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White Paper

Latency in optical fiber systems

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Introduction

Latency is a time delay between a stimulation and its response. It is caused by velocity limitations in a physical system. In simplest terms, latency is the time it takes for a signal to travel (or propagate) from point A to point B. In telecommunications, latency describes the time delay of a packet traveling through a network or the delay imposed on a signal traveling in a transmission medium such as a copper cable, optical fiber waveguide, or even free space; in radio transmissions it is the time it takes a radio signal to propagate through free space from the transmitter to the receiver; for electrical transmissions, it is the time the electrical signal takes to propagate through a metallic or conductive medium; and, in optical transmission, latency describes the time required for the optical signal to propagate through free space or in the core of an optical fiber.

Speed of Light

The speed of light in a vacuum is a universal physical constant denoted by the symbol c and is used to determine velocity limitations in all transmission media. It is based on two physical constants: the permittivity in a vacuum (electric constant), denoted as ε_0, and the permeability in a vacuum (magnetic constant), denoted as μ_0. Using these two values, the speed of light in a vacuum can be determined using the formula:

$$c = \frac{1}{\sqrt{\varepsilon_0 \, \mu_0}} \ [\mathrm{m/s}]$$

Latency is a function of distance and the speed of light. In a vacuum (or free space), light travels at 299,792,458 meters per second (m/s). To make the math easier, the value is rounded up to 300,000,000 m/s (or 3×10^8 m/s). Therefore, light traveling over a distance of 1 kilometer in a vacuum will result in a time delay, or latency, of 3.33 microseconds (µsec). While the speed of light in air is slightly slower than in a vacuum, the difference (0.3 percent) is so slight it is usually ignored.

To the human eye, electrical and optical phenomena are perceived as being instantaneous. When we turn on a flashlight, the object at which it is pointing appears to illuminate instantly. However, we know it takes a finite amount of time for the flashlight's beam to travel to the object—and a finite amount of time for the reflected light to return to our eye. If the object to be illuminated is 100 meters from the flashlight and the latency from flashlight to object is 0.33 µsec, the time required for the light to travel from the observer's flashlight to the object and back to the observer (round-trip delay), is 0.66 µsec.

$$t_{Latency} = \frac{Distance}{Velocity} = \frac{100\ \mathrm{m}}{300{,}000{,}000\ \mathrm{m/s}} = 0.33\ \mu\mathrm{sec}$$

