An Overview of High-Speed Communications Over Twisted-Pair Cables

by Mark Sauerwald, Applications Engineer, MTS
National Semiconductor Corporation

We have been installing and using twisted-pair cable since the late nineteenth century. Now in the twenty-first century it is still the most widely used cable type for high-speed data communications. Twisted-pair cable (Fig. 1) is commonly used for telephone lines, including the DSL service that brings high-speed internet connectivity into millions of homes. It's also used for Ethernet connections and the HDMI and DVI connections to your TV receiver and computer monitor, among others. Despite finding twisted-pair cable pretty much everywhere you look, if you search for articles that provide an in-depth analysis of the properties of these cables, you find very little.

There is plenty of material available discussing coax cables, and PCB traces, but despite the broad use of twisted pair, there is not a lot available showing how it behaves under various circumstances. Looking into this, I discovered that one of the reasons for the lack of twisted-pair cable analysis is because you quickly get into some really nasty math. When doing the analysis of coax or a PCB layout, you can get a pretty good model of the cable's behavior with a two dimensional analysis, but twisted-pair cable is intrinsically a 3D structure: without the third dimension, there is no difference between twisted and untwisted pairs of conductors! Therefore, this article is intended to provide designers with an overview of high-speed communications over twisted-pair cable and identify the issues in getting high-speed data from point A to point B.

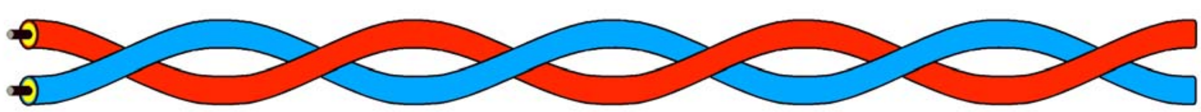

Fig. 1: Simplified Illustration Of Twisted-Pair Cable

One of the major attractions to twisted-pair cable is that it allows signals to be sent in balanced pair operation, where the signal is referenced not to ground, but to the opposite side of the twisted-pair cable. In balanced pair operation, if there is interfering magnetic or electric fields, they will couple into both lines of the twisted pair equally, and since the receiver is looking at the difference between the two lines in the twisted pair, the interference has a much smaller effect. Because of this relative insensitivity to interference, differential signals – which have smaller signal swings – can be used, saving power over a single-ended system under similar circumstances.

Signal Loss in Differential Cables

Although the mathematics involved in deriving the attenuation characteristics of twisted pair are a lot more complicated than for coax, the end result is very similar: there are three loss mechanisms:

- Resistive loss, which comes as a result of the resistance of the cable. This effect is independent of frequency, and is quite small. In most cases, it is not a factor. You need to worry about this if you are sending very low data rate signals or power over long distances of cable
- Skin effect loss in which the attenuation increases as a function of the square root of the frequency. It does not take a very high frequency for this effect to become the dominant form of attenuation, so for most of the useful applications of twisted-pair cable, this is the primary loss to be concerned with. For a more detailed description of skin effect losses, please read *With A Good Cable Equalizer, An Engineer Can Go Far In This World* http://www.en-genius.net/includes/files/iot_011209.pdf
- Dielectric losses, which increase linearly with frequency, but start out quite low

If you consider the signal from a data rate perspective, at very low rates the dominant form of attenuation is the resistive loss, but it does not take a very high data rate for the skin effect losses to dominate. Once you get to data rates above 1 Gbit/s or 2 Gbit/s, the dielectric loss begins to come into the picture, and quickly dominates. Since the dielectric loss is proportional to both the data rate and the cable length, once it enters the picture things start to go downhill in a hurry, and its appearance represents the practical upper limit to the data rate at which the cable can be used.

Category Cables

Much of the twisted-pair cable that is used for communications is “Category Cabling” described with something like CAT3 cable. CAT1 and CAT2 cables are rarely seen anymore, with CAT3 being the minimum standard of cable recommended for use in the telephone network. CAT3, CAT5e and CAT6 cable are all specified by the EIA/TIA standard 568B.

