

A Rocky Mountain Chapter White Paper: “Velocity of Propagation”

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The following is adapted from an article I wrote about understanding velocity of propagation, which originally appeared in the March 2010 issue of *Communications Technology*.

If you’ve looked at a spec sheet for coaxial cable, you’ve no doubt seen a parameter called velocity of propagation. For instance, the published nominal velocity of propagation for a widely used Series 59 headend cable is 85%, and .500 feeder cable often has a published value of 87%. What do these numbers mean, and where do they come from?

We know that the speed of light in free space is 299,792,458 meters per second, which works out to $299,792,458/0.3048 = 983,571,056.43$ feet per second, or $983,571,056.43/5,280 = 186,282.4$ miles per second. The reciprocal of the free space value of the speed of light in feet per second is the time it takes for light to travel 1 foot: $1/983,571,056.43 = 1.02\text{E-}9$ second, or 1.02 nanosecond. In other words, light travels a foot in free space in about a billionth of a second. Light is part of the electromagnetic spectrum, as is RF. That means RF zips along at the same speed that light does – in a vacuum.

Now let’s define velocity of propagation: It’s the speed at which an electromagnetic wave propagates through a medium such as coaxial cable, expressed as a percentage of the free space value of the speed of light. Based on this definition, RF travels through the Series 59 headend cable at 85 percent of the free space value of the speed of light, or 836,035,397.97 feet per second. RF travels through the .500 feeder cable at 87 percent of the free space value of the speed of light, or 855,706,819.09 feet per second. The time it takes for RF to travel through 1 foot of each of these cables is $1.20\text{E-}9$ second (1.20 nanosecond) and $1.17\text{E-}9$ second (1.17 nanosecond) respectively.

This brings up another question: Why does RF travel through coaxial cable at a slower speed than it does through free space?

Let’s look at the basic construction of coaxial cable, which is a two-conductor transmission line. The inner or center conductor is covered by a plastic material called the dielectric, and the dielectric is surrounded by a tubular-shaped outer conductor or shield. A plastic covering, or jacket, may be used to protect the outside surface of the shield. The dielectric keeps the center conductor supported in the middle of the cable, and also insulates it from the shield.

When RF travels through coaxial cable, RF currents propagate on and near the outer surface of the center conductor, and on and near the inside surface of the shield. Skin effect keeps the RF currents on and near the surfaces of the two conductors. At the same time, an electromagnetic field is propagating through the cable in the dielectric-filled space between the

center conductor and shield. The electromagnetic field configuration or mode that we're interested in here is what's known as the transverse electromagnetic (TEM) mode. It's called TEM because the electric and magnetic fields belonging to that mode are normal or perpendicular to the direction of propagation.

If you could see the fields' lines of force from, say, the end of the cable, the electric field lines would resemble spokes "connecting" the center conductor and shield, and the magnetic field lines would look like concentric circles around the center conductor. If there were no dielectric, the conductors were perfect, and the space between the center conductor and shield were a vacuum, the TEM waves would propagate through the cable at the free space value of the speed of light. But they don't. They are slowed down an almost negligible amount by losses in the conductors. The major culprit that slows the waves down is the dielectric—and it slows TEM waves down a bunch, often by as much as 10 to 20 percent or more! Here's an analogy: It's easy to walk along a smooth concrete sidewalk, but if you were trying to walk through deep mud it would take longer to cover the same distance.

The ratio of the speed of TEM waves in a vacuum to their speed in a dielectric is mathematically defined as $n = v_{\text{TEM}}(\text{vacuum})/v_{\text{TEM}}(\text{dielectric})$, where n is a dimensionless number greater than 1 that is the index of refraction. The reciprocal of index of refraction is the velocity factor, $v_{\text{TEM}}(\text{dielectric})/v_{\text{TEM}}(\text{vacuum})$.

The dielectric's magnetic permeability and electric permittivity are two properties that determine the velocity of TEM waves in coaxial cable. The ratio of the dielectric's permittivity to the permittivity of a vacuum is the relative permittivity (also called relative static permittivity), or dielectric constant ϵ_r . The speed of a TEM wave in a dielectric is equal to the ratio of its speed in a vacuum to the square root of the dielectric constant: $v_{\text{TEM}}(\text{dielectric}) = v_{\text{TEM}}(\text{vacuum})/\sqrt{\epsilon_r}$. A little number crunching with the latter equation and the ratio that defines index of refraction gives us $1/\sqrt{\epsilon_r} = \text{velocity factor}$.

If we go back to the two cable types discussed earlier, the headend cable's velocity factor is 0.85 and the feeder cable's velocity factor is 0.87. Velocity of propagation is velocity factor expressed as a percentage, so $0.85 = 85$ percent, and $0.87 = 87$ percent. A little more number crunching tells us that the headend cable's calculated dielectric constant ϵ_r is about 1.42, and the feeder cable's is about 1.32.

Over the years the coax manufacturers have gone to great lengths to improve dielectric composition and chemistry in an effort to lower the dielectric constant, reduce dielectric losses, and improve attenuation performance of the cable. Some of you may be familiar with solid polyethylene dielectric cables that have a velocity of propagation around 66 percent. Old copper braid drop cables used this kind of dielectric. Solid poly cables are still used in some two-way radio and similar applications, but they do have greater per-foot attenuation than a foam dielectric cable of the same size. Coax used by the cable industry today generally has a gas injected/expanded foam dielectric (some earlier designs had chemically expanded foam dielectrics). Drop cables have a velocity of propagation in the 84 to 85 percent range, and outside

plant trunk and feeder cables are around 87 to 88 percent. The old MC² cable was a disc-and-air dielectric design that had a published velocity of propagation of 93 percent.

Here's a final question: Does RF travel through coaxial cable faster or slower than light travels through single mode optical fiber? Surprisingly, light travels through fiber slower than RF travels through coax! For example, the published effective group index of refraction for a popular single mode optical fiber is 1.4676 at 1310 nanometers. That puts the velocity factor at $1/1.4676 = 0.6814$, and the velocity of propagation at just over 68 percent. The light makes its way through the fiber at the leisurely pace of 670,190,144.75 feet per second, or through 1 foot of fiber in $1.49\text{E-}9$ second (1.49 nanosecond).