$$Round\ trip = 2 \times t_{Latency} = 0.66\ \mu\mathrm{sec}$$

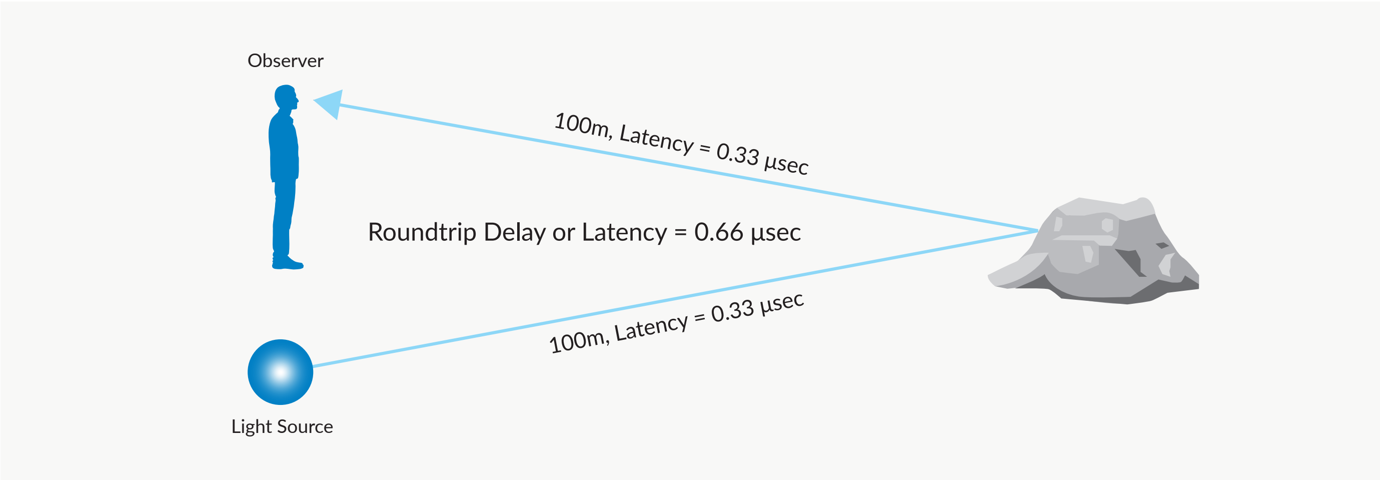

Figure 1: Basic latency example. The symbol c is used to denote the speed of light.

In the same way, we can calculate the time it takes light to travel from the sun to the Earth (approximately 8.3 minutes) or for a radio signal to travel from Earth to Mars (about 12.5 minutes).

Contributors of latency

In any optical fiber system, there are a minimum of five latency contributions (**Figure 2**). Two are created as the signal moves from the electrical domain to the optical; another contribution occurs as the signal travels down the optical fiber; and two more are created as the signal is converted from the optical domain back to the electrical.

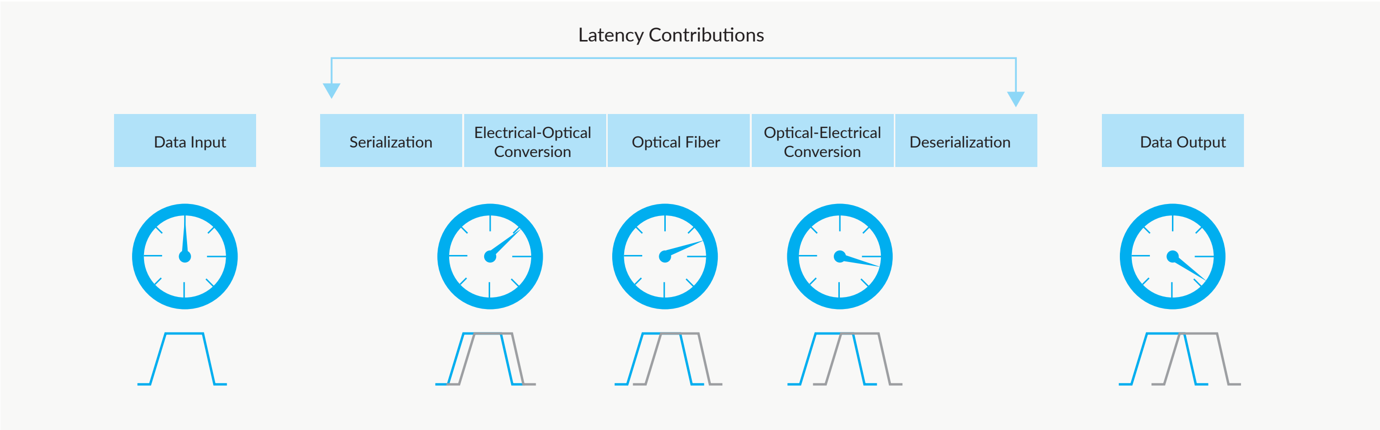

Figure 2: Conversion latency in an optical fiber data path. Relative contributions of each element are shown by the "latency clocks." In any case, the data arrives at the output at a later time than when it was input into the system.

Prior to entering the optical fiber, blocks of data bits—sometimes referred to as "words"—must be broken down into individual bits that can be more easily transported by the optical fiber. This process is known as "serialization" and contributes to the end-to-end latency of the signal. Next, the signal must be converted from an electrical current to optical pulses of light. This process also contributes to overall latency.

