needs, as shown in Figure 2.

Feature	Thunderbolt™ 5 Technology	Thunderbolt™ 4 Technology
Exceptional Performance		
PC speed requirements	80 and 120 Gbps	40 Gbps
PC video requirements	Dual 6K	Dual 4K
PC data requirements	PCIe: 64 Gbps USB 3: 10 Gbps*	PCIe: 32 Gbps USB 3: 10 Gbps
Required PC charging on at least one computer port ⁴	Required up to 140W Available up to 240W	Required up to 100W Available up to 140W
Required PC wake from sleep when computer is connected to a Thunderbolt dock	✓	✓
Minimum PC port power for accessories	15W	15W
Thunderbolt networking ⁵	64 Gbps	32 Gbps
Unrivalled Simplicity		
One universal computer port (USB Type-C)	✓	✓
Universal cables up to 2 meters in length	120 Gbps	40 Gbps
Accessories with four Thunderbolt ports	✓	✓
Reliable Connectivity		
Mandatory certification for all shipping computers, accessories, and cables	✓	✓
Cable testing and cable quality audits for Thunderbolt cable manufacturers	✓	✓
Required Intel® VT-d-based DMA protection ⁶	✓	✓
USB4 specification compliance required	✓	✓

* Available up to USB 3: 20 Gbps

Figure 2. Characteristics of Thunderbolt 5 and Thunderbolt 4

Thunderbolt: Universal Connectivity

Thunderbolt supports multiple protocols over a single connection. It enables various accessories to connect to PCs, and to one another, simply and reliably. A single Thunderbolt connection provides a productive, clutter-free, and secure solution for notebook and desktop computers, enhancing convenience for the user. Thunderbolt 5 supports a wide range of accessories, increases data transfer rates, and enables outstanding experiences on a wide range of displays,⁷ as illustrated in Figure 3.

In addition, Thunderbolt 5 offers the simplest, most reliable, and fastest docking solutions available for connecting

all the accessories on your desk with a single, flippable, reversible cable. These solutions provide 80 Gbps to 120 Gbps throughput and are designed for compatibility with current and future devices. They also deliver up to 240W of power to drive even the highest-performance, feature-rich PCs.

A PC with Thunderbolt technology enables great connectivity even to devices that are not Thunderbolt-compliant; conversely, Thunderbolt-equipped devices work well with all PCs, whether or not those systems are equipped with Thunderbolt technology.