Cable Category	Characterized to	Data Rate	Construction	Common Applications
CAT3	16 MHz	10 Mbit/s	UTP	Telephone
CAT4	20 MHz	16 Mbit/s	UTP	10 Base T, 16 Mbit/s Token Ring
CAT5e	100 MHz	80 Mbit/s	UTP	100BASE-T Ethernet, 155 Mbit/s ATM
CAT6	250 MHz	200 Mbit/s	STP	Gigabit Ethernet
CAT7	600 MHz	500 Mbit/s	Individual screen shield	10 Gigabit Ethernet

Each of these category cables has its own, fairly well defined characteristics. For example, as per ANSI TIA/EIA-568-B.2, the insertion loss of CAT5e must be less than or equal to:

$$InsertionLoss = 1.967\sqrt{f} + 0.023f + \frac{0.050}{\sqrt{f}}$$

where, f is measured in MHz and the end result is loss, measured in dB, per 100 m of cable.

The first term in this equation represents the skin effect loss, and the second term relates to dielectric loss. To find out where the crossover point is, where the dielectric loss becomes dominant, we look for the value of f such that the first and the second terms are equal. This happens at a frequency of about 4 GHz

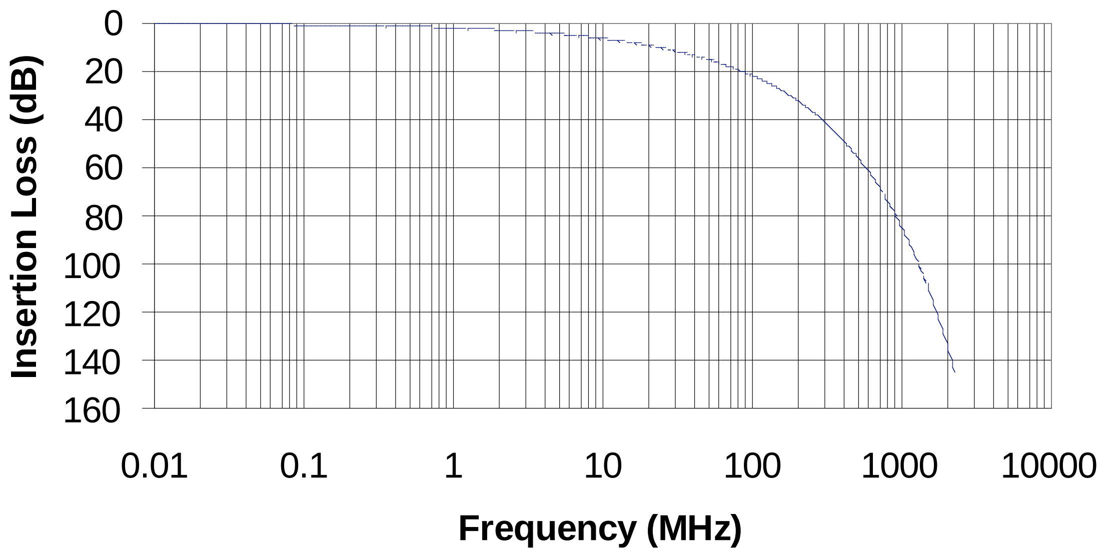

Fig. 2: CAT5e Insertion Loss Vs. Frequency

As can be seen in Fig 2, although the dielectric loss might dominate after 4 GHz, by the time the frequency gets up to 1 GHz, loss is already on the order of 80 dB, making this cable difficult to use except for very short runs.

One way to extend the reach of twisted-pair cable is to use an adaptive cable equalizer such as the DS15EA101 which has an analog filter in it, with an inverse characteristic to the loss and a servo mechanism that adjusts the gain of the filter to compensate for the cable insertion loss. Using such an equalizer will enable cable lengths as long as 75 m at a data rate of 1 Gbit/s.