Once inside the optical fiber, the signal takes time to go from one end to the other, resulting in transmission media latency. As the optical signal exits the other side of the fiber, it must be converted from optical energy back to electrical and from its deserialized format in bits, back to its original serialized form—words. As this scenario reflects the most basic transmit path for an optical signal, we can say there are, at minimum, five contributions to latency in any optical fiber path.

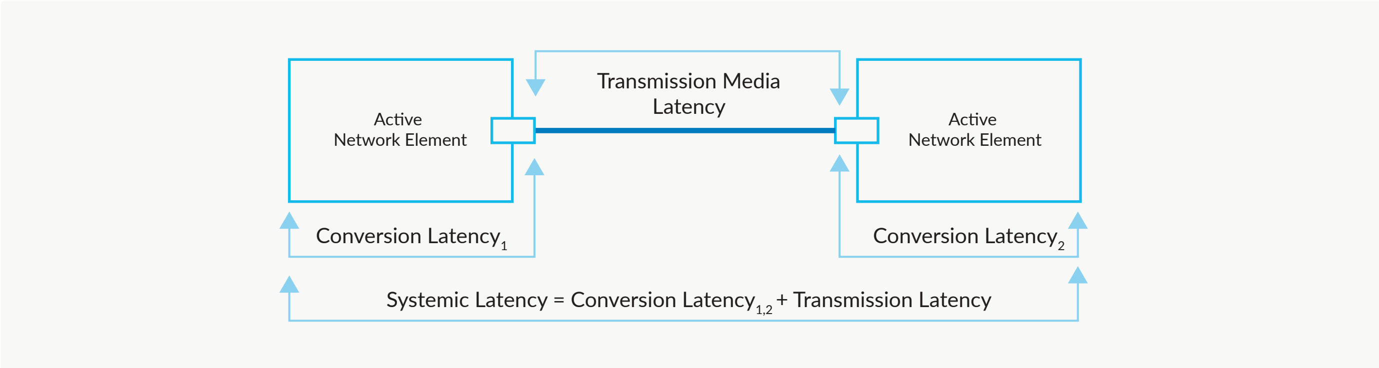

Figure 3: Systemic latency is a cumulative phenomenon; any delay introduced by an element such as transmission media or active network element adds to the total delay.

Conversion latency is specific to the application, protocol, and active equipment involved. It is based on the design of the system and its contribution to overall latency is not affected by distance. However, the latency contributed by the transmission media is a fixed value per unit length, so the longer the transmission line the greater the latency contribution. Systemic or total latency is the sum of all latency contributions and varies depending on the total length or distance of the transmission media.

Transmission media

Latency in transmission media is the consequence of velocity limitations in the transmission medium and is caused by its physical properties. Communication systems use various types of transmission media to transport signals. The type of media used is based on the bandwidth and transmission distance required by the application.

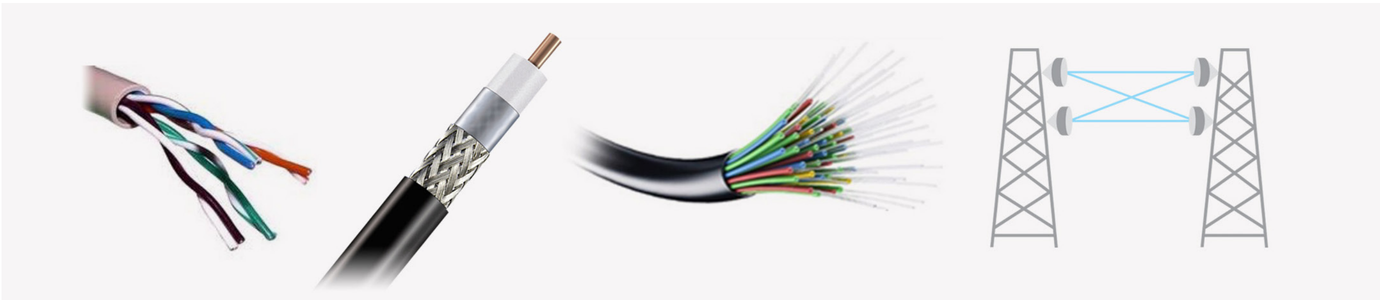

Figure 4: Examples of transmission media. From left to right, unshielded twisted pair, coaxial cable, fiber-optic cable, and free space.