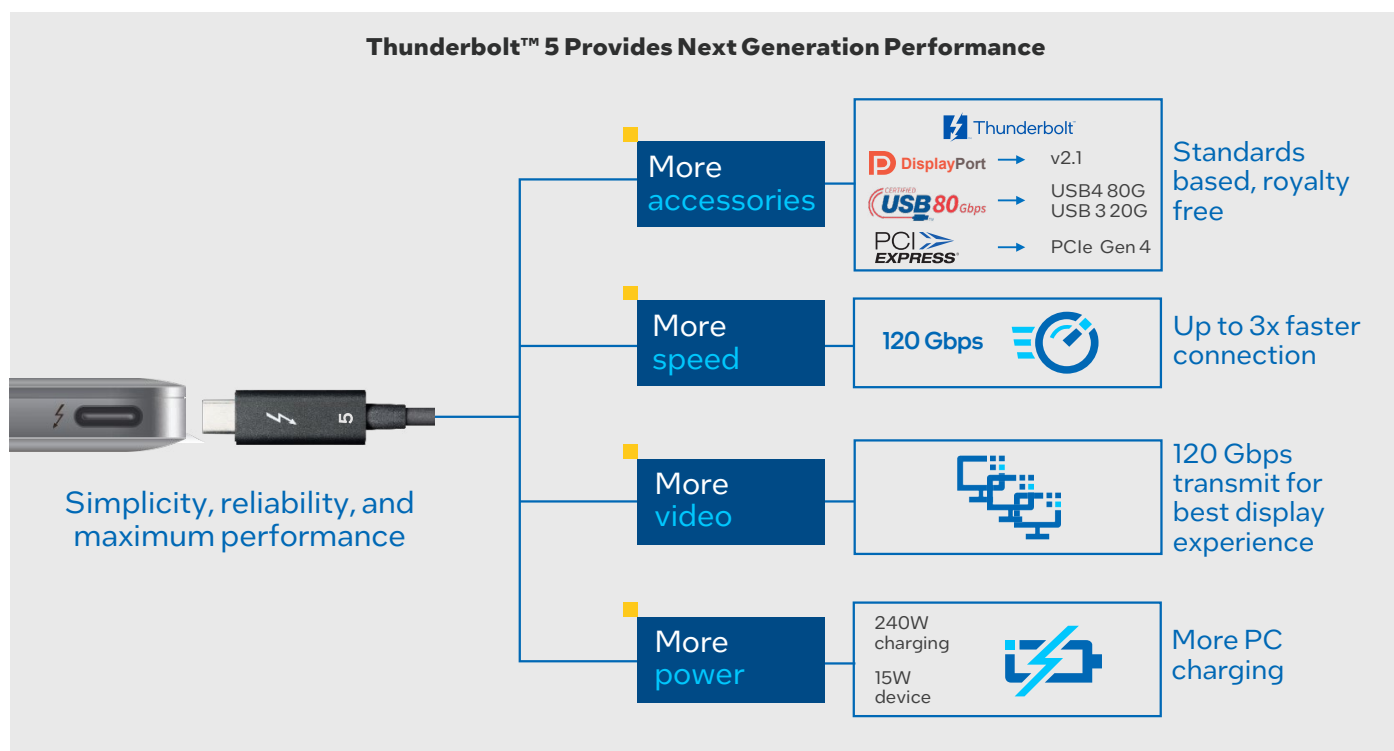


Figure 3. Universal connectivity

New Benefits and Technologies in Thunderbolt 5

Bandwidth Boost

While Thunderbolt 5 delivers 80 Gbps of bidirectional bandwidth for data, a completely new capability called **Thunderbolt Bandwidth Boost** provides the user with added flexibility. Bandwidth Boost can rebalance the Thunderbolt link when the system needs high levels of video bandwidth, increasing the transmit speed to 120 Gbps, as illustrated in Figure 4. This provides up to 3x more video bandwidth than Thunderbolt 4, and up to 50% more video bandwidth than DisplayPort 2.1 (UHBR20).

Bandwidth Boost is based on the asymmetry mode in the USB4 v2 spec. When transmit and receive are evenly distributed, users get 80 Gbps upstream and downstream

bandwidth. But when a high volume of display traffic is needed, Bandwidth Boost is activated to redistribute the bandwidth to better match demand, dedicating 120 Gbps for transmit traffic while providing 40 Gbps for receive, as shown in Figure 4.

This new capability lets users connect multiple high-definition monitors at the resolutions they want and still have ample bandwidth for data. It especially benefits gamers and content creators, where high-quality visuals at high refresh rates are critical, and makes a Thunderbolt 5-enabled USB-C connector the most capable display connector in the PC client ecosystem.

The ability of Thunderbolt 5 to efficiently handle bandwidth allocation between display and data traffic sets it apart as a versatile connectivity solution.