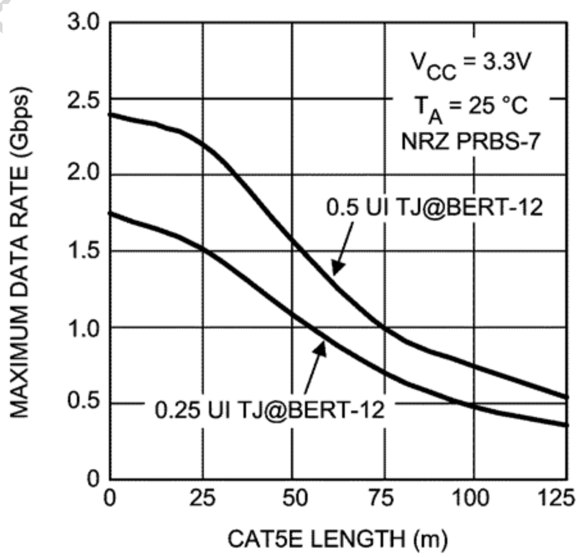

Fig. 3: Max Data Rate Vs. Cable Length For CAT5e Cable Using Equalizer

In many cases, when a twisted-pair cable is being used to transmit data across a link, it is being driven by a serializer. Many serializers have the ability to predistort the signal they're driving into the cable, boosting the high frequency components of the signal. In pre-emphasis, the high frequency components are boosted, giving the signal the appearance of overshoot and undershoot. Because pre-emphasis actually increases the peak-to-peak (p-p) signal swing beyond the nominal values, care must be taken that the receiver can accommodate this voltage if a shorter cable is used. Another way to achieve the same effect is with de-emphasis.

With de-emphasis the first portion of the unit interval is left the same, but a short time after an edge transition, the amplitude is brought down to a lower level. The signal looks similar to the signal with pre-emphasis, but the overall amplitudes are smaller. De-emphasis takes advantage of the fact that with twisted-pair cables and differential signals, we generally have a surplus of noise immunity. An example of a serializer that offers programmable de-emphasis is the DS32EL0421. This serializer can generate serial data streams at rates up to 3.125 Gbit/s.

Crosstalk and Interference

As mentioned in the introduction, one of the attractions of twisted-pair cable is its relative immunity to interference. Despite this insensitivity, there are cases where interference does manage to have a negative impact on a twisted pair communication system. One of the useful features of twisted-pair cable is that it often comes with multiple twisted pairs together within one sheath, making it easy to install one cable and get several conductor pairs. However as with most silver linings, this one comes with a dark cloud: crosstalk. When you put more than one twisted pair inside the same sheath, they invariably interfere with one another. There are several methods that are used to decrease the amount of crosstalk in cables with a wide range of different costs and effectiveness.

The most common way to reduce crosstalk is to simply twist the pairs at different twist rates within the cable (the twist rate or pitch of the twist is usually defined in twists per meter). If two pairs have different twist rates, then when they lie next to each other, any interference from one pair will tend to cancel out when looked at differentially. If different twist rates are not providing enough isolation between the pairs, an alternative solution would be to use shielded twisted pair (STP) cable.

With STP, there is a thin foil shield wrapped around each pair within the sheath which holds all of the twisted pairs together. If installed correctly, the foil shields are connected to GND at each end of the cable, and this provides an effective barrier, preventing the electromagnetic fields generated by one pair from interfering with another pair in the same cable. Although STP provides better pair-to-pair isolation than the more common unshielded twisted pair (UTP), STP has several disadvantages, including:

- STP is more expensive than UTP
- STP is more difficult to install than UTP
- STP is bulkier than UTP

Near-End Crosstalk

One issue that commonly comes up with multiple twisted-pair cables is that different pairs on the cable might be used to send data in opposite directions. In this case, crosstalk can become an even greater issue. Let's assume a system in which a signal with 300 MHz bandwidth is being sent from point A to point B, using 100 m of CAT5e cable, and at the same time, a return signal is being sent from B to A. Referring to Fig. 2, we see that we could expect about 40 dB of attenuation, which will require a cable equalizer to recover the signal, but is still quite feasible to implement.

Now, consider the issue of crosstalk in the section of cable closest to point A. The signal that has been sent from point B has been attenuated by 40 dB, but the signal which is being sent from point A is still full strength: so it is a very strong aggressor! Even a small amount of crosstalk might swamp out the received signal and make it impossible to recover. This is referred to as near-end crosstalk, or NEXT. Most cable manufacturers specify the NEXT of their twisted-pair cables, and the category cables specify the maximum allowable amount of NEXT for each particular cable.