Media	% of c	Description
Thick coaxial cable	77%	Originally used for ethernet, referred to as “thicknet”
Thin coaxial cable	65%	Referred to as ethernet “thinnet” or “cheapernet”
Unshielded twisted pair	59%	Multipaired copper cabling used for LAN and telecom applications
Microstrip	57%	PCB trace on FR4 dielectric, µr = 3.046
Stripline	47%	PCB trace in FR4 dielectric, µr = 4.6
Optical fiber	67%	Silica waveguide used to transport optical energy
Vacuum	100%	Vacuum or free space

In the table above, % of c indicates how fast a signal will travel through the media compared to the speed of light in a vacuum. That percentage is inversely proportional to its contribution to latency. As the percentage of c decreases, the latency increases. Note the degree to which the material and construction of the transmission media impact latency.

It is also interesting to note that thick coaxial cable and stripline are based on electrical transmission over copper conductors, whereas optical fiber (or waveguide) is used for the transmission of optical energy. Even though thick coaxial cable provides the best percentage of c value, it is not commonly used in modern telecommunications because of its distance and bandwidth limitations. Every transmission medium has a distance limitation, which is due to numerous physical phenomena. Overall, optical fiber is ultimately superior in terms of percentage of c, distance, and bandwidth over any copper transmission media.

Latency in optical fibers

An optical fiber consists of a cylindrical core of silicon dioxide (fused silica glass) surrounded by a cladding. The core and cladding comprise the optical transmission media (or optical waveguide) and are usually coated for protection.

OPTICAL FIBER

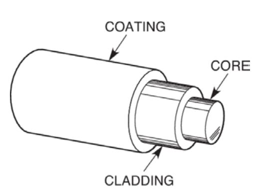

Figure 5: View of a single optical fiber. The diameter of the core is 50 µm for a multimode optical fiber and nine µm for a singlemode optical fiber. The diameter of the cladding is 125 µm for both fiber types.

Latency in optical transmission media is a consequence of limited velocity in the optical media. To determine the latency contribution of an optical fiber, it is necessary to know the refractive index of the glass used in the core, as well as the length of the optical fiber. Refractive index is a measure of the degree to which the light rays will be bent (or refracted) when light enters the media. The refractive index also determines how much slower light will travel in the optical fiber compared to a vacuum. The refractive index for the core and cladding is denoted as n1 and n2. The use of n for the refractive index is the standard nomenclature used in optical fiber data sheets.

$$t_{Fiber\_Latency} = \frac{L}{c}\, n \; [\mu sec]$$

Because light travels approximately 1.5 times slower through optical fiber than in a vacuum, the latency is 5 µsec per kilometer. The number 1.5 is referred to as the Index of Refraction and will vary slightly based on the wavelength of light being propagated and composition of the optical fiber.

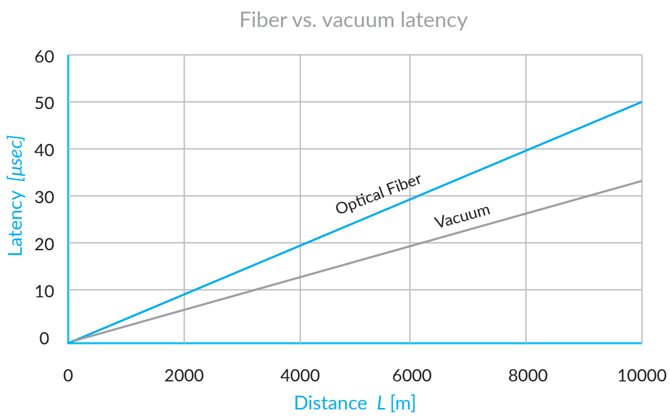

Figure 6: Latency of light travelling in a vacuum versus an optical fiber with n = 1.5.