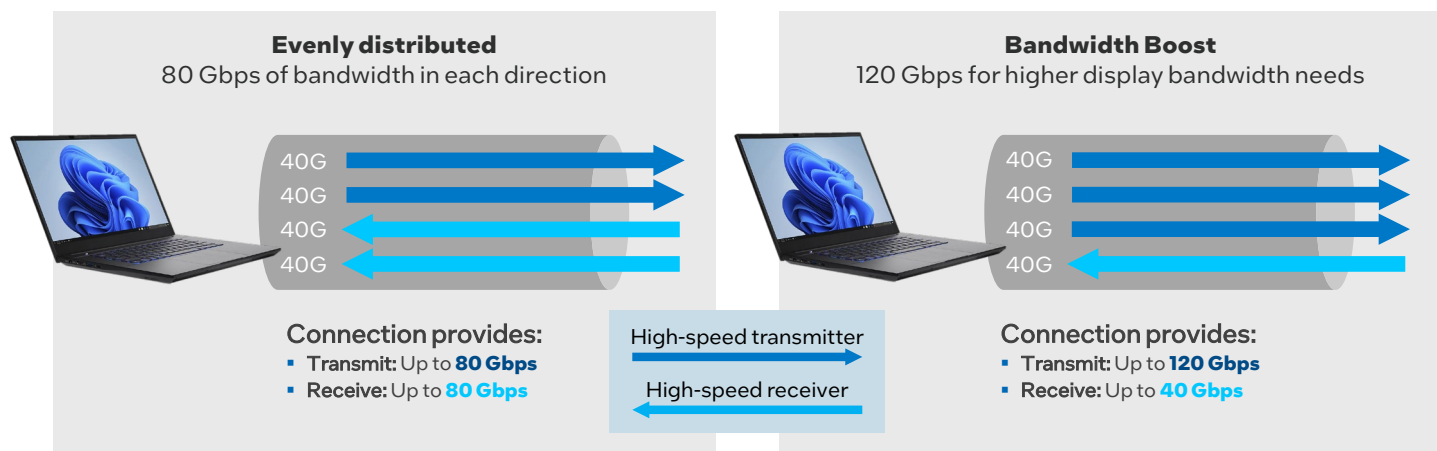


Figure 4. Bandwidth flexibility based on usage

The Latest Signaling Technology

Thunderbolt technology enables superior data integrity with a Bit-Error-Ratio less than a miniscule 10^{-19} . To achieve this, Thunderbolt 5 takes advantage of Pulse Amplitude Modulation with three-level (PAM-3) signaling technology.

A comprehensive analysis of many different modulation technologies established that PAM-3 is the only technology available that meets the USB Implementers Forum specification target, providing meaningfully better performance than alternative technologies. It enables a substantial rate reduction compared to PAM-2 (see Figure 5), with a better signal-to-noise ratio than PAM-4. PAM-3 enables more data to be transmitted per clock cycle over existing Thunderbolt cables, connectors, and

motherboards, eliminating the need for new (and often more expensive) hardware.

PAM-3 provides significant performance benefits thanks to its optimal balance between baud rate and noise tolerance, which enables robust operation with substantial electrical margins. This technology ensures that Thunderbolt 5 can deliver exceptional performance while supporting increased bandwidth and maintaining compatibility with existing solutions.

PAM-3 works within manufacturers' existing board materials and designs, making the addition of Thunderbolt 5 an easy and cost-effective solution for implementation across a wide range of devices.