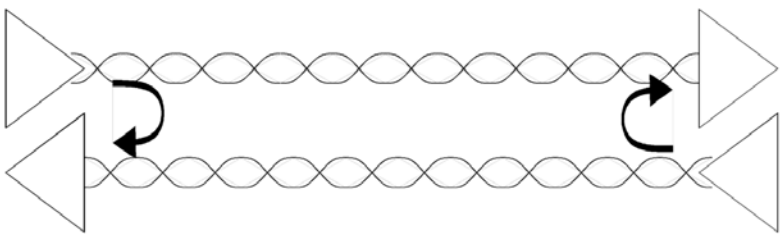

Fig. 4: Near-End Crosstalk (NEXT) With Transmitter Interfering With Receiver

In the case of the CAT5e cable that we used in our example above, allowable NEXT is given by the equation:

$$NEXT \leq 35.3 - 15\log_{10}\left[\frac{f}{100}\right] \text{ dB}$$

And looking at the maximum allowable crosstalk at 300 MHz, we see that the NEXT is only guaranteed to be less than 28 dB. Given that the received signal will be down by 40 dB, we are going to have a problem trying to recover that signal.

There are a few options available in this case. One would be to use a higher grade of cable and, for example, the losses with CAT6 cable are a bit less and NEXT is guaranteed to be about 10 dB better, so the margins are improved significantly.

Moving up the cost/quality curve there are cables such as CAT7 which have foil shields around each individual twisted pair within the sheath. This provides a much greater degree of isolation between adjacent pairs, but at the cost of more expensive cable and more complicated installations.

Another thing that can be done is to make the signals you're transmitting less likely to interfere by limiting their high frequency content and energy. If your transmitter has a pre-emphasis option, don't use it if it's not needed.

***Noise* In Twisted-Pair Cables**

When a signal is traveling down a controlled impedance line and it encounters an impedance discontinuity, there is a reflection that occurs at the discontinuity. If the transmission line has many small discontinuities, all of these reflections add up, each with a corresponding time delay, which appears as noise. In the case of twisted-pair cable, the impedance is dependent on how closely the two lines in the twisted pair are aligned. Because of this, if a length of twisted-pair cable is kinked; or forced into a sharper radius bend than is specified; or is stretched by being pulled too hard to get it to go through a conduit; or is abused in a variety of other ways, these minor impedance discontinuities show up along the length of the cable. The net result is that when the received signal is examined, it will appear noisy. For this reason, it is important to gently install the twisted-pair cable.

Summary

Twisted-pair cable is everywhere. It is used for everything from telephones to multi-gigabit per second HDMI connection to your plasma TV display. The broad use of twisted-pair cable comes from its compelling advantages – it is inexpensive, easy to work with and install, and has a broad range of different types available for different applications. Despite these compelling benefits, there are some issues with twisted-pair cable that the alert designer needs to be aware of. For example, attenuation through twisted pair is greater than through coax cable, and crosstalk, especially near-end crosstalk can be a deal-breaker. In addition, when operating twisted-pair cable near the edge of the performance envelope, that performance can be impaired by rough handling. So long as the designer is aware of these shortcomings and takes them into consideration, twisted-pair cable is often the best solution to getting high-speed data from point A to point B.

References

High Speed Signal Propagation by Howard Johnson and Martin Graham, 2003 Prentice Hall, ISBN-13 978-013084408X
Wire, Cable and Fiber Optics for Video and Audio Engineers by Stephen H Lampen, 1997, McGraw-Hill, ISBN-13 978-0070381346
Grounding for Screened and Shielded Network Cabling by Carrie Higbie
http://www.siemon.com/us/white_papers/06-07-20-grounding.asp
DS15EA101 Data Sheet by National Semiconductor
http://www.national.com/ds/DS/DS15EA101.pdf
DS32EL0421 Data Sheet by National Semiconductor
http://www.national.com/ds/DS/DS32EL0421.pd

About The Author

Mark Sauerwald earned a BEE from the University of California at San Diego in 1982. Since graduation, Mark has been involved in semiconductor components for digital video – first at TRW LSI products, working on ADCs for digital video, then at Comlinear, later acquired by National Semiconductor. Mark spent a few years working for Gennum Corporation before returning to National Semiconductor where he now works as an Applications Engineer with the Mixed-Signal Product Division. When not working, Mark is an avid cyclist, and a serious amateur photographer. mark.sauerwald@nsc.com