As shown in **Figure 6**, a straight section of a single fiber that is 10 kilometers long will contribute approximately 50 µsec of latency as compared to 33 µsec in a vacuum. However, fiber between two locations is not always routed along the most direct path, so the latency of an optical fiber path must be measured after installation.

Summary

Latency is the time it takes a signal to travel (or propagate) in a medium or system from point A to point B and is a phenomenon in all transmission media. In today's world, bandwidth demand is growing at an exponential rate, so latency in telecommunication networks is constantly being evaluated and methods are being developed to monitor, and, if possible, minimize latency. In optical fibers, latency is dependent upon the refractive index of an optical fiber and is relatively constant at a specific optical wavelength. This enables data center operators—especially those that provide co-location services to the financial sector—to "calibrate" optical links to ensure uniform latency among all customers.

There is a direct correlation between latency and maximum bandwidth in optical fiber systems. Latency limits the maximum rate information can be transmitted because all systems have limits on the amount of information that can be "in-flight" at any one moment. Excessive latency can have a detrimental effect on high-bandwidth applications.

Latency cannot be eliminated—only managed. In optical network applications where latency can be detrimental, the contribution from active network equipment, optical transceivers, optical cable, and even optical cable routing must be carefully considered. Selecting an optical fiber that has the lowest index of refraction for the wavelength of interest will mitigate latency. Using the shortest possible optical fiber during routing can also mitigate latency. **Figure 7** illustrates why an 11-kilometer link contributes five µsec more latency than a 10-kilometer link.

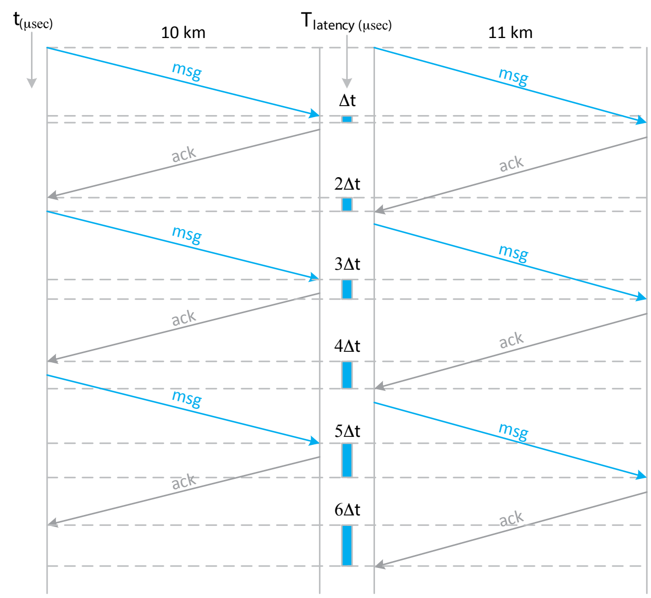

Figure 7: Latency contributed by the optical fibers only. No active equipment or processing delays are included.

Both links have a data rate of 10 Gbps. Due to its shorter distance, the 10-kilometer lower latency link will receive 50,000 bits before the 11-kilometer link has received any. The effects of latency are cumulative. Each message cycle (msg, ack) on the 10-kilometer link requires 100 µsec, while the 11-kilometer link, which is 10 percent longer, requires 110 µsec. So, in the time it takes to transmit 10 message cycles on the 11-kilometer fiber, the 10-kilometer link would have transmitted 11.

Active elements that contribute to latency—such as active network equipment and optical transceivers—have enough data provided in their technical documentation so the contribution of each element can be determined. This information, in combination with the use of good optical fibers, will enable an experienced network designer to develop the best implementation strategy for a latency-sensitive application.

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