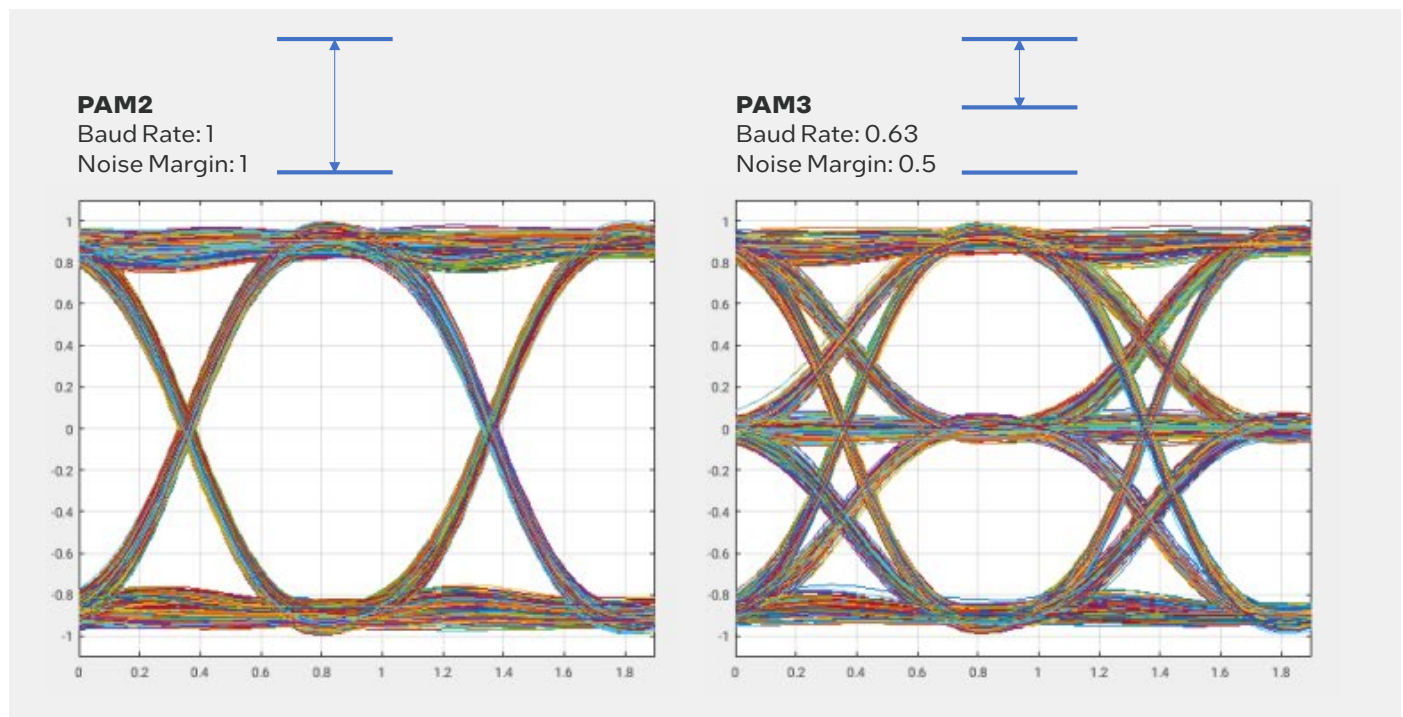


Figure 5. Pulse Amplitude Modulation Schemes

Blazingly Fast Data Transfer

With 64 Gbps of PCIe bandwidth, Thunderbolt 5 delivers 2x the data transfer speeds of Thunderbolt 4 to accelerate storage-intensive applications and support high PCI-demanding data devices such as eGFX and capture devices.

2x Data for Improved Networking

Using Thunderbolt networking, power users can move massive amounts of data quickly and easily between PCs and workstations. 64 Gbps throughput enables faster file transfers, backups, PC migration, and more.

Increased Power for Charging

Thunderbolt 5 supports (but does not require) Extended Power Range (EPR) support, delivering up to 240 watts of power. USB Power Delivery 3.1 enables quick charging of even the most demanding notebooks.

Why Thunderbolt 5 Matters

By delivering new enabling technologies and features, Thunderbolt 5 provides users with critical benefits now and into the future:

- **Improved display experiences:** Thunderbolt 5 enables users to connect more monitors at higher resolutions and faster refresh rates than ever for uncompromised display experiences.
- **Leading performance:** Thunderbolt 5 meets demanding requirements for faster upstream and downstream transfer speeds. Fast access to large amounts of data means faster file transfers, quicker access to application data, and improved productivity.
- **Connectivity and support for essential accessories:** Combining multiple protocols into a single, compact interface allows for seamless connection of devices, all using a single Thunderbolt cable.
- **Enhanced power delivery:** Users can charge laptops and USB-equipped accessories directly, reducing the need for multiple chargers and adapters, streamlining the user experience, and reducing clutter.

Into the Future

As we've seen, the evolution of Thunderbolt technology is driven by the ever-increasing demand for higher display and data performance. Previous generations of Thunderbolt offer impressive performance, but as file sizes and resolutions continue to increase, there is a need for even faster data transfer rates and improved connectivity options. Today's systems demand more power for processing and for charging ever-more-demanding PCs, and Thunderbolt 5 substantially improves both performance and power delivery. With increased data throughput rates, Thunderbolt 5 raises the bar as the fastest USB-C connector on the market, and also as the fastest data and display connector available in client PCs.

Thunderbolt technology will continue to support a wide range of use cases across the computing industry. Whether for general users, corporate environments, creators, gamers, SMBs, or large enterprises, Thunderbolt will remain a versatile and high-performance solution for display, data transfer, and connectivity needs thanks to its ability to simplify setup, enhance productivity, and support future advancements.



1. 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.
2. Calculations are based on the total bandwidth available for video and data and compare Thunderbolt 4 at 40 Gbps to Thunderbolt 5 at 120 Gbps for transmit.
3. Calculations are based on the total bandwidth available for video and data and compare Thunderbolt 4 at 40 Gbps to Thunderbolt 5 at 80 Gbps for transmit/receive.
4. Thunderbolt 4 is required for thin and light notebooks that require less than 100W to charge via the Thunderbolt connection. Thunderbolt 5 is required for thin and light notebooks that require less than 140W to charge via the Thunderbolt connection and is able to be designed to deliver up to 240W.
5. Maximum theoretical bandwidth, realized performance dependent on specific hardware and software configuration.
6. Or equivalent when utilizing a non-Intel CPU.
7. Thunderbolt 4 and Thunderbolt 5 provide DisplayPort, which can natively connect to all displays with DisplayPort and mini-DisplayPort, and via adapters can connect to all other modern display interfaces, including HDMI, DVI, and VGA.

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Data transfer rates, different from the total available bandwidth for data and display traffic, depend on system configuration